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THE GEOLOGY OF THE VOLCANIC ISLAND JAN MAYEN ARCTIC OCEAN

by

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C O N T E N T

ABSTRACT

The island of Jan Mayen is built up by potassic alkaline (dominantly basic) volcanic rocks. The volcanism is fed by a NE trending fissure system. On Nord-Jan eruptions have mostly occurred through the central crater of the volcanic cone Beerenberg and short radial fissures or single craters on its flanks. On Sör-Jan the eruptions have occurred on short NE trending fissures, single craters and domes. In many cases the eruptions were submarine resulting in hyaloclastites and other structural types typical of aqueous environments. Faults were not observed in the field.

The rocks are divided into five main stratigraphic units: 1) "Hidden" formations, which are of volcanic origin and extend up to the present sea-level. These formations are most probably younger than 1 m. years. 2) Havhestberget hyaloclastite formation, produced by submarine eruptions mostly in shallow water, while the island was emerging from the sea during middle Brunhes. 3) Nordvestkapp subaerial rock formation, a pile of lavas of variable structures and compositions, erupted after the land was emerged and until probably about 10 thousand years ago. 4) Inndalen subaerial rock formation, the youngest lava cover of the island, younger than 10 thousand years, and made of basaltic to trachytic lavas. 5) Unconsolidated detritus, a collection of all loose sediments on the island. These are mostly coastal sediments, glacial sediments, screes and frost action cover on flat terrain.

Relative sea-level changes have been lively in the area. Originally the island emerged from the sea by volcanic uppiling and then submerged again down to at least 170 m lower position than at present. This is recognized from marine fossils and the passage zone between subaerial lava structure and a flow foot unit in a lava. Since this lowest position the land has been rising.

Traces of the Pleistocene glaciation are surprisingly scarce and the island is believed to have been without major glaciers during the Pleistocene. This is probably mostly because of the small size and narrow shape of the island. The position of the island relatively far behind the sea-ice margin during maximum glaciation in the northern hemisphere could have resulted in relatively dry climatic conditions.

The size of the average erupted lava on the island is calculated to 0.07 km^3 and the average time between eruptions is 100-133 years. The total volume (200 km^3) of Jan Mayen above sea-level would by this productivity be produced in the last 0.37 m. years, which is in agreement with the normal magnetic polarity of the rocks. Comparison of calculated productivity within volcanically active areas of the North Atlantic shows the productivity of Jan Mayen to be closely similar to that of the Snæfellsnes volcanic zone in western Iceland, which produces alkaline rocks similar to the Jan Mayen ones. The tholeiitic volcanic zones of Iceland are much more productive. Production calculated on the basis of equal area gives 1.4 km^3 per 100 km^2 for Jan Mayen compared to 2.1 km^3 for the volcanic zones of Iceland and $\sim$ 0.5 km^3 for the oceanic ridges in the North Atlantic.

1. INTRODUCTION

Jan Mayen is an island in the Arctic Ocean built up by volcanism. This volcanism is connected to the well known mid-ocean ridge-fracture zone system of the world´s oceans.

The island is 53.6 km in NE-SW direction and the width is 2.5 - 15.8 km. It covers the area of 380 km^2. It extends from 7°56´W - 9°05´W and 70°50´N - 71°10´N. The highest mountain is Beerenberg, 2277 m (see Fig. 1 for all local names), an impressive volcanic cone on the northernmost part of the island.

The upper part of Beerenberg is covered by an ice cap, which sends glacial tongues in all directions. Several of these are typical outlet glaciers (skridjökull) and 5 of them calve into the sea, 2 on the eastern coast and 3 on the northwestern coast. The biggest one is Weyprechbreen, which is the outlet of the top crater of the volcano, more than one km in diameter. The front of the ice cap between the outlet glaciers is mostly a thin ice cover of slow movements. There is no permanent ice on the island outside Beerenberg.

Drift-ice comes to the island in the wintermonths but is not seen in the summertime. The weather is cool and humid, with nearly constant fog, making fieldwork difficult.

The history of the island and of its scientific investigation has been given by several authors of which the following references are among the most useful ones: Th. Thorsteinsson (1913), J.M. Wordie (1926), A. King (1939), S. Richter (1946), A.K. Orvin (1960), F.J. Fitch (1964) and T. Siggerud (1972). A very short review will be given here. The history of Jan Mayen may be divided into four periodes. The first one goes up to about the year 1600, during which the island was unknown, unless it is the Svalbardi mentioned in ancient Icelandic Sagas, lying 4 night and days of sailing northeast of Langanes

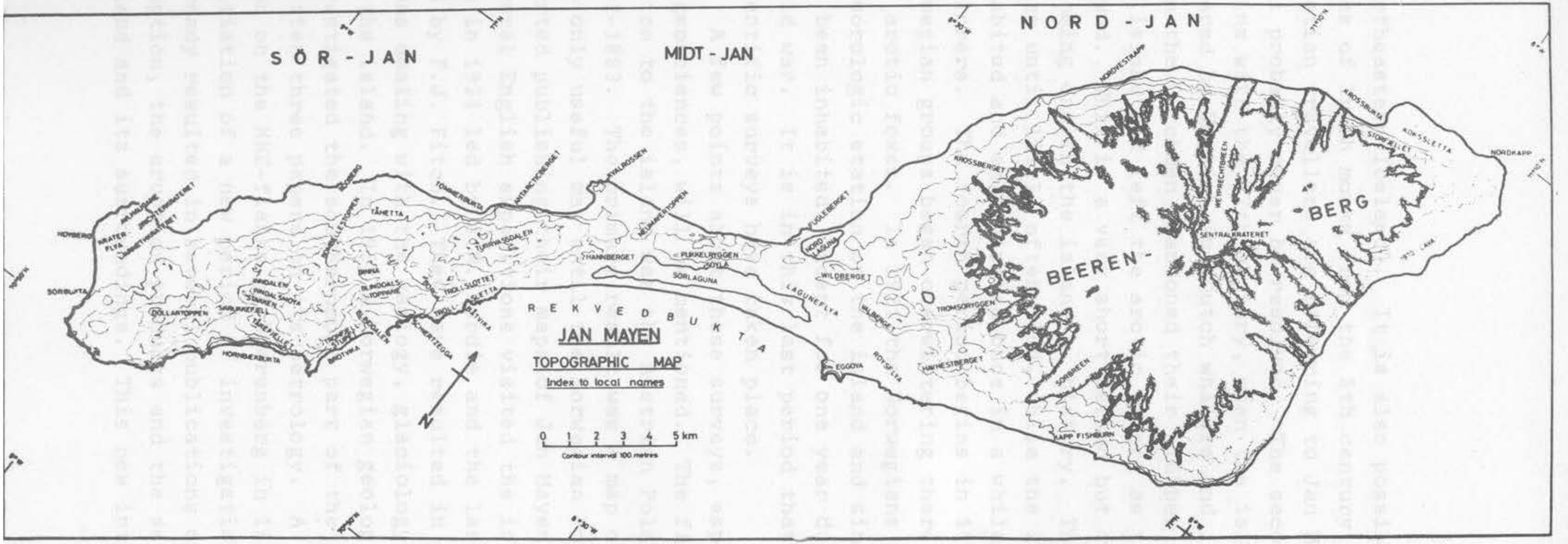

Fig. 1. Topographic map of Jan Mayen with the local names used in text (based on Norsk Polarinstitutt maps from 1959 and Orvin, 1960).

(northeastern Iceland). It is also possible that unclear tales of Irish monks from the 6th century and medieval Venetian travellers are referring to Jan Mayen but this will probably never be resolved. The second period begins with the 17th century, when the island was discovered by English and Dutch whalers and it ends in 1642, when the Dutchmen abandoned their blubber boiling gear on the island and left the arctic waters as their whaling ground. This is a very short period but truly the most blooming one in the island´s history. The third period lasts until little after 1900, while the island is not inhabited and only visited once in a while by seamen or explorers. The fourth period begins in 1906, when small Norwegian groups began overwintering there for hunting of the arctic foxes. In 1921 the Norwegians founded their meteorologic station on the island and since the island has been inhabited, except for one year during the second world war. It is in this last period that most of the scientific surveys have taken place.

A few points about these surveys, especially related to geosciences, will be mentioned. The first major expedition to the island was the Austrian Polar Expedition 1882-1883. The primary result was a map of the island; the only useful map until the Norwegian Polar Institute started publishing their maps of Jan Mayen in 1954. Several English expeditions visited the island. The first one in 1921 led by J.M. Wordie and the last one in 1961 led by F.J. Fitch. They have resulted in several publications dealing with the geology, glaciology and petrology of the island. In 1959 a Norwegian geologist, H. Carstens, investigated the southernmost part of the island and has written three papers on its petrology. A volcanic eruption on the NNE-flanks of Beerenberg in 1970 was the initiation of a new period of investigations, which has already resulted in several publications on the volcanic eruption, the eruption products and the seismicity of the island and its surroundings. This new interest led to an expedition from the Norwegian Polar Institute of 14 members including scientists of various diciplin within the natural sciences to the island in 1972.

The present author took part in this expedition and has since visited the island once, in 1974. Each visit lasted about a month. Data was sought to enable the division of the volcanic formations into stratigraphic units. Rocks were collected and field magnetic measurements were made. Petrological studies show the rock suite to be of potassic, alkaline nature and range from ankaramites to trachytes in composition.

2. THE STRUCTURE AND EVOLUTION OF THE ENVIRONMENT OF JAN MAYEN

The marine geology and the evolution of the Atlantic between Iceland and the Jan Mayen Fracture Zone is much more complex than south of Iceland and north of the Jan Mayen Fracture Zone. This area and its history has been discussed by several authors. These authors mostly agree on both structure and the evolutionary history of the area. The following review is based on a recent paper by Talwani & Eldholm (1977) if other references are not given. Fig. 2 is a sketch map of the North Atlantic showing the main structural features of the area.

The complex pattern of volcanic zones in Iceland is offset WNW by the Tjörnes Fracture Zone (Sæmundsson, 1974) to the Kolbeinsey Ridge (Iceland-Jan Mayen Ridge by Talwani & Eldholm, op.cit.), which is the active spreading ridge north of Iceland. The Kolbeinsey Ridge extends to the Jan Mayen Fracture Zone with small offsets by minor fracture zones. Towards the east the Kolbeinsey Ridge is then offset by the Jan Mayen Fracture Zone towards the Mohns Ridge, which is the active spreading ridge north of Jan Mayen. The Jan Mayen Fracture Zone extends from the Greenland continental shelf in the west and along the southwestern escarpment of the Vöring Plateau to the Faeroe-Shetland escarpment in the east. This fracture zone is bisected. The western part has a WNW direction and contains the offset segment active at present while the eastern part has a NNW direction and is fossil. The eastern part of the Jan Mayen Fracture Zone was created in early Tertiary time while the Kolbeinsey Ridge was not existing, but the spreading ridge of the area was in the Norway Basin, where a spreading ridge existed from the opening of the North Atlantic (about 58 m.y. ago) and up to about 27 m.y. ago. This extinct spreading axis is called the Aegir Ridge by Johnson & Vogt (1973). With the extinction of the Aegir Ridge the axis of spreading

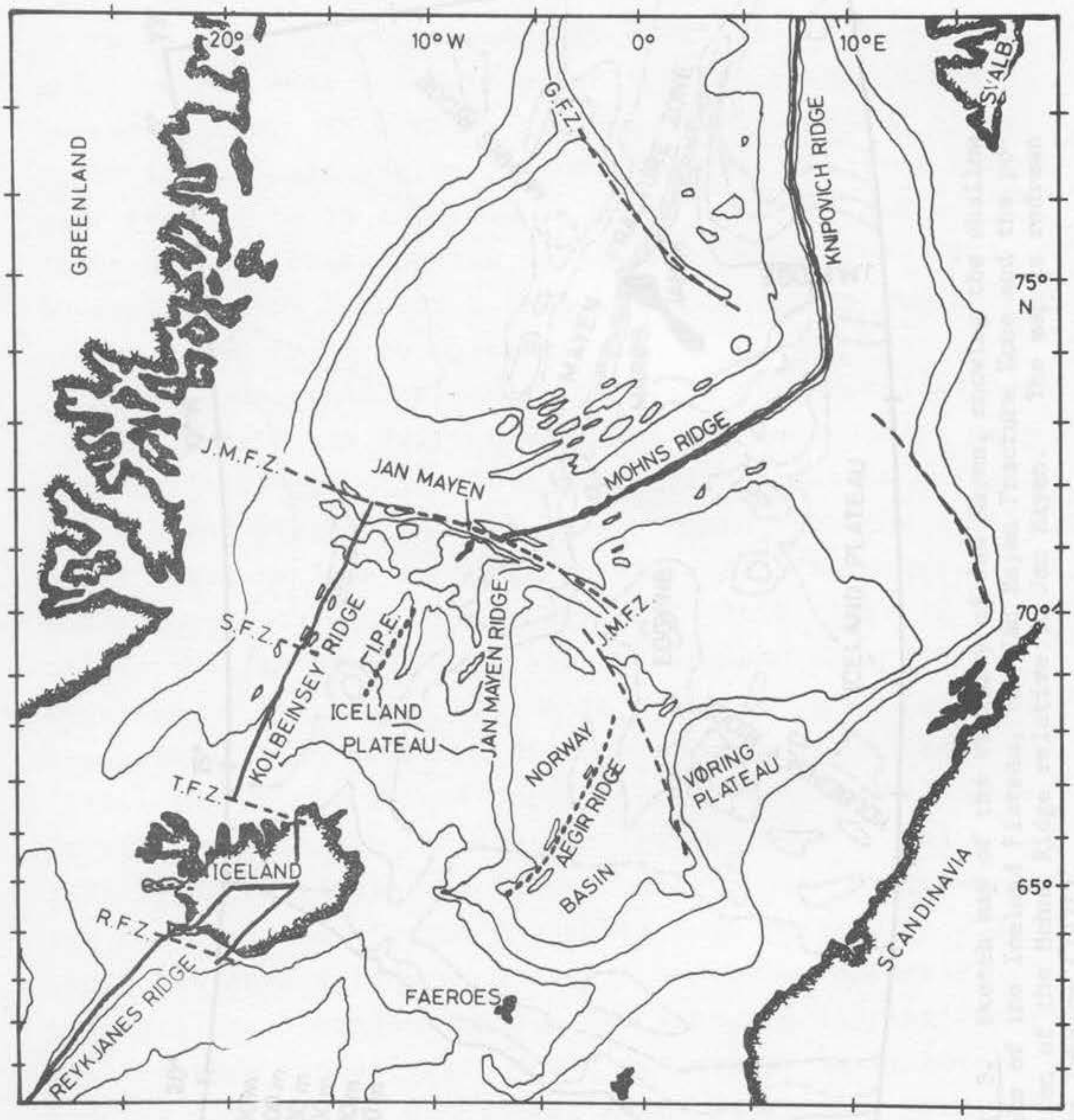

Fig. 2. Sketch map of the North Atlantic redrawn mostly from Talwani & Eldholm (1977), showing the major structural features of the area. Bathymetric contours for 500, 1000 and 1500 fathoms.

J.M.F.Z. = Jan Mayen Fracture Zone,
S.F.Z. = Spar Fracture Zone,
T.F.Z. = Tjörnes Fracture Zone,
R.F.Z. = Reykjanes Fracture Zone,
G.F.Z. = Greenland Fracture Zone,
I.P.E. = Iceland Plateau axis (extinct rift zone).

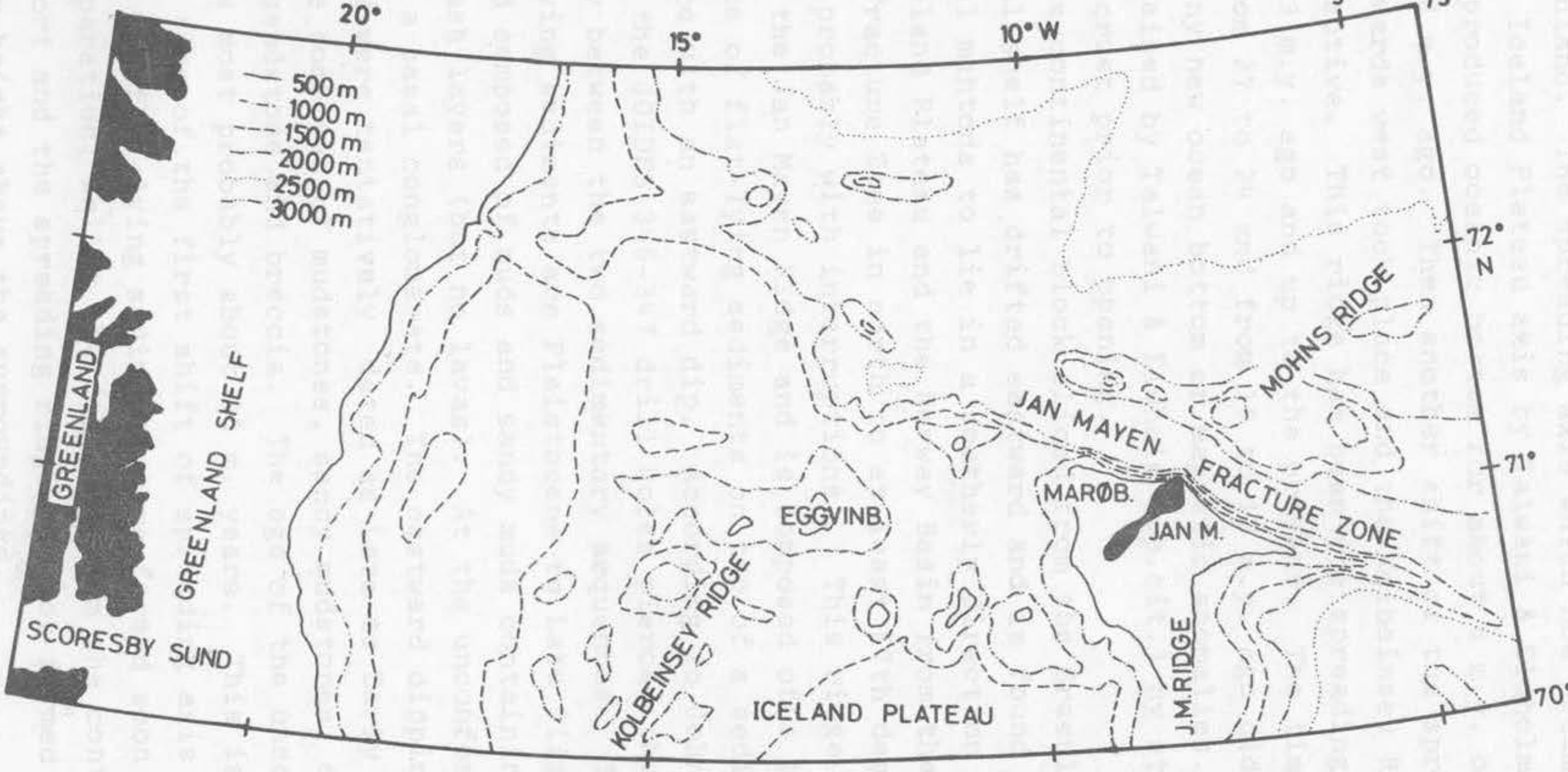

Fig. 3. Sketch map of the vicinity of Jan Mayen, showing the shallow banks of the Iceland Plateau, the Jan Mayen Fracture Zone and the position of the Mohns Ridge relative to Jan Mayen. The map is redrawn from Johnson (1975).

shifted towards west, where it cut the continental shelf of Greenland. The spreading axis which now became active (called Iceland Plateau axis by Talwani & Eldholm, op. cit.), produced oceanic bottom for about 6 m.y. or from 24 to 18 m.y. ago. Then another shift of the spreading axis towards west took place and the Kolbeinsey Ridge became active. This ridge has been the spreading ridge since 13 m.y. ago and up to the present. The time intervals from 27 to 24 and from 18 to 13 m.y. ago did not leave any new ocean bottom or magnetic anomalies. This is explained by Talwani & Eldholm (op.cit.) by stretching of the crust prior to opening.

The continental block sliced from the Greenland continental shelf has drifted eastward and is found by geophysical mehtods to lie in a southerly direction between the Iceland Plateau and the Norway Basin from the Jan Mayen Fracture Zone in north to at least 67th degree N in south (probably with interruptions). This ridge is called the Jan Mayen Ridge and is composed of a 100 m sequence of flat-lying sediments on top of a sedimentary sequence with an eastward dip. According to Johnson (1975) the JOIDES 346-347 drill holes pierced the unconformity between the two sedimentary sequences. The flat-lying sediments are Pleistocene to Late Oligocene in age and composed of muds and sandy muds containing volcanic ash layers (but no lavas). At the unconformity occurs a basal conglomerate. The eastward dipping layers drilled were tentatively dated as Late to Early Eocene and are composed of mudstones, sandy mudstones, conglomerate, sandstone and breccia. The age of the unconformity is thus most probably about 30 m. years. This is close to the time of the first shift of spreading axis towards west. The flat-lying sediments were formed soon after the separation, whilst the distance from the continent was short and the spreading ridge had not formed a topographic height above the surroundings.

On top of the Jan Mayen Ridge close to the Jan Mayen Fracture Zone and opposite to the Mohns Ridge lies the volcanic island of Jan Mayen. According to this interpretation of the marine geology of the environment of Jan Mayen the island is superimposed on a sequence of sedimentary rocks, probably mostly of continental origin.

Jan Mayen is surrounded by relatively shallow banks to the east, south and west (Fig. 3), which belong to the Jan Mayen Ridge. Several other shallow banks occur on the Iceland Plateau further west, f.i. Eggvinbanken (close to the Kolbeinsey Ridge), where the depth is only a few fathoms. Further south on the Kolbeinsey Ridge is the small island Kolbeinsey, the only place on the ridge extending above sea-level. East of the Jan Mayen Ridge is the deep Norway Basin and immediately north of Jan Mayen is the Jan Mayen Fracture Zone. This fracture zone is a deep channel ($>$ 2000 m) of WNW direction, characterized by en echelon escarpments and small ridges (Johnson & Heezen, 1967).

The Jan Mayen volcanism has been attributed to the presence of a mantle plume beneath the area (Wilson, 1973). Vogt (1974) believes mantle plumes to feed magma material down below the oceanic ridges where it advances in more or less clear channels. The main plume of the North Atlantic area should be the Iceland plume. Its material flows south under the Reykjanes Ridge and north under the Kolbeinsey Ridge. Jan Mayen, he maintains, could be a small plume feeding the system of ridges north of Iceland in cooperation with the Iceland plume. If the Jan Mayen mantle plume is existing it has not left any trace of a topographic height so often attributed to the productivity of oceanic mantle plumes after a long time of activity. This is probably not to be expected in this case because of the young age of the area and irregularities in drift caused by the frequent shifting in rift axis and relatively long periods of almost no drift while the new rift axis are bisecting the crust.

The application of the mantle plume hypothesis to the Jan Mayen volcanism does not celar up or simplify the picture of the evolution of the oceanic island. It adds an element which may be unnecessary. The high thermal gradient under the Mohns Ridge may be enough to account for the Jan Mayen volcanism. The thermal gradient of the Mohns Ridge just northeast of Jan Mayen may be expected to fade out slowly towards southwest below the fracture zone and the island and cause the volcanism as it there appears in a crust and probably the upper mantle of different origin and composition (continental) from the usual oceanic ones at other ridge-fracture zone junctions, where no extra volcanism appears as f.i. at the Kolbeinsey Ridge Jan Mayen Fracture Zone junction.

3. THE GEOLOGY OF JAN MAYEN

A) GENERAL GEOLOGY AND GEOMORPHOLOGY

Jan Mayen is almost entirely built up of untilted volcanic rocks erupted from short fissures of north-easterly trend and single craters. These volcanic rocks occur as scoria craters and hills, lavas, domes, dikes and hyaloclastites. The volcanism has been mostly sub-aerial and submarine but occasionally also subglacial.

A shallow marine bank made of subaerial rocks was existing before the formation of the rocks now exposed above sea-level. This is recognized from xenoliths of volcanic rocks of subaerial structures and textures found in rocks exposed near sea-level and very small outcrops of lavas underlaying hyaloclastites at sea-level. Upon this foundation were built many small islands of hyaloclastites in submarine eruptions. The islands were gradually connected by further submarine eruptions and did at last form a continuous island when it started to erupt sub-aerially through the hyaloclatites and lavas began to flow over them and fill the channels and depressions between them. The island has been steadily growing since, mostly by subaerial eruptions like these and submarine eruptions at or near the coast.

The basic subaerial volcanism has usually been of Strombolian to Vulcanian type (Macdonald, 1972) producing viscous lavas mostly of aa-type and steep sided high scoria craters and hills sometimes without any crater depression. The more silicic volcanics are usually found as domes but silicic lavas do occur. When submarine the basic volcanism has been more explosive; of the type called Surtseyan by Walker (1973). One submarine silicic eruption is known to have occurred. Relatively few dikes are exposed, except in some places in the sea-cliffs of Beerenberg.

Chemically the volcanic rocks are potassic alkaline. They range from ankaramites through basalts and tristanites to trachytes. Plutonic rocks are not exposed on Jan Mayen but occur as xenoliths. Metamorphic rocks are not found and sedimentary rocks only in very minor amounts intercalated between volcanic rocks. These are tillites and fossil scree or blocky ground.

Faults were not found in the field but air photos reveal some structures that might be faults (see map). Open fissures are very few, short and narrow. They have the same northeasterly trend as the volcanic fissures and are in all known cases thought to be an extension of a volcanic edifice. They are not to be interpreted as an evidence of crustal extension.

The topography of Jan Mayen is a reflection of the volcanism. It is characterized by craters, lavafields and domes in Sör-Jan and by the picturesque volcanic cone, Beerenberg, on Nord-Jan.

Small brook channels are cut down between craters or lavas or in lava channels and other favourable places, but they usually dry up in early summer. Where older rocks are exposed on a flat terrain it is characterized by a blocky ground. In the steep sea-cliffs the lavas are exposed in sections interrupted in places by heaps of hyaloclastites. In the older sea-cliffs, now isolated from the sea by young lavas and sandbars, only few lavas are visible in the upper part of the cliffs, the lower part being totally covered by scree.

The ice cap on Beerenberg sends its glacial tongues down in every direction. Most of these tongues are thin and almost without movement and seem to be almost unable to erode. The rest of the ice tongues are typical outlet glaciers, fast-moving and lying in narrow relatively deep channels. They are active eroders having ridges of lateral moraine on both sides but most of them calve in the sea and the eroded material is largely carried directly into the ocean. The glaciers have retreated from their maximum extension (Jennings, 1948) leaving a cover of moraine and outwash, otherwise the young lavas on the flanks of Beerenberg are mostly unaffected by the presence of the glaciers, except close to the glacier front where melt water has left its solid material on the lava surface.

Sandy beaches are found in bays everywhere along the coast. On Midt-Jan two sandbars have formed locking behind them a lagoon. On the southeastern coast is a big and shallow lagoon, Sörlaguna, that dries up in summertime. The other lagoon, Nordlaguna, on the northeastern coast is smaller but deeper.

Jan Mayen is usually divided into three areas. The northeastern part is called Nord-Jan, the middle part Midt-Jan and the southwestern part Sör-Jan.

Nord-Jan is in this case another name of Beerenberg (Fig. 4). Beerenberg is a stratovolcanic cone, differing from most stratovolcanoes in being almost entirely composed of basic rocks, mostly lavas. Intermediate and acid tephra accumulations typical for stratovolcanoes are totally absent. Basic tephra of three different structural forms is found in the stratigraphic sequence. It is found as thin layers between lavas, i.e. bottom and surface scoria of the lavas themselves, as craters on the flanks of Beerenberg itself, sometimes surrounded by scoria fields, and as hyaloclastite heaps in the lowest sections of the mountain. Beerenberg reaches 2277 m height a.s.l. with a regularily shaped top crater, a little more than 1 km in diameter. The upper part of the mountain is rather steep-sided and the lower part has a more gentle slope, frequently ending in high precipitous sea-cliffs. The mountain is somewhat elongated in NE-SW direction reflecting a fissure system of this trend (which is the same trend as the elongation of the island itself). Both Fitch (1964) and Birkenmajer (1972) have drawn maps of the structural pattern of Beerenberg. They show this NE-SW linear pattern, but add to it a minor radial pattern.

Midt-Jan is a narrow ridge-formed connection between Nord- and Sör-Jan (Fig. 5). It is only partially covered by young volcanics and then only by scoria. No lava eruption has occurred there in recent times. The older rocks

Fig. 4. Beerenberg seen from Sör-Jan. Note the steeper summit cone. The small cloud on the NE-flank of Beerenberg is steam emitted from the 1970 eruption sites. The picture is taken in August 1972.

Fig. 5. Midt-Jan and Sör-Jan seen in early spring from about 1400 m height on the southern slopes of Beerenberg. Photo: Jan Heltne.

are mostly basic lavas exposed in young and old sea-cliffs. Trachyte lavas are found in the northern part of it, and basic hyaloclastites at the bottom of the exposures as in Nord-Jan. Marine erosion has formerly been active on both sides of this ridge, but now the eastern side is isolated from the sea by a sandbar and a lagoon.

Sör-Jan is a mountainous plateau or ridge, about 6 km wide (Fig. 6). The highest peaks are more than 700 m a.s.l. This part of the island is extensively covered by very young lavas, scoria and domes. The volcanism is fed by short NE-trending fissures and single craters. The craters are often surrounded by scoriaceous cover. Most of the eruptions have occurred on top of the mountain chain and lavas have flowed down the slopes, especially to the west, where they have accumulated in front of the sea-cliffs. They now form a continuous lava platform along the south-western coast from Sörbukta to Tömmerbukta. The older rocks are mostly basic lavas, but intermediate lavas occur. Hyaloclastites are abundant, especially among the lowest rocks on the southeastern coast.

B) STRATIGRAPHY

The rocks of Jan Mayen are here divided into five units on the basis of stratigraphic sequence, and lithology. One formation is entirely composed of unconsolidated materials derived by erosion of the other formations. The remaining four formations are primary volcanic rocks and include only minor amounts of consolidated fragmental deposits.

This division is based on the author´s observations especially on Sör- and Midt-Jan. With modifications the stratigraphic divisions of Carstens (1962) for Sör-Jan and of Fitch (1964) for Nord-Jan are fitted into this division. The result is given in Table 1. The stratigraphic column of Carstens fits in without any major changes. Fitch´s more detailed stratigraphic column is modified by grouping

Fig. 6. Sör-Jan from the air from southwest. Note the lava plateau in the foreground and up along the western coast and the rough topography of the highland. Photo: Sigurdur Thorarinsson.

together some of his formations and a reinterpretation of some of his observations leads to a simpler stratigraphic column.

Schematic section along the island, showing the position of the formations is given in Fig. 7. Fig. 8 is a schematic section across Sör-Jan indicating the mode of uppiling of the island. Some actual sections from Sör-Jan are shown in Fig. 9. Fig. 10 is a map showing the surface distribution of the mapped formations. Fig. 11 is a map showing more detailed the relation within the youngest formation.

I. "Hidden" formations

The basement rocks of Jan Mayen are mostly of volcanic origin. These are grouped together under the name "Hidden" formations.

The drill holes of Leg 38, D.S.D.P. on the Jan Mayen Ridge about 150 to 200 km south of Jan Mayen island (Talwani et al., 1975; Johnson, 1975) pierce more than 300 m of the ocean floor. The only rocks found were sediments and sedimentary rocks with only minor interruptions of volcanic material, which is all in the form of tephra (Johnson, 1975). No lavas interrupt the sedimentary sequence of which the upper 120 m are flat-lying sediments of up to about 30 m.y. old (Middle to Late Oligocene, Talwani et al., 1975).

The rocks below the island of Jan Mayen, on the other hand, seem to be mostly of volcanic origin. This is indicated by the xenoliths found in the hyaloclastites around the island, which are especially prominent in Eggöya and Borga. The xenoliths are both of subaerial lavas and old hyaloclastites. They show the same lithological characteristics as the younger Jan Mayen island rocks. The extent of this lava pile (probably overlying older hyaloclastites) is uncertain but it probably reaches consider-

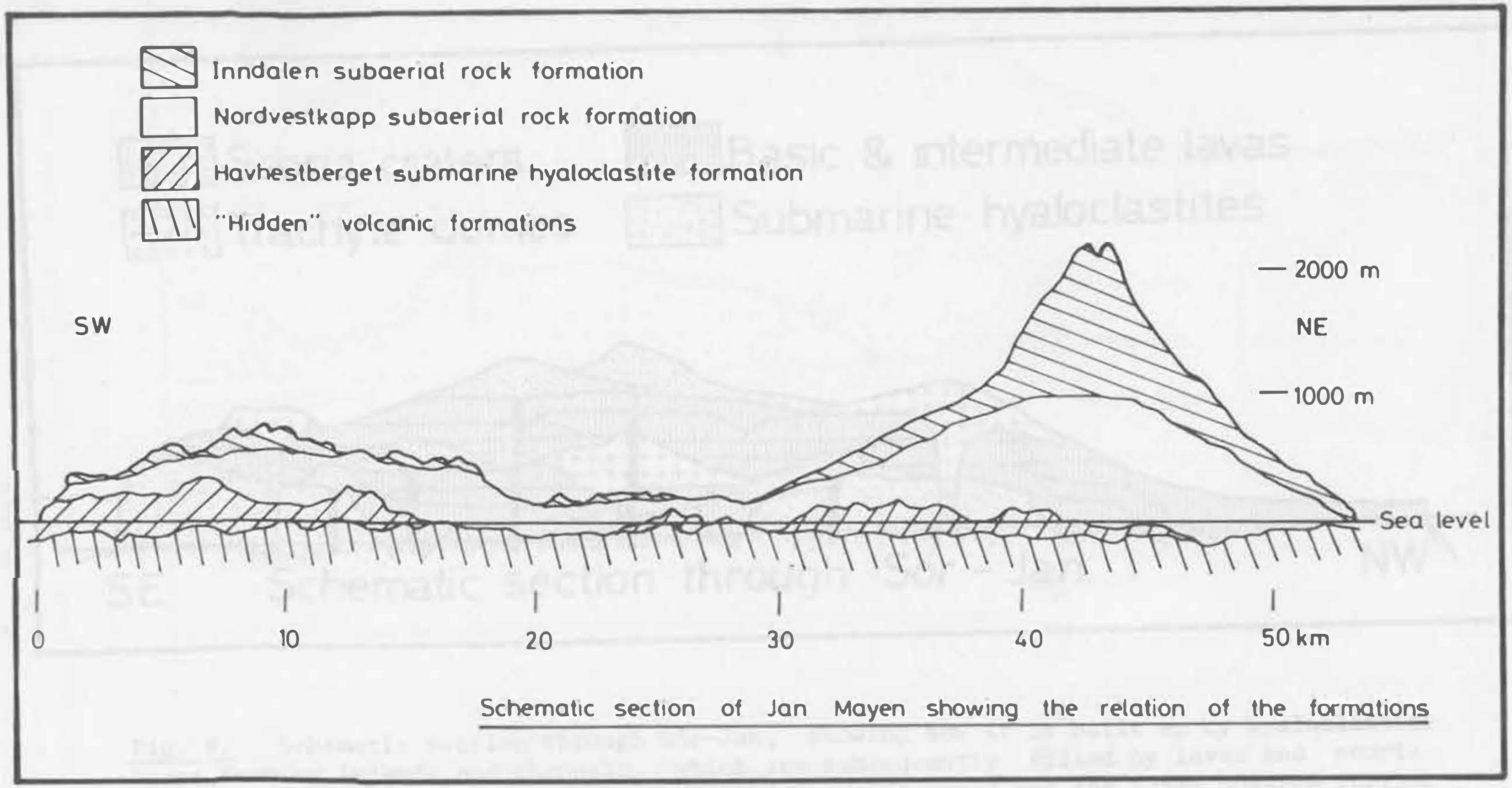

Fig. 7. Schematic section of Jan Mayen along its length (from NE to SW), showing the relations between the major formations.

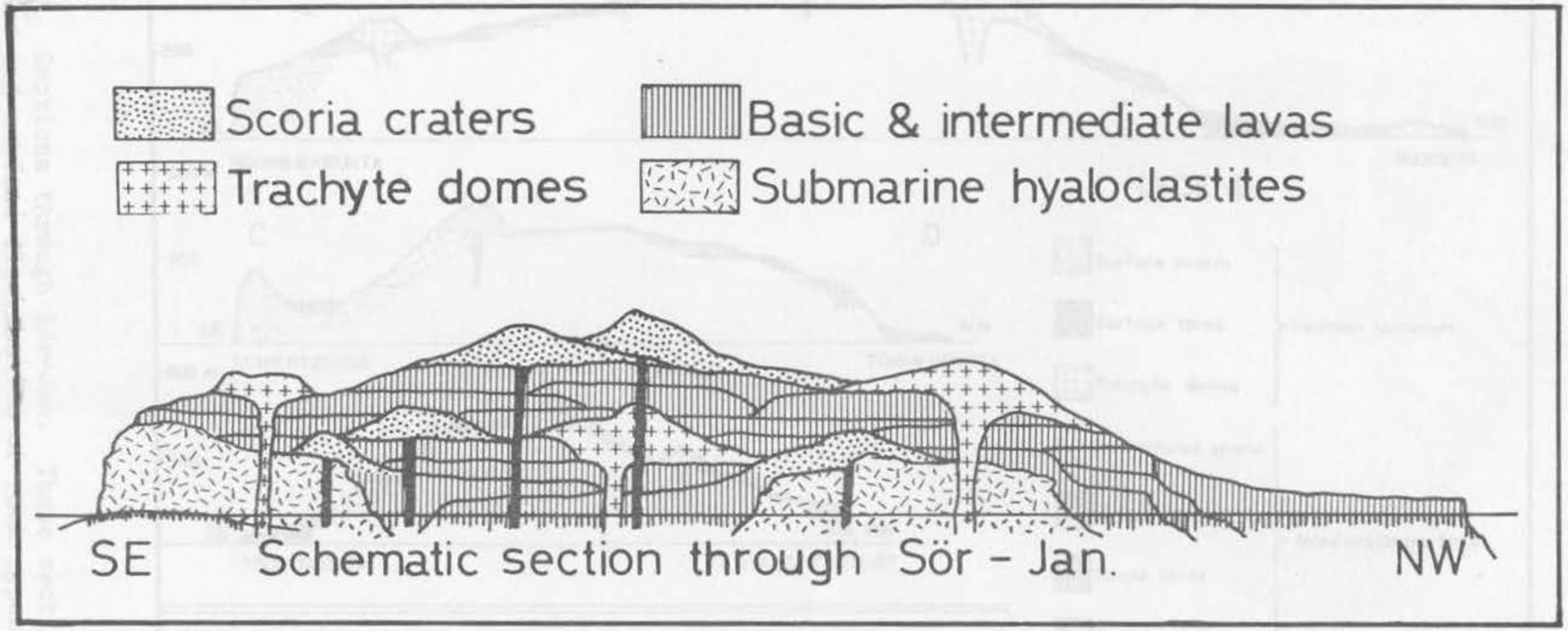

Fig. 8. Schematic section through Sör-Jan, showing how it is built up by hyaloclastite heaps forming islands and channels, which are subsequently filled by lavas and scoria. When the channels are filled the hyaloclastites are covered and the lavas advance further out into the sea.

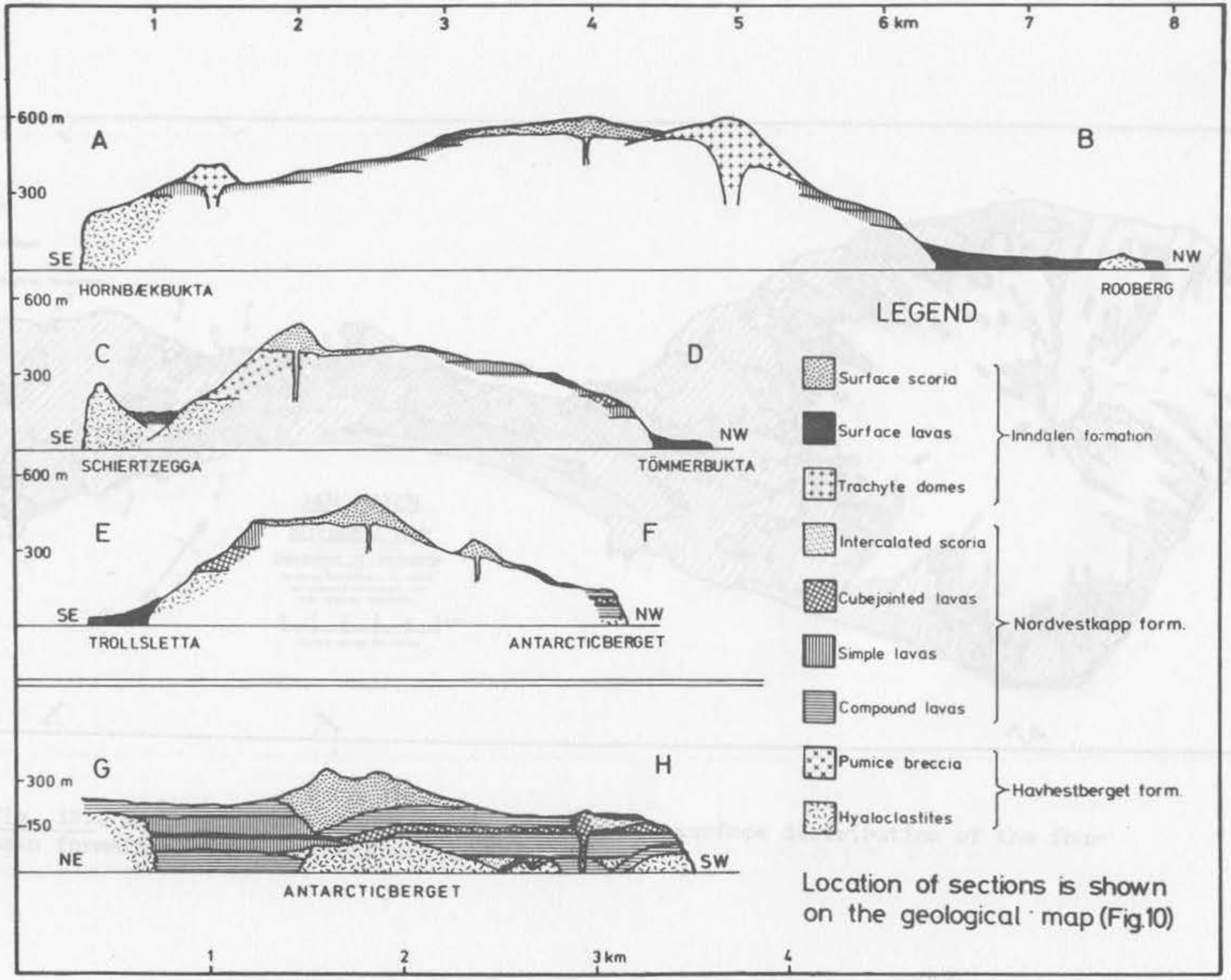

Fig. 9. Sections through Sör-Jan. These sections show actual profiles and surface distribution of rock types. The location of the sections is shown on the geological map (Fig. 10).

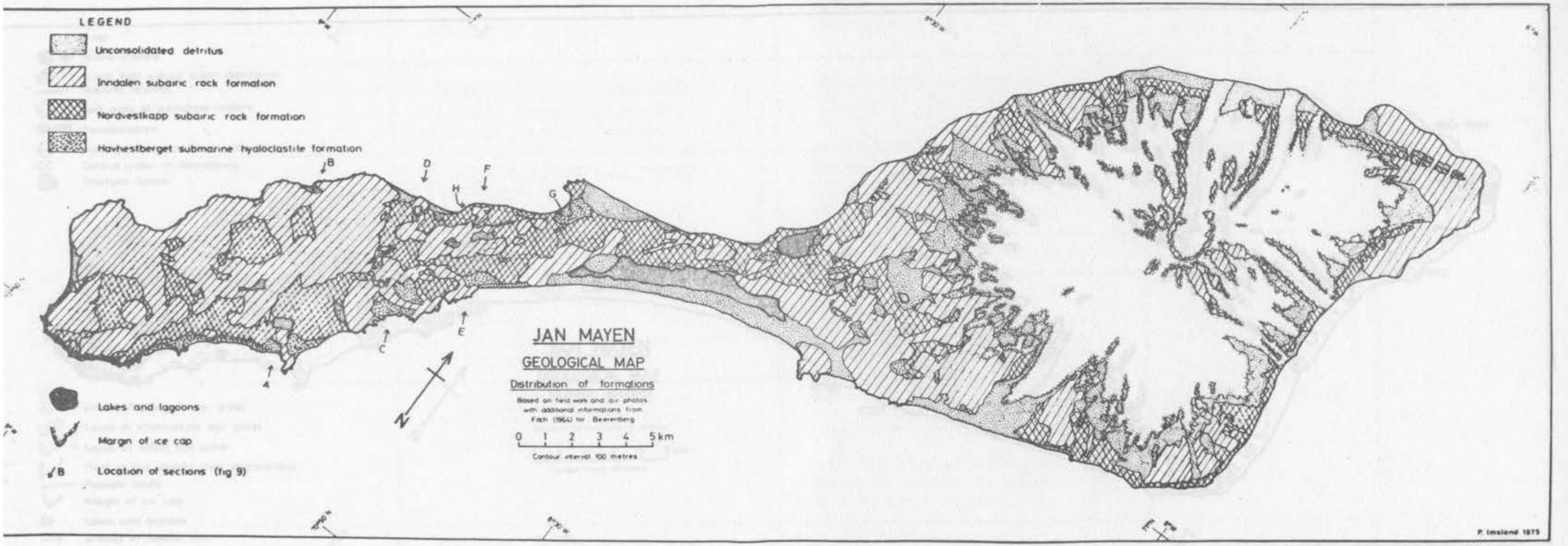

Fig. 10. Geological map of Jan Mayen, showing the surface distribution of the four main formations exposed above sea-level.

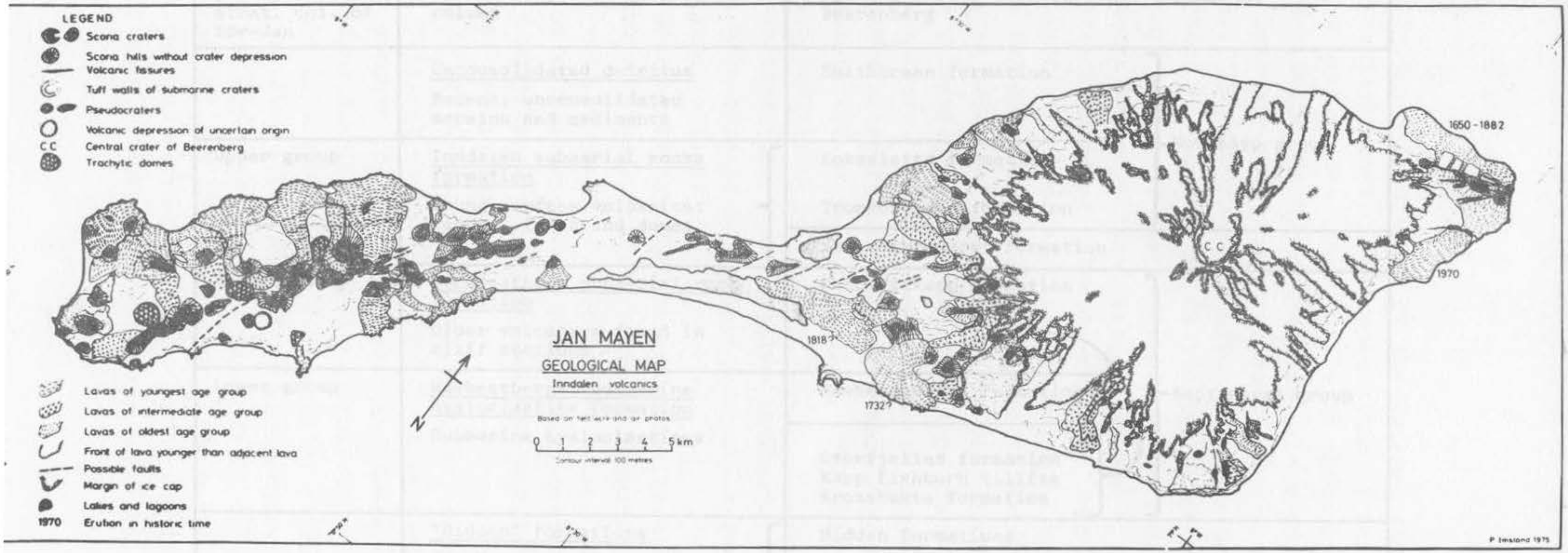

Fig. 11. Geological map of Jan Mayen, showing the relations within the "postglacial" volcanics (Inndalen formation).

TABLE 1. Stratigraphic columns of Jan Mayen

Carstens (1962) strat. col. of Sör-Jan	The Jan Mayen stratigraphic column	Fitch´s (1964) stratigraphic column of Beerenberg	
	<u>Unconsolidated detritus</u> Recent, unconsolidated morains and sediments	Smithbreen formation	Nordkapp group
Upper group	<u>Inndalen subaerial rocks formation</u> Young surface volcanics: tephra, lavas and domes	Koksletta formation Tromsöryggen formation	Nordkapp group
		Sentralkrateret formation	
Middle group	<u>Nordvestkapp subaerial rock formation</u> Older volcanics found in cliff sections	Nordvestkapp formation	Kapp Muyen group
Lower group	<u>Havhestberget submarine hyaloclastite formation</u> Submarine hyaloclastites	Havhestberget formation	Kapp Muyen group
		Storfjellet formation x) Kapp Fishburn tillite Krossbukta formation	Kapp Muyen group
	<u>"Hidden" formations</u> Jan Mayen shelf, a part of the Jan Mayen ridge	Hidden formations Submerged volcanic formations	

x) Fitch interprets the Kapp Fishburn tillite as a more or less regional tillite layer in the lower section of Beerenberg. The author believes it to be originally an isolated lateral moraine and the hyaloclastite immediately overlying it to be a small subglacial hyaloclastite, younger than the Havhestberget submarine hyaloclastites. Both the tillite and the overlying subglacial hyaloclastite belong thus to the Nordvestkapp formation, which is overlying the Havhestberget formation.

able depth, as indicated by the intense alteration some of the xenoliths show. The upper limit of this lava pile is at the present sea-level. This is shown by a few lava exposures below the hyaloclastites, where one or two metres of a lava are seen on the shore to underlie the hyaloclastites. The informations given by these exposures, on the diversity of these rocks is limited because of the small size and number of the outcrops, which usually occur on the shore below vertical sea-cliffs, as f.i. in Brotvika and Antarcticberget. The diversity of the xenoliths on the other hand indicates a wide range of rock types. They range in composition from ankaramitic basalts to trachytes and when unaltered they cannot be distinguished from the other volcanic rocks of Jan Mayen, neither in lithology nor chemistry. Mostly they are fresh but may show considerable alteration. Xenoliths from Eggöya, taken to be representative of this formation, have been described by Tyrrell (1926).

No xenoliths of conclusive sedimentary or metamorphic rocks have been found. Their presence below the island is indicated, though.

Small pebbles of flint are occasionally found on the sea shore. These pebbles could be carried by drift-ice or drift-wood, or even brought to the island by the Dutch whalers as ballast in the ships transporting whaleoil back to the continent. Their presence on the island is therefore not conclusive.

One of the xenoliths collected by the author might be of an original sedimentary rock. It is composed of about equal amounts of granular quartz and clear glass closely resembling alkali feldspar in composition. The quartz is arranged in discontinuous semiparallel strings in the glass, a texture reminiscent of sedimentary rocks. The overall composition of this xenolith is quite different from that of all the other samples from the island, both xenoliths and extrusive rocks. It is rhyolitic and relatively poor in alkalies, while the other silica-rich rocks are alkali-rich trachytes. This rock might be a partly remelted arkose.

In a description of Jan Mayen rocks, Berwerth (1886) shortly mentions gneiss, dolomitic limestone and quartzite. His quartzite might be the same or similar rock as the xenolith described above. The gneiss sample is of unknown locality and whether this is a pebble from the shore or xenolith from a volcanic vent is therefore unknown, and no conclusions can be drawn of its presence. It is made of quartz, red orthoclase and small amount of greenish mica. The dolomitic limestone is most probably a magnesite. This mineral has been found both as loose pebbles and as secondary fillings in vesicles in basalt blocks on the shore. They are therefore probably just a secondary alteration product of the volcanic rocks themselves.

The extent of the volcanic nature of the "Hidden" formations or the basement of Jan Mayen island is thus unknown, but a considerable lava pile is indicated. The muddy sediments and sedimentary rocks recovered by the D.S.D.P. drilling on the Jan Mayen Ridge south of the island are not recognized in the xenolith collection from the island, but sedimentary rocks below the island are indicated by partly remelted arkose-like xenoliths.

II. Havhestberget hyaloclastite formation

This formation is found almost all over the island. It mostly occurs lowest in the sections. It is made up of hyaloclastites, mostly forming isolated heaps or a chain of heaps. In the lowest sections of Beerenberg, especially in the south and west, many such heaps are exposed, e.g. Havhestberget, Valberget and Krossberget. In Midt-Jan it is well exposed in Söyle. The lower parts of the sea-cliffs on the southeastern part of Sör-Jan are made of a continuous chain of hyaloclastite heaps. The isolated heap of Schiertzegga is a good example.

Usually the base of this formation is not exposed. At Kapp Fishburn, however, the hyaloclastite overlies the Kapp Fishburn tillite. On Midt- and Sör-Jan furthermore very small lava outcrops are seen underlying the hyaloclastites at sea-level. These lavas belong to the "Hidden" formation.

The rocks of the formation are with one exception ankaramitic and basaltic tuffs and breccias. The tuffs are yellowish to brownish glassy tuffs rich in small vesiculated rock fragments. The ankaramitic tuffs are furthermore rich in crystals and crystal fragments, mostly of olivine and pyroxene. The breccias are darker in colour and richer in rock fragments. All gradations are found from almost 100 per cent glassy tuffs to coarse almost 100 per cent stony breccia. The glass particles are often crowded with small vesicles. Palagonitization of the glass is found in different degree. Fragments of volcanic bombs are common in the hyaloclastite and xenoliths occur. In some places irregular veins and dikes or even pockets of compact rocks, sometimes cube-jointed, occur in the hyaloclastites, but pillow-lavas are never seen connected to them. Stratification of the fine-grained hyaloclastites is variable, in cases quite well developed but occasionally absent or unclear.

Fitch (1964) has described this formation (Havhestberget formation) from Nord-Jan as "agglomeratic basalt pumice-tuff and tuff-breccia" and called it "non-welded ignimbrite or sillar". He believed it to be the result of violent explosive eruption or a series of such eruptions from the central crater of Beerenberg, and that they were deposited by an "ash-flow mechanism". Later he changed his mind about his formation as can be seen in his discussion of a paper by Walker & Blake (1965). There he refers to the rocks overlying the Kapp Fishburn tillite as "a partly palagonitized sub-glacial alkali-basalt hydroclastic vitrolithic tuff-breccia". He does not want to use the term hyaloclastite or the commonly used terms referring to the palagonitization of the rocks (palagonite tuff, palagonite breccia). These rocks have later been referred to by Hawkins & Roberts (1972) by saying: "they may possibly be unwelded ash-flow tuffs, but are now considered to be palagonite tuffs, probably produced beneath ice".

The irregular distribution and heap-formed structure of the rocks speak against ignimbrite origin. It is clear when compared with the abundant Icelandic hyaloclastites, that most of the characteristics of these rocks are the same, but few if any are common to ignimbrites. It is also clear from features in the other formations, that the volcanism of the island has frequently occurred in an aqueous environment.

Fitch´s (op.cit.) and Hawkins & Roberts´ (op.cit.) reasons for believing these rocks to be produced beneath ice are not given, but it is most probably the tillite at Kapp Fishburn underlying a hyaloclastite. This is in fact the only tillite known on the island connected to a hyaloclastite and this particular hyaloclastite is of rather small dimensions. The subglacial origin is in this case rather convincing. Yet the bulk of the Jan Mayen hyaloclastites is believed to be formed in submarine eruptions. Reasons for this are the general absence of glacial morphology and glacial sedimentary rocks on the island, the presence of marine fossils in the top layer of one of the hyaloclastites (Borga, described later), and the obvious relations between the structure of the tuffs and breccias of some of the very young hyaloclastites (f.i. Eggöya and Fugleberget) and the present sea-level, which show that these particular hyaloclastites were formed in submarine eruptions relatively short time ago. The two examples, Eggöya and Fugleberget, are much younger than most of the hyaloclastites and belong to younger formations described below.

The small lava exposures below some of the hyaloclastites suggest eruptions in the sea at somewhat higher sea-level at the time of formation than at present, but this cannot be argued. The relatively great difference in stratification of the tuffs indicates that they are produced at different sea-levels and have in cases not even reached the sea-level during uppiling and thus not been above sea-level until long after the eruption ceased. The hyaloclastites are thus probably mostly formed at relatively high sea-level when compared to the present one. The absence of pillow-lavas from the hyaloclastites indicates eruptions in rather shallow water (Sigvaldason, 1968).

The exception to the basic hyaloclastites is a thick pile of trachytic pumice-breccia overlying basic hyaloclastite in Borga. The pumice-breccia is 220 m thick and divided into four main units. The lowest unit is 100 m thick made of light grey pumice lumps in a lighter coloured fine-grained glassy matrix. The pumice lumps are highly porous with large vesicles. Abundant volcanic xenoliths and a few obsidian bombs occur within this unit. Above this is a 40 m thick unit of yellowish pumice lumps in a similar matrix. This unit contains more obsidian bombs but less xenoliths and the pumice lumps are not so porous as below. Then comes a unit of 30 m thickness of reddish pumice lumps. The amount of matrix is small and the vesicles of the pumice are now much smaller. Xenoliths are few but the amount of obsidian bombs has increased. The uppermost unit is 50 m thick, made of grey pumiceous rock almost without a glassy matrix. The unit is composed of layers or bands of dark grey, microporous, occasionally near compact rock and light grey, fine-porous pumiceous bands. Xenoliths and bombs are absent. Possibly a still another unit is hidden below the scoria cover from the young crater on the top of the mountain. This is shown by big blocks of pink-coloured massive trachyte in the uppermost scree on the southern slope of the mountain just below the scoria.

The fragmental nature of this formation is unique among the trachytes on the island, all the others being domes and lavas. Immediately below the breccia is a submarine hyaloclastite containing traces of marine fossils of shallow sea origin. These fossils are only found in the top layer of the hyaloclastite, where the animals most probably lived. The reason for the fragmental nature of the material is thus that the eruption took place in a shallow sea. The decreasing fragmentation found upwards in the mass reflects the gradually decreasing sea-water access to the hot magma. The sea-level at this time was at least 170 m (the height of the fossiliferous bed and the bottom of the pumice-breccia), but probably nearer to 200 m above the present sea-level.

III. Nordvestkapp subaerial rock formation

This is the most voluminous formation on Jan Mayen and it contains the greatest number of rock types. The major part of the formation is made up of effusive, subaerial rocks, ankaramitic and basaltic lavas, usually with thin scoriaceous partings. Intermediate lavas are found on Sör- and Midt-Jan, but they are absent from Nord-Jan. Hyaloclastites also occur in the formation.

The formation is present all over the island. The best exposures are in sea-cliffs of active erosion, e.g. the cliffs to the southeast, east and west of Beerenberg, in Antarcticberget and Sörbukta. Good exposures are also found in old sea-cliffs, e.g. on the eastern side of Midt-Jan, around the settlement in Båtvika and above Tömmerbukta. On top of Midt-Jan and in several places on top of the mountainous plateau of Sör-Jan, a slightly weathered surface of this formation occurs, covered with blocky gravel probably mostly due to frost action.

When the earliest lavas of this formation were erupted, Jan Mayen was composed of many small islands. Eruptions on these islands produced subaerial lavas that flowed out over the older hyaloclastites and gradually filled the shallow depressions between the islands. The underlying rocks of the formation thus belong to the Havhestberget hyaloclastites. Some of the Havhestberget hyaloclastites are most probably of the same age or even younger than the oldest lavas of the Nordvestkapp subaerial rock formation. Long after the island had become a single island eruptions occurred in the surrounding coastal water thus producing more hyaloclastites and increasing the size of the island. The hyaloclastites of younger age than the Havhestberget hyaloclastites are included in the Nordvestkapp formation on basis of their age, even though they are not subaerial rocks. These younger hyaloclastites will be discussed briefly below.

The effusive rocks of this formation are divided into five different structural types:

1) Thick massive lavas, basic in chemical composition, jointed to big irregular blocks. The lavas are made of one big flow unit, i.e. simple lavas (Walker, 1971) or by few relatively thick flow units.

2) Compound lavas (Walker, op.cit.) made of many thin, vesiculated flow units, often separated by thinner brown scoriaceous partings. The thickness of each flow unit is from about 40 cm up to few metres. Excellent examples can be seen in Antarcticberget (Fig. 12).

3) Thick massive lavas, intermediate in chemical composition, with flow structures or split up by platy cleavage.

4) Variably sized and shaped masses of cube-jointed rocks. The jointing is usually rather irregular and the size of the cubes is up to about 40 cm.

5) Forset bedded pillow-breccia and pillow-lava, which can be traced upwards to normal lavas. This type of breccia is called flow-foot breccia by Jones & Nelson (1970).

Although the original surface of these lavas is hidden it seems likely that most of them were typical aa-lavas. Pahoehoe-lavas seem to have been much more scarce. A typical example of a pahoehoe-lava can, however, be seen in Trollslottet. A part of it has flowed into the sea and formed a big forset bedded pillow-lava.

The hyaloclastites of this formation are mostly submarine. The most prominent one is Kvalrossen. It is mostly built up of stratified glassy tuffs but a scoriaceous breccia occurs near the top which in turn is covered by a thin lava. In the sea-cliffs to the west the vent filling is exposed, made of massive coarse-grained basalt with perfect columnar jointing. This shallow-marine eruption seems to have had a similar course of events, in most respects, as the recent Surtsey eruption near Iceland (Thorarinsson et al., 1964; Thorarinsson, 1966 & 1969a) except that much less lava was produced in the final phase. Wind erosion has sculptured a spectacular scenery in the steep tuff cliffs. Another submarine hyaloclastite, Fugleberget, is among the latest products of this formation. It is formed while the sea-level was about 20 m higher than at present. This is indicated by a flow-foot breccia in the northern corner of the heap, where a viscous lava reached the sea at this 20 m level.

Subglacial hyaloclastites belonging to this formation do exist but are small in volume. The hyaloclastite at Kapp Fishburn (see pp. 51) rests on the Kapp Fishburn tillite and is taken to be of subglacial origin. A two to three meter thick tuff layer in the cliff behind Koksletta is probably of subglacial origin as well.

A very small hyaloclastite is found at 450-500 m a.s.l. in the slopes south of Blinddalstoppane on Sör-Jan. This is a relatively young stratified mass of glassy tuff and breccias rich in xenoliths. It is unlikely that sea-level has ever been so high. At present this is the area on Sör-Jan where snow most frequently outlasts the summer melting. In colder times a permanent snow-patch surely existed here. However, no direct indications in the form of glacial sediments or glacial erosion morphology were found. In the author´s opinion this Blinddalstoppane hyaloclastite is the only hyaloclastite on Sör-Jan that could be of subglacial origin.

IV. Inndalen subaerial rock formation

This is the youngest volcanic rock formation on Jan Mayen (Fig. 11). It contains rocks formed after the present sea-level was reached and is thought to correspond to postglacial times in other countries of similar latitude. The surface phenomena of the individual units of the formation are practically unaffected by weathering processes. It is made up of the youngest basic lavas and accompanying scoria craters and scoria cover, several trachytic domes and two hyaloclastite occurrences.

The formation is found on the surface almost all over the island, the biggest gaps being on Midt-Jan and the southeastern corner of Sör-Jan. It usually rests on the Nordvestkapp formation but sometimes on the Havhest-berget formation. In many places the lavas have flowed over and beyond the sea-cliffs forming coastal plains, which partly fringe the island. This is especially the case on northeastern Nord-Jan and southwestern Sör-Jan.

The basic lavas on Sör-Jan are all vesicular aa-lavas containing pyroxene, olivine and plagioclase phenocrysts. On Nord-Jan the lavas are mostly vesicular aa-lavas, but the phenocryst content is variable. The lavas from the central crater of Beerenberg are usually plagioclase glomeroporphyritic, but the flank-lavas are ankaramitic to plagioclase porphyritic.

The lavas of this formation have added considerably to the size of the island by flowing out over the sea-cliffs. They have mostly been viscous and usually flowed in channels rather than advancing on a broad front. Where they have flowed over steep cliffs they have often left spectacular lava-falls. The sections exposed in coastal cliffs are mostly of simple lavas, which usually contain irregular masses of various sizes of grey-brown scoria. These irregular scoria masses could be due to mild secondary explosions as the result of cooling in contact with water. The bottom part of these lavas is never exposed but is probably made of cube-jointed masses and flow-foot breccia.

Big masses of basic tephra have been produced in the eruptions of this formation. This tephra is mostly red scoria and may be divided into three different groups:

1) Scoria craters and heaps above feeder channels.

2) Scoria cover, distributed by wind at the time of eruptions.

3) Root-less vents and heaps of tephra.

The craters are numerous and it is often difficult to trace individual lava streams back to their craters, especially on Sör-Jan, where all the lavas are of the same lithological character. The craters are usually high compared to diameter, suggesting a viscous and volatile-rich magma. Steep-sided heaps without any crater bowl in the top are relatively common and occasionally without any associated lava flow (e.g. Neumayertoppen on Midt-Jan). In most cases the vents do not form crater rows or only very short ones. Occasionally the vicinity of the craters is extensively covered by red scoria, blown out over the surroundings at the time of eruption. Occasionally the loose material consists of fine-grained black tephra.

The root-less phenomena are all found on the south-western corner of the island, except one scoria hill in Lavastraumen. This hill, Tåhetta, is located in the middle of a big lava-stream. It is thought to be a part of a crater wall, that has broken loose and moved downhill on top of the viscous lava. This same phenomenon was seen to occur in the Heimaey eruption in Iceland in 1973 (Einarsson, 1974). The other root-less phenomena are two types of root-less vents, the one being a littoral cone and the other a tephra ring. Littoral cones have been described from Hawaii (e.g. Moore & Ault, 1965) where lava flows out into the sea, and similar groups of pseudocraters (formerly thought to be the result of areal eruptions (Reck, 1930)) have been described from Iceland (Thorarinsson, 1953), where lava flows out over shallow lakes or waterlogged ground. It is thought that considerable amount of rather viscous lava must flow into the sea to form a littoral cone. The explosions are caused by steam generation inside and beneath the molten lava and only a very small part of the lava is converted into tephra (Moore & Ault, op.cit.). There is one typical littoral cone, Hoyberg, on Jan Mayen. It is a 68 m high regular scoria crater on the shore west of Sörbukta. The scoria is red and grey and contains small vesiculated blocks or lumps. The vesicles are long and narrow and sometimes extend right through the blocks. They are covered on the inside by glass, sometimes drawn into threads. This is probably the result of a stream of gas and steam through the vesicles. These blocks appear to be consanguineous rather than xenolithic. Further inland on the lava-plateau behind Hoyberg are two craters, Arnethkrateret and Richterkrateret. They are much bigger than Hoyberg and more irregular in shape. Whether they are littoral cones or true craters is not clear. If they are littoral cones they are about the same size as the biggest Hawaiian ones.

A tephra ring about 700 m in diameter is at Avlhaugene between Richterkrateret and Hoyberg (Fig. 13). The walls are built of fine-grained grey ash and lapilli and inside them is a flat floor. The walls are relatively low, about 50 m on the southern side and much lower on the northern side. This is probably the result of strong northerly wind during its formation. Tephra rings like

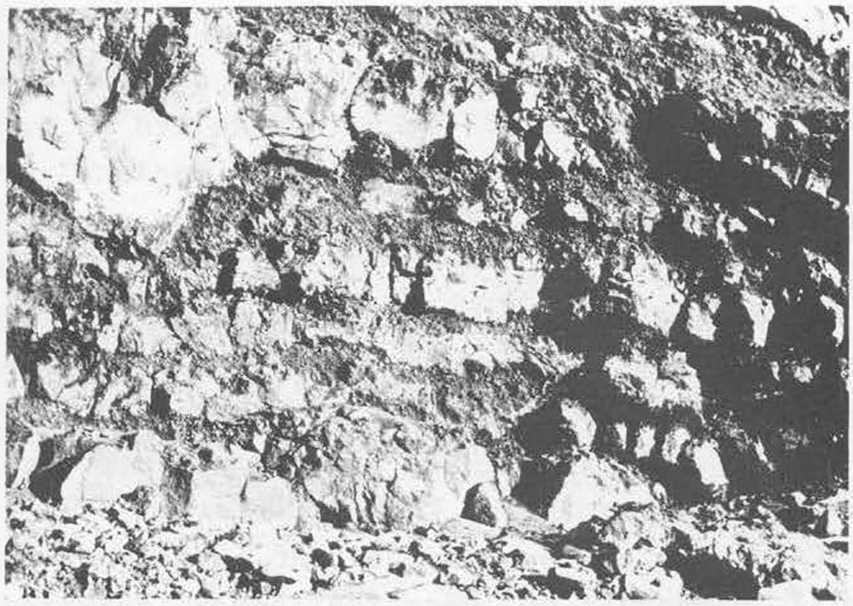

Fig. 12. Compound lava of the Nordvestkapp formation exposed in Antarcticberget. The height of the cliff is about 5 m. The brown scoria partings between each massive units are quite well developed in this lava.

Fig. 13. The Avlhaugene tephra-ring on Kraterflya, Sör-Jan. The southern wall is much higher, probably because of a northerly wind during formation.

Diamond Head on Hawaii and Hverfjall in Iceland are thought to form in hydromagmatic explosive eruptions (Macdonald, 1972). Whether this small Jan Mayen tephra ring was formed in a magmatophreatic or simply a phreatic one cannot be disclosed.

Traces after few small steam explosions are to be found on the lava-plateau where the 1970-lava advanced into the sea, but they were not big enough to form any pseudo-craters.

The trachytic rocks of this formation are only found on Sör-Jan and do only occur as domes (Fig. 14) (Inndalsmöya-Stakken, Bombéllestoppen, Dollartoppen, Skrukkefjellet, Avdalsmöya, Tåkefjellet and Binna). They usually rise more than 100 m over the surroundings and are between 600 and 1000 m in diameter at the base. They often are rather steepsided with a flat top. Binna is a very small dome, which may be largely buried by younger lavas. They all occur on top of the mountainous plateau of Sör-Jan. The rocks are usually light coloured, porphyritic with slight vesiculation and flow banding. The slopes are covered by thin scree of pumiceous trachyte. The vesicles are small but numerous.

In Stakken traces of extinct hydrothermal activity is found. The rock is slightly altered and has taken on a secondary colour from bright yellow through red to dark purple. This thermal activity was most probably connected with the cooling of the dome itself and its feeder. It cannot be traced to the surrounding rocks.

Two hyaloclastites are found in this formation, Hannberget and Eggöya (Fig. 15). Hannberget is one of the oldest parts of the formation, but Eggöya one of the youngest. They are both primarily made of fine-grained glassy tuffs, no lava was produced. A minor amount of breccia is found, especially in Hannberget. The tuffs are well stratified, which is clearly exposed in Eggöya.
Both eruptions occurred in the sea. The Hannberget eruption was close to the shore and the island became connec-

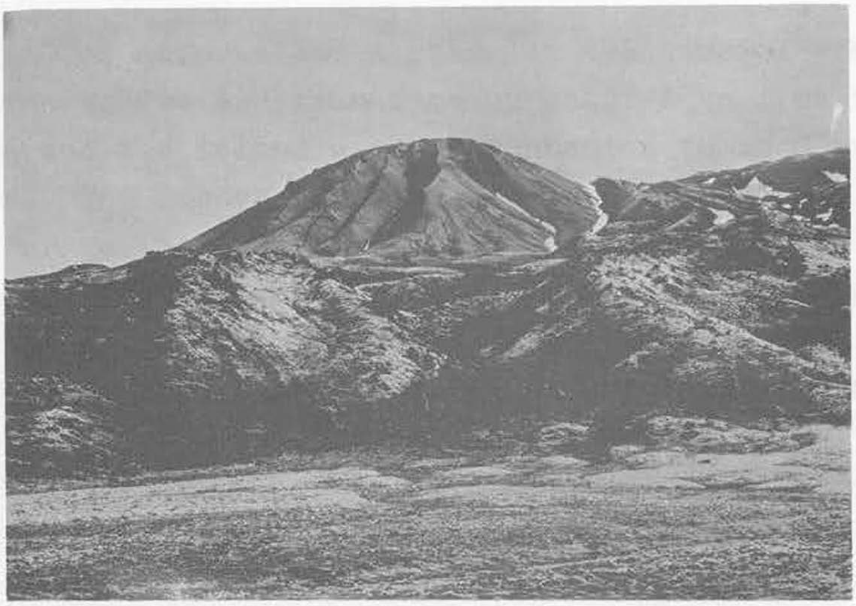

Fig. 14. Bombéllestoppen, a trachytic dome and a typical aa-lava front in the foreground.

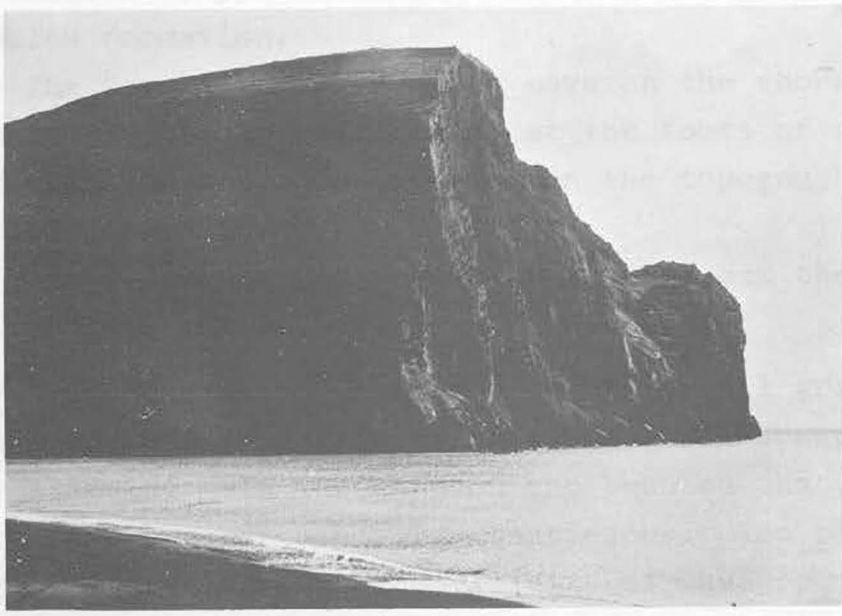

Fig. 15. The stratified hyaloclastite tuff walls of the Eggöya crater. The height of the walls is just over 200 m.

ted to the main island already at the time of eruption, but the Eggöya eruption came up about 2 km from the shore and the island was not connected to land until later. The Eggöya eruption has in many respects been similar to the Surtsey eruption, except that the Surtsey eruption (Thorarinsson, 1969) finished by an effusive lava production, but the Eggöya eruption was entirely explosive. The Eggöya tuff is unconsolidated except on the top of the crater rims, where thermal activity is still recorded. The Eggöya eruption took place a few hundred years ago, when sea-level was similar as today. The height of the crater rims is 215 m a.s.l.

V. Unconsolidated detritus

Unconsolidated detritus formed by weathering and erosion mostly of the rocks of Nordvestkapp and Havhest-berget formations are widespread on the island. The unconsolidated pyroclastic volcanics are included in the Inndalen formation.

The formation is found in bays on the shore, at the glacier margins on Beerenberg, at the foots of steepsided cliffs inland and in depression in the topography between volcanic formations.

The sediments have not been studied but they can be divided into the following main groups:

1) Beach sediments. This group contains all grain sizes and is made of particles of all the rocks exposed to weathering. In the sand on the beaches the yellow olivine grains are very conspicuous. The biggest blocks are found in the vicinity of lava promontories and the smallest grains in the lagoons behind sandbars.

2) Moraines. These are both the lateral moraines of the outlet glaciers and a till in front of retreating thinner glaciers. This group is only found on Beeren-berg.

3) Screes. They are found below the old sea-cliffs now isolated from the sea by sandy beaches and young lavas.
4) Outwash deposits. These are small sandur areas or gravel plains around the small streams from the glacier on Beerenberg and minor outwash fans in front of seasonal streams around the island.
5) Blocky ground. This is a thin cover of blocks covering the Nordvestkapp formation on flat terrain. This is mainly the result of frost action processes.

The screes, blocky ground and some of the minor outwash fans are not shown on the maps, because the underlying volcanic formation is obvious. The various groups of sediments are not distinguished on the geological map.

C) THE AGE OF JAN MAYEN

Potassium-Argon ages of rocks from Jan Mayen have been published by Fitch et al. (1965a). The limits of error of these early analyses are great or more than 24 per cent. These analyses can therefore not be used as actual datings, but they show the rocks to be young as expected. The highest age found gives 0.49±12 m.y. for a sample from Sörbukta.

Fitch et al. (1965b) did a magnetic study on 10 samples from Nord-Jan, which turned out to be normally magnetized. Field magnetic measurements made by the author at various places all over the island in 1972 gave normal magnetization for all investigated rocks. A special care was taken not to leave exposures of suspected old rocks unmeasured.

The conclusion can be drawn, that all rocks on Jan Mayen above sea-level were formed during Brunhes and that the oldest rocks are younger than 0.7 m.y. (Cox, 1969).

The Jan Mayen Ridge broke loose from the Greenland continental shelf about 25 m.y. ago according to Talwani

& Eldholm (1972). The maximum age of the Jan Mayen foundations must be younger. How much younger is not known. The relatively steep eastern side of the Jan Mayen Ridge shortly east of the Jan Mayen island shows that the eastward drifting plate has not carried with it an earlier produced pile of volcanic rocks for any length of time. It is probably only a matter of a million years since the volcanism started to pile up the foundations of the island as shown by productivety calculations.

The surface features of the Inndalen formation lavas are mostly unaffected by weathering processes indicating formation during postglacial time. What postglacial time in this case exactly means, counted in years, is on the other hand uncertain. The frost action weathered surface of the Nordvestkapp formation points to a formation in colder climate, which in this case would correspond to Late Pleistocene. No gap seems to be in the volcanism between these two formations. How long back into the Pleistocene it extends is difficult to judge. The productivity calculations (see later) give 0.37 m.y. as the time it would take to produce Jan Mayen island above sea-level. The oldest parts of the Havhestberget formation are of this age. As said above the productivity calculations indicate that volcanism started in the area about one million years ago. The "Hidden" formations are thus formed between 1 m.y. ago and about 0.4 m.y. ago, if there have not been any drastic changes in the rate of volcanic activity. The general lack of evidence of glaciation prevents speculation, as to which rocks formed during the glacial times as opposed to the interglacial times of the Pleistocene. The Kapp Fishburn tillite might indicate a glacial period, but which one is difficult to say. It is also possible that the maximum glaciation on Jan Mayen does not take place at the same time as in other countries, because of its different position in relation to the sea-ice margin, and different precipitation in glacial times. If this is the case, the Kapp Fishburn tillite is probably not formed at the same time as a glacial period occurred in other Arctic countries.

It should be mentioned that it is most likely that the youngest part of the Havhestberget formation and the oldest part of the Nordvestkapp formation have formed contemporaneously. Eruptions were going on in the sea while lavas of the Nordvestkapp formation were flowing out over the older hyaloclastites and filling up the depressions between them. This has been happening all the time as shown by the Eggöya and the lavas inland from it and other examples. As the rocks have been divided up here the boundaires are not sharp time-boundaries.

More can be said about the age relations within the Inndalen formation. The lavas from the central crater of Beerenberg seem to be among the oldest rocks of this formation (Fitch´s (1964) Sentralkrateret formation). On the flanks of Beerenberg lavas occur showing very slight weathering on the surface. These are older than others showing no weathering at all. These are Fitch´s Tromsöryggen formation and Koksslette formation respectively, but their age difference is probably very small. On Sör-Jan all the lavas have unweathered surfaces and because of their extremely similar lithological character it is difficult to tell them apart. Therefore, age difference cannot be accessed. Because of pumiceous scree cover and scoria fields it is also difficult to judge the age relation between the basic lavas and the intermediate domes. Most of the domes are believed to be rather old relative to most of the lavas.

In the older literature two descriptions of volcanic eruptions are to be found. Johan Anderson (1746) describes an eruption in 1732. No lava flow was observed but other described phenomena are clear evidence for a volcanic eruption. The same applies for William Scoresby´s Jr. (1820) description of an eruption in 1818. Both these eruptions took place on the southern flanks of Beerenberg behind Eggöya and most probably produced lavas although no lava was flowing during the short time the observations were made. As pointed out by Siggerud (1971) several trustworthy old maps of Jan Mayen exist. From them it is clear that several lavas have changed the shoreline since the time of drafting of the maps. The oldest one was published by Johannes Bleau in 1650, just after the period of Dutch whaling finished. On this map Kokssletta on the northeastern corner of the island is not shown. Eggöya is shown as an island a short distance from the shore and Rekvedbukta extends right up to Söyla and Pukkelryggen. Scoresby (1820) also gives a map of the island. The northwestern coast of the island is not original on his maps but based on Zorgdrager´s (1750) map which again is based on the map of Bleau. On his map the southeastern coast on the other hand is original and shows exactly the same features as Bleau´s map. On the map of the Austrian Polar Expedition (1882-1883) (Boldva, 1886), Kokssletta is shown and Eggöya is connected to the main island. This indicates that Kokssletta has formed sometime between 1650 and 1882 and Eggöya was connected to the main land between 1818 and 1882. It is therefore rather safe to conclude that Anderson´s and Scoresby´s eruptions did produce the two lavas behind Eggöya, Röysflya and Laguneflya. After the formation of these lavas, that both advanced out into the sea and left only a narrow channel between them and Eggöya, the sea easily filled these channels by sand and gravel to connect Eggöya to the lavas. Then the sea started to build the long sandbar to southwest and left the lagoon, Sörlaguna, behind it. Röysflya is probably the older one of these two lavas, if judged by its sandpolished surface. When looking at these old maps it might seem as if Kraterflya at Sörbukta was not yet formed, but it was in fact. That is shown by the existence of the littoral cone Hoyberg, which is shown on these maps and is now close to the shore. Eggöya itself is a very young formation as shown by the unconsolidated nature of the tuffs and a weak present thermal activity.

The last volcanic activity on Jan Mayen was the well described eruption on the northeastern slopes of Beerenberg in 1970 (Siggerud, 1971 and 1972; Gjelsvik, 1970). In this eruption lava flowed down the mountain-sides, advanced into the sea and formed a considerable lava plateau like most other lavas of the Inndalen formation have done.

The age relations of the unconsolidated detritus have not been studied, but Fitch (1964) made a study of it, to which can be referred.

D) CHANGES OF SEA-LEVEL AND STRAND LINES

Changes of the sea-level around Jan Mayen can be followed by tracing structural changes of the volcanic rocks, by marine fossils and the topography of the sea bottom.

The volcanic rocks on Jan Mayen that clearly reflect subaqueous volcanism are hyaloclastites, flow-foot breccias and pillow-lavas, and in some cases also cube-jointed lava masses, as will be discussed later.

The highest sea-level known on Jan Mayen is 170 m above present sea-level. It is recognized from two types of evidence. The first one is the occurrence of marine fossils at this height. They occur in the top layer of a hyaloclastite in the Havhestberget formation just below the pumice breccia in Borga. The fossils themselves are poorly preserved. They are of small marine bivalves, bryozoans and barnacles. The shells are long since dissolved, but the molds are clear. The other evidence of this sea-level is the interface between subaerial lava structure and a forset bedded pillow-lava flow-foot unit (Fig. 16) in a basalt in Trollslottet some two km further northeast. The fragmental nature of the pumice-breccia in Borga overlying the fossiliferous layer is caused by sea-water access to the hot lava during eruption. Thus the sea-level was most probably somewhat higher than the 170 m the fossils indicate when the pumice-breccia was formed, probably around 200 m.

It is clear from the subaerial lavas underlying some of the hyaloclastites of the Havhestberget formation, that the sea-level has been much lower before this 170 m sea-level was reached. This is also indicated by the xenoliths of volcanic rocks of the "Hidden" formations. Fitch (1964) wrote that the submerged features off the east coast of Nord-Jan indicated that the sea could have been as low as 150 m below the present sea-level, judged from the bottom topography. This would be at the time of formation of the subaerial part of the "Hidden" formations. Undoubtedly the first volcanic activity in the area, building the foundations of the island, was submarine.

Among the last eruptions in the Nordvestkapp formation is the one producing the hyaloclastite of Fugleberget. At this time the 170 m sea-level had sunk down to about 20 m above present sea-level as shown by a flow-unit in the hyaloclastite. At the time of formation of the oldest lavas of Kokssletta (Inndalen formation), the sea-level was still 10 m above the present sea-level as shown by Fitch (1964).

All this indicates rather lively vertical movements of the area. The sea-level lower than at present is though probably, at least partly, the result of eustatic changes in sea-level during the Pleistocene due to the storage of sea-water in the glaciers of the Pleistocene ice-age.

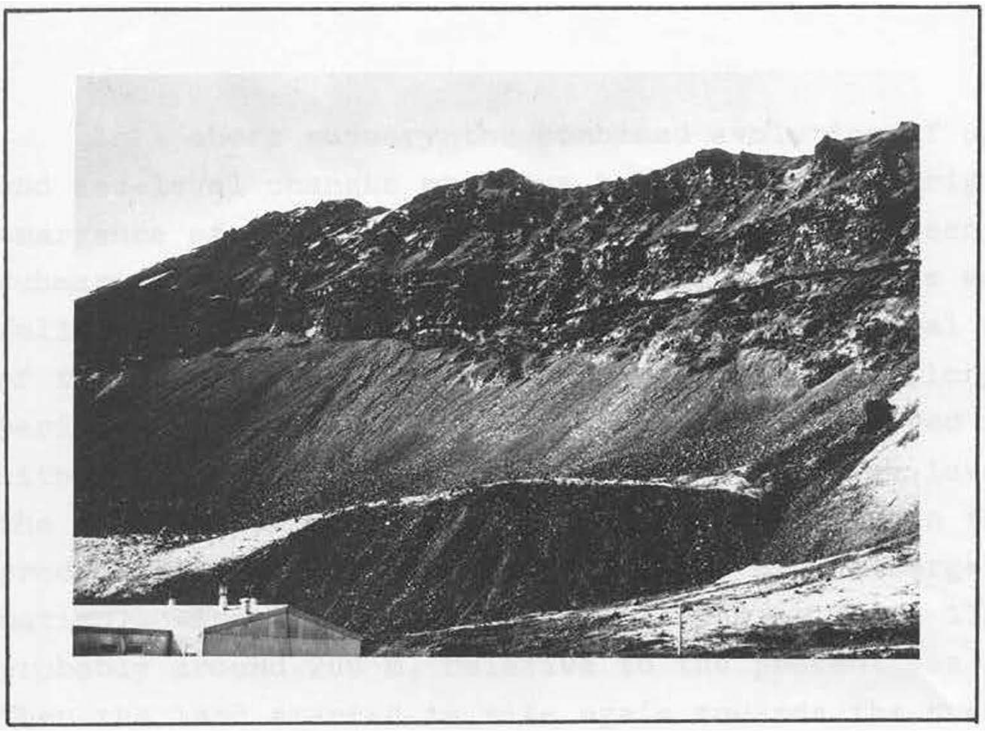

Fig. 16. Trollslottet. The drawn boundary line separates the upper subaerial sheeted lava from the lower forset bedded pillow lava.

In a short summary the combined evolution of uppiling and sea-level changes may have been such: The original emergence of the island from the sea must have been by submarine eruptions forming hyaloclastites. This was followed by eruptions which produced the subaerial rocks of the "Hidden" formations. After a relatively long period (indicated by fresh to considerably altered xenoliths from this formation) of uppiling of these lavas, the land was submerged and eruptions continued in the sea producing submarine hyaloclastites (of Havhestberget formation). The total submergence reached at least 170 m, probably around 200 m, relative to the present sea-level. Then the land started to rise again towards the present position. In this period of rise the Nordvestkapp formation was produced mostly by subaerial eruptions and occasionally by submarine eruptions close to the shore. The 20 m level (above the present) is recognized in a late submarine eruption of this formation in Fugleberget and a 10 m level was described by Fitch (1964) occurring in the lavas of Kokssletta of the postglacial Inndalen formation. The combined procedure of uppiling and vertical movements is shown graphically in Fig. 17.

The shore line changes can only be traced for the postglacial time or the time of formation of the Inndalen rocks. Considerable new areas have been added to Jan Mayen during this time or almost 20 per cent of the total area. This new land is made of equal parts of lavas and sandy beaches. The old shore line is drawn on Fig. 18.

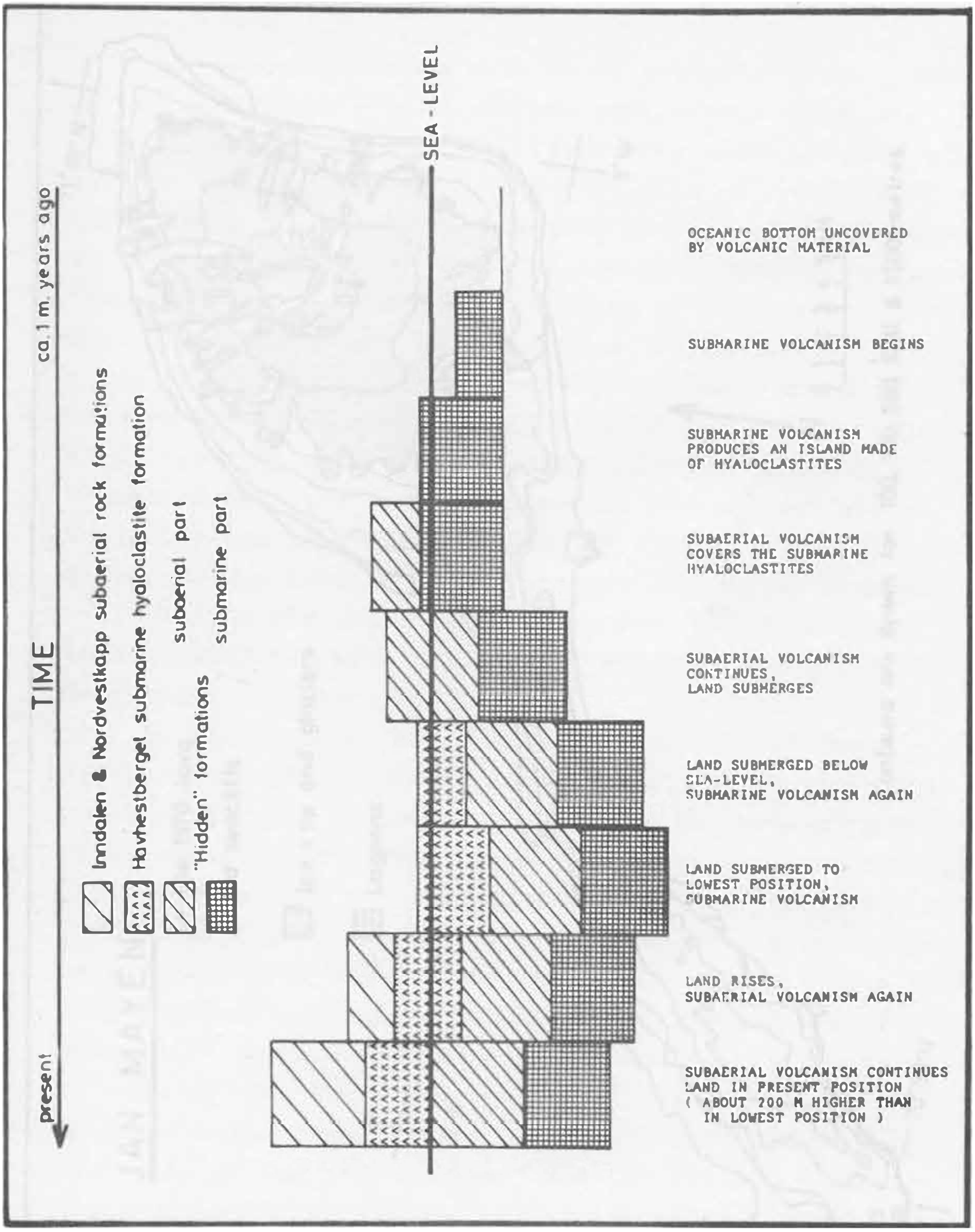

Fig. 17. Schematic diagram of combined vertical movements and volcanic uppiling of Jan Mayen, step by step, relative to a fixed sea-level. The figure is not drawn to scale. The basement rocks below the lower submarine hyaloclastites are probably the same sedimentary rocks as reported from the D.S.D.P. Leg 38 holes on the Jan Mayen Ridge south of the island (Talwani et al., 1975).

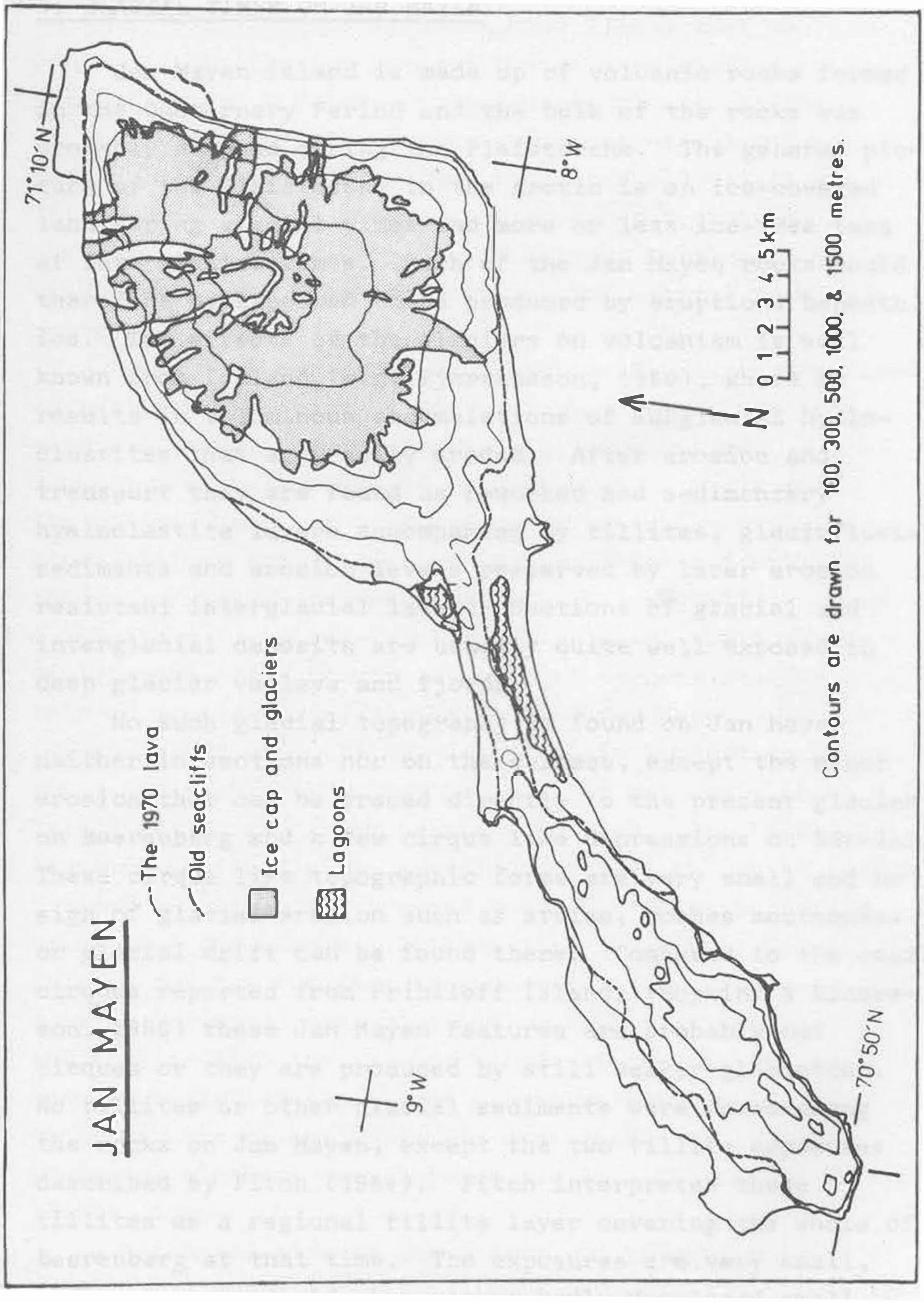

Fig. 18. Map of Jan Mayen, showing the old sea-cliffs and the growth of the island during "postglacial" time.

4. GLACIAL TIMES ON JAN MAYEN

Jan Mayen island is made up of volcanic rocks formed in the Quaternary Period and the bulk of the rocks was probably erupted during the Pleistocene. The general picture of the Pleistocene in the Arctic is an ice-covered land during glacial times and more or less ice-free land at interglacial times. Much of the Jan Mayen rocks could therefore be expected to be produced by eruptions beneath ice. The effects of the glaciers on volcanism is well known from Iceland (e.g. Kjartansson, 1960), where it results in voluminous accumulations of subglacial hyaloclastites that are easily eroded. After erosion and transport they are found as reworked and sedimentary hyaloclastite layers accompanied by tillites, glaciofluvial sediments and erosion levels preserved by later erosion resistant interglacial lavas. Sections of glacial and interglacial deposits are usually quite well exposed in deep glacier valleys and fjords.

No such glacial topography is found on Jan Mayen neither in sections nor on the surface, except the minor erosion that can be traced directly to the present glacier on Beerenberg and a few cirque like depressions on Sör-Jan. These cirque like topographic forms are very small and no sign of glacial erosion such as striae, roches moutonnées or glacial drift can be found there. Compared to the small cirques reported from Pribiloff Islands (Hopkins & Einarsson, 1966) these Jan Mayen features are probably not cirques or they are produced by still weaker glaciation. No tillites or other glacial sediments were found among the rocks on Jan Mayen, except the two tillite exposures described by Fitch (1964). Fitch interpreted these tillites as a regional tillite layer covering the whole of Beerenberg at that time. The exposures are very small, widely separated and show rather badly developed small tillites, one occurring on the northern and another on the southern side of Beerenberg. His interpretation is doubtful and to the author it seems more likely that the glaciers responsible for these tillites were similar to the present outlet glaciers on Beerenberg or even still smaller. At least the present glaciers have left much more voluminous moraines than these two old tillites are. This indicates that the glacial cover of Beerenberg at that time was even smaller than today. Beerenberg was at that time a much lower mountain as the central cone had not yet formed.

There are no indications that Jan Mayen has ever been much bigger than today. Sör- and Midt-Jan form a long, narrow (2-6 km) and topographically rough ridge. A continuation of this ridge is Nord-Jan, up to 16 km wide. The island thus is a long and narrow rough mountainous mass. Before the production of the Inndalen formation, the island was 20 per cent smaller in area. If we allow a 100-150 m lower sea-level in the glacial times of the Pleistocene (as a result of water storage in glaciers) this of course increases the size of Jan Mayen. The island is 380 km^2. If the sea-level is lowered down to 100 m the resulting island becomes 710 km^2 and a small island of 160 km^2 south of the main land. Sea-level lowering to 150 m gives an island of 1300 km^2 or an island 3 times as big as the present one. The shape is in all cases long and narrow. Islands like these will not be able to collect and keep an extensive, thick glacier. The snow or ice would most probably creep out of the island and combine with the sea-ice before it reached the thickness of a glacier capable of extensive erosion and able to affect the volcanism to the same degree as it does where the glaciers were thicker, as f.i. in Iceland during glacial times.

This small size of the island and general absence of glacial sediments and glacial erosion topography leads to the conclusion, that Jan Mayen was never extensively glaciated. More probably the Pleistocene was in Jan Mayen characterized by thin local glaciers, similar to the present Beerenberg one, with a thin cover of loose or unpacked snow in between. Another thing which may have helped to keep the glaciation down is the island's position relative to the sea-ice margin. In glacial times the sea-ice margin is thought to have been at the latitude of Iceland or even south of it (Wagner, 1959). This means that Jan Mayen was positioned far behind the sea-ice margin so most of the precipitation can be expected to have been fallen already before the air masses reached the island. Jan Mayen had then comparable position to the sea-ice margin as Northeastern Greenland has today and this part of Greenland is almost without ice-cover.

The conclusion is thus, that Jan Mayen was much less glaciated than other Arctic countries during glacial times. Subglacial volcanics are therefore scarce. The effect of thin small glaciers and snow-cover on volcanism is poorly known, but the relatively common cube-jointed lava masses on Jan Mayen might probably be related to nival environment as will be discussed below.

5. THE AQUEOUS ENVIRONMENT OF JAN MAYEN VOLCANISM

An extensive formation of subglacial hyaloclastites was formed by volcanic eruptions below the Quaternary ice cover in Iceland. Since the hyaloclastites on Jan Mayen are of Quaternary age it might seem a controversy to consider them to be submarine instead of subglacial. The reasons for believing them to be submarine are the occurrence of marine fossils, their obvious relation to the known sea-levels and the general lack of glacial erosion features and glacial sediments on the island. The hyaloclastites are the most voluminous evidence of an aqueous environment of the Jan Mayen volcanism. The lack of pillow-lavas (proper) and the dominant tuffs among the hyaloclastites indicate that most of the eruptions took place in shallow water (Sigvaldason, 1968). Most of the eruptions have occurred at sea-level similar to the present one or higher. Several small hyaloclastites have formed by subglacial eruptions under local glaciers, existing where the topography was favourable.

Besides the hyaloclastites the rocks show structures indicating other types of wet or aqueous environment of the volcanism. These structures are the flow-foot units (forset bedded pillow-lavas and breccias) and the cube-jointing.

Flow-foot units in volcanic rocks are well known from several places in the world, e.g. Iceland, Hawaii, Sicily and the Columbia River Plateau (Waters, 1960; Jones, 1969; Jones & Nelson, 1970; More et al., 1971, 1973; Furnes & Fridleifsson, 1974). They are formed below water level when subaerial lavas flow into water. As previously mentioned, littoral cones and some other pseudocraters are the surface phenomena formed under similar conditions. The main factors affecting the structures formed under these conditions are: the degree of degassing of the magma, temperature and viscosity (solidification state) of the magma, the rate of flow and the structure of flow of the magma, the morphology of the shore where the magma enters the water (steepness of slope, height of cliffs, depth of water and so on). Most of the occurrences described in the literature show inclined tongues of pillows and lumps in a matrix of vitric breccias and tuffs. The matrix is in most cases very similar to the breccias and tuffs of the subglacial or submarine hyaloclastites. The best example of such flow-foot unit on Jan Mayen is found in Trollslottet above the settlement at Båtvika, where the passage zone between the flow-foot pillow-lava and the sheet lava above occurs in 170 m above sea-level. This height marks the sea-level at the time when this particular lava was erupted. The lava is a compound lava of many thin flow units and the flow-foot unit is mostly made of forset bedded pillows. The amount of matrix is very small. This lava seems to have been very fluid with pahoehoe structure, which is very uncommon on the island.

Two explanations of the formation of cube-jointed lavas are known to the author. The older one (Waters, 1960; Spry, 1962) explains the jointing by irregular stress distribution inside the cooling mass, caused by the cooling pattern and a moving fluid interior. But the more recent one (Sæmundsson, 1970) explains it by aqueous chilling, when hot lavas are overflowed by rivers. The cube-jointed (entablature, hackly jointed, kubbaberg) masses are very similar to the well known culumnar jointed ones, except that the structure of the joints is more irregular and forms a smaller network of cracks, that results in much smaller columns, often approaching cubes. The internal texture of the cube-jointed rocks is much finer than of usual columnar jointed rocks and very often with glassy groundmass, an indication of rapid cooling. Cube-jointed rocks are very common in Iceland, especially as more or less irregularly shaped masses in the finer hyaloclastites or as the upper part of interglacial lavas, which at the time of formation flowed down shallow valleys, where they occasionally dammed up the rivers of the valley. The dammed rivers were then able to overflow the hot lava and hasten the cooling. The frequent occurrence of cube-jointed masses in the hyaloclastites and other indications of aqueous environment in Iceland, their fine-grained to glassy textures and their occurrence in very thin layers, where differing stress distribution must be small, are the reasons for favouring the aqueous chilling explanation of cube-jointing.

Two types of cube-jointed masses are found on Jan Mayen, thin sheets and voluminous masses. It is obvious, that they are not formed under the same aqueous conditions. A good example of the thin sheets is found in the upper part of Pukkelryggen behind Söyla. This is a layer less than two metres in thickness, and the cube-jointing is well developed right through it. It is very unlikely, that a layer of this small thickness, with uniform cube-jointing, has ever developed but a very small difference in stress distribution, and only minor internal flow can be supposed to have taken place after congelation of the surface and bottom. The cube-jointing can therefore not be explained by such a process. Overflowing of water can explain it, but the circumstances on the island do and did not allow rivers of the necessary size. The only explanation seems to me to be a nival environment, where the snow is melted by the hot lava and the water and steam generated penetrates the lava causing more rapid cooling than else and resulting in a fine-grained and fine-cracked rock.

Voluminous cube-jointed masses are best exposed in Tronfjellstupet just south of Blinddalen. This particular mass covers the mountain side and is more than 100 m thick made of small cubes and columns up to ca. 50 cm in length and with irregular small pockets of breccias and tuffs. It is thought to be formed in similar way as the flow-foot units. The different structure is ascribed to differences in the influencing factors listed above. The description of Moore et al. (1971 & 1973) refers to a broad lava front advancing in small tongues of both pahoehoe- and aa-lavas entering the sea. The Tronfjellstupet example is thought to have reached the sea in a bigger closed or open channel and instead of advancing further out step by step as new lava tongues entered the sea, it was collected into a bigger unit isolated from direct contact with the sea by a crust of more or less waterlogged fragmental material, similar to an intrusion. The fragmental crust allowed moderate access of water, enough to result in rapid cooling and cube-jointing. A comparison of these two extreme different cases is shown graphically in Fig. 19.

What has been said here refers to basic volcanism. Much less is known about silicic volcanism in an aqueous environment. The silicic volcanism in Iceland in glacial times has not yet been satisfactorily described, but it is known to result in the formation of voluminous masses of fine ash containing irregular up to gigantic pillows or lumps of obsidian and pitchstone. Nothing of this kind has been found on Jan Mayen, but the pumice breccia of Borga rests directly on a basic hyaloclastite containing marine fossils and made of fragmental trachytic material; a pumice-breccia, where pumice lumps and obsidian mombs occur in an ash matrix. The eruption was explosive and the reason for the explosive nature is thought to be sea-water chilling. It is believed to be erupted in a shallow sea. The gradual isolation of the sea-water from the magma as the material was heaped up is then reflected in the decrease of vesiculation, increase in bombs and other vertical structural changes occurring in the pile.

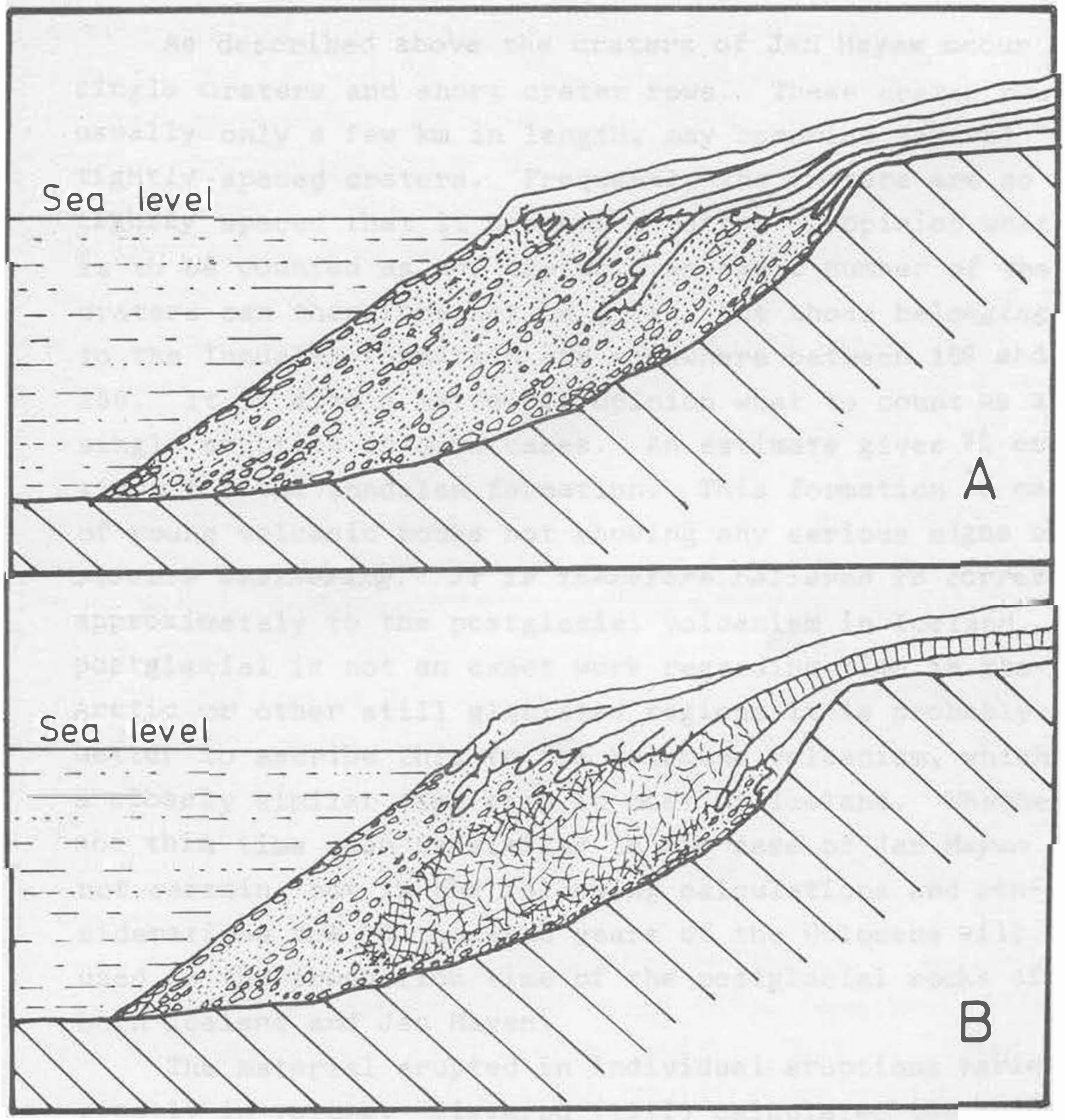

Fig. 19. Schematic comparative figure of two extreme types of formation of flow-foot units. A shows the well described example of fluid lava tongues (modified after Moore et al., 1973) resulting in forset bedded pillow lavas and pillow breccias, as in Trollslottet. B shows the proposed Jan Mayen example of cube-jointed lavas formed by lava entering the sea in one closed lava tunnel or an open lava channel. Most of the red-hot lava is then collected in one big "pocket" already isolated from immediate contact with the sea-water. Instant quenching is prohibited, steam generation is at a minimum and minor mechanical breaking of the material by collapse or explosions takes place.

6. PRODUCTIVITY OF THE JAN MAYEN VOLCANISM

As described above the craters of Jan Mayen occur as single craters and short crater rows. These crater rows, usually only a few km in length, may comprise several tightly spaced craters. Frequently the craters are so tightly spaced that it becomes a matter of opinion what is to be counted as one crater. An exact number of the craters can therefore not be given, but those belonging to the Inndalen formation are somewhere between 100 and 150. It is also a matter of opinion what to count as a single eruption in some cases. An estimate gives 75 eruptions for the Inndalen formation. This formation is made of young volcanic rocks not showing any serious signs of surface weathering. It is therefore believed to correspond approximately to the postglacial volcanism in Iceland. As postglacial is not an exact work regarding time in the Arctic or other still glaciated regions it is probably better to ascribe this to the Holocene volcanism, which has a closely similar time span in most of Iceland. Whether or not this time span is similar in the case of Jan Mayen is not certain, but in the following calculations and considerations the 10 thousand years of the Holocene will be used as the production time of the postglacial rocks of both Iceland and Jan Mayen.

The material erupted in individual eruptions varies greatly in volume. Siggerud (1972) calculated the volume of the lava produced by the 1970 eruption in Beerenberg to be at least 0.5 km^3. This is not the biggest eruption on Jan Mayen but among the bigger ones. Neumayertoppen is a small scoria cone isolated from other young volcanics and might be the result of a single eruption. Its volume is 0.015 km^3 and if the volume of vesicles and intergrain cavities is estimated to be 50 per cent the compact lava erupted has the volume of 0.007 km^3. Still smaller eruptions have apparently occurred. To estimate or calculate the volume of most of the lavas with any accuracy is extremely difficult. The total volume of the Inndalen formation is more easily reached. The calculation is based on the total area of the lavas (107 km^2) and an estimated average thickness of 50 meters. This might appear to be a fairly high figure for the thickness of the lavas, but they are known to have been viscous and frequently they have flowed into the sea, where they had to fill up considerable depth before the lava could advance further out. This figure is a rough estimate, but it is believed to be reasonable. The total volume of the Inndalen formation, thus obtained, is 5.35 km^3. If the eruptions are 75 the average size of an erupted lava is 0.071 km^3. This figure is 10 times the size of the lava erupted in the Neumayertoppen eruption and 7 times less than the one of the 1970 eruption.

Using 10 thousand years and 75 eruptions we get 133 years on the average between eruptions of the Inndalen formation. As previously said four eruptions have occurred in the historic time of Jan Mayen, which spans back to about the year 1615. Thus we have almost 4 centuries of history and at least four eruptions (1732, 1818, 1970 & 1650-1882) occurring in that time. This gives around 100 years on the average between eruptions.

If the last 10 thousand years produced 5.35 km^3 of lava, the total volume of Jan Mayen above sea-level, (about 200 km^3) was produced on 0.37 m. years. This is in agreement with the fact that all the products are normally magnetized and thus younger than 0.7 m.y. and in a fairly good agreement with the K-Ar datings of Fitch et al. (1965), which give maximum age 0.49 ($\pm$ 0.12) m.y. A rough estimate of the volume of the volcanic formations of Jan Mayen below sea-level, based on the sea-bottom topography, gives twice the volume above sea-level. This means that, by the same volcanic productivity, the island and its volcanic foundations are produced during the last 1 m.y. The main figures of these calculations are collected in Table 2.

Dredge samples from the Maröbanken west of Jan Mayen (and along the Jan Mayen Fracture Zone) show only alkaline

TABLE 2. Some estimated and calculated figures related to the volcanic productivity of Jan Mayen volcanism

Number of craters of Inndalen formation	100-150
Number of eruptions of Inndalen formation	75
Average time between eruptions of Inndalen formation	100-133 years
Average thickness of lavas of Inndalen formation	50 m
Volume of biggest lavas of Inndalen formation	$>$ 0.5 km^3
Volume of smallest lavas of Inndalen formation	$<$ 0.007 km^3
Volume of average lava of Inndalen formation	0.071 km^3
Total volume of Inndalen formation	5.35 km^3
Production time of the island above sea-level	0.37 m.years
Time since beginning of the Jan Mayen volcanism	$\sim$1 m.years

volcanic rocks (Campsie, 1976), which might indicate a more extensive volcanic formation in the island´s vicinity. Some of the samples are however striated, a fact which casts some doubts on their volcanic origin on the Maröbanken itself. The rocks of the Eggviabanken, which is still further west and further away from the fracture zone than Maröbanken, are on the other hand typical tholeiitic rocks. This is shown by partial analyses of Dittmer et al. (1975) and an unpublished whole roch analysis by the author.

Even though productivity calculations like these are not accurate they may be supposed to give informations within an order of magnitude and are thus informative. It is therefore of interest to extend these calculations to other volcanic areas in the North Atlantic for comparisons. The comparative figures are collected in Table 3. Jakobsson (1972) has given volume figures for the postglacial volcanic production in Iceland. The Snæfellsnes volcanic zone is the only area in Iceland producing potassic alkaline rocks. These are in fact closely similar to the Jan Mayen rocks regarding chemistry (Sigurdsson, 1970). The total postglacial production of this zone is about 6 km^3 (Jakobsson, op.cit.) or very similar to the Jan Mayen one. Jóhannesson (pers.comm.) estimates the number of postglacial eruptions in Snæfellsnes to be about 55. This gives an average lava of 0.11 km^3 for Snæfellsnes or slightly bigger than on Jan Mayen (0.071 km^3). A study of the volcanism in Iceland in historic times has showed, that in the past centuries the average time between eruptions is 5 years (Thorarinsson, 1960). In 10 thousand years this gives 2000 eruptions, which have produced 480 km^3 of lava (Jakobsson, op.cit.). The average postglacial lava in Iceland is then 0.24 km^3 or 3.4 times the size of the average Jan Mayen lava. Single eruptions in Iceland vary greatly in volume, still more than on Jan Mayen. The biggest eruption in Iceland in historic times is the Lakagígar eruption of 1783, which was 12.5 km^3 (Thorarinsson, 1969b). This is in fact the biggest eruption on the

TABLE 3. Comparison of Holocene volcanic productivity in the North Atlantic

	Jan Mayen	Snæfellsnes	Iceland, total volcanic zones	Iceland, thol. volcanic zones	Ocean Ridges
Number of eruptions	75	55	2000		
Total production, km^3	5.35	$\sim$6	480	427	$\sim$120
Volume of average lava, km^3	0.071	0.11	0.24		
Production, km^3 per 100 km^2	1.4	0.4	2.1	2.2	$\sim$0.5

earth in historic times. The smallest Icelandic eruptions are extremely small or of the order of magnitude 0.000X km^3, which is an order of magnitude smaller than the Neumayertoppen eruption on Jan Mayen. The total post-glacial volcanic production in Iceland (480 km^3) is about 90 times that of Jan Mayen (5.35 km^3). When compared on the basis of equal area on the other hand, it is only 1.5 times as great in Iceland (2.1 $km^3/100\ km^2$) as on Jan Mayen (1.4 $km^3/100\ km^2$).

Jakobsson (op.cit.) believes the volcanic production of the Oceanic Ridges both north and south of Iceland to be 4-5 times less than in middle Iceland. The productivity of the ridges would then be about 0.5 $km^3/100\ km^2$ or nearly 3 times less than the productivity of Jan Mayen. This is in a good agreement with the fact, that both Iceland and Jan Mayen are islands extending high above sea-level. On the other hand it is clear that the productivity of the ridges is far from being evenly distributed along their length. This is especially the case for the Kolbeinsey Ridge, where the depth varies from several hundred metres to shallow extensive banks as Eggviabanken (see Fig. 2) or even to small islands as Kolbeinsey.

Yoder (1976, p.105) gives 5 km^3 as the annual production of the combined mid-ocean ridges of the world and 2 km^3/year for the 490 active volcanos; or 7 km^3/year as the total volcanic production of the world. According to the above estimations and calculations the annual production of Jan Mayen is 0.000535 km^3 or only 0.0076 per cent of the world´s annual production. For Iceland the annual production is 0.0427 km^3 or 0.61 per cent of the world´s production

7. SUMMARY OF GEOLOGY

Jan Mayen is entirely built up of volcanic rocks. The relation of the volcanism to the elements of global tectonics is not fully understood. That Jan Mayen is a hot spot relative to its surroundings is obvious, but whether it is situated over a mantle plume or not is more speculative. Jan Mayen (and many other oceanic volcanic islands) is situated close to a fracture zone where the volcanism is regretably little known. The possibility that Jan Mayen is a spreading center (a continuation of the Mohns ridge) can be ruled out because of lack of rift features on the island and due to the highly alkaline nature of the volcanics.

The rocks may be divided into formations, which do not have strict time boundaries, but reflect different volcanic environment and show differences in lithology. The formations are: 1) "Hidden" formations, 2) Havhestberget submarine hyaloclastite formation, 3) Nordvestkapp subaerial rock formation, 4) Inndalen subaerial rock formation and 5) Unconsolidated detritus.

The oldest parts of the "Hidden" formation are at least partly made of products of submarine volcanism (when the island was first emerging). After the submarine volcanic phase subaerial volcanism took over forming the known (by xenoliths and lavas) subaerial parts of the "Hidden" formation. A subsidence followed accompanied by submarine volcanism forming the Havhestberget formation. The heaps of hyaloclastites formed during this period formed small islands that were later to be connected by lavas erupted through the hyaloclastites (Nordvestkapp formation) and flowing down to the sea and progressively filling the depressions between the hyaloclastites and building a continuous island. These lavas were mostly viscous basic lavas, some intermediate lavas and trachytic domes. Finally this volcanism drowned the hyaloclastites and began advancing further out into the sea. This advance is especially the case with the youngest lavas, the Inndalen formation.

Accompanied by the Inndalen volcanism is a growth of the ice-cap on Beerenberg and later its mild retreat. At this stage the morainic material is formed and bays are filled with strand-sediments. These sediments are the result of glacial and marine erosion of the Inndalen, Nordvestkapp and Havhestberget formations.

The sea-level around Jan Mayen is known to have been changing. The highest sea-level known is at 170 m above present sea-level and is evidenced by shallow marine fossils and the transition from sheet lavas to flow-foot units.

Jan Mayen is thought to have been nearly ice free in the glacial periods of the Quaternary ice age. This is recognized by lack of glacial sedimentary rocks and glacial erosion features in the lava pile and on its surface.

According to paleomagnetic polarity measurements and K-Ar datings the rocks of Jan Mayen are all very young. The rocks above sea-level are all younger than 0.7 m. years, probably younger than 0.37 m.y. The initiation of volcanism in the area is probably around one million years ago. No rhythm or gaps are recognized in the volcanic activity, which seems to have been continuous. An exception may be, that the trachytic rocks are most abundant in the youngest formation.

The volcanism on Jan Mayen has frequently taken place in an aeuqous environment. Three types of wet environment are recognized:

1) Submarine environment resulting in hyaloclastites and pumice-breccia.

2) Snow-covered or subglacial environment resulting in cube-jointed lava sheets and hyaloclastites.

3) Littoral environment (subaerial volcanism feeding hot lava into the sea) resulting in flow-foot units of inclined pillow-lava and pillow-breccia and cube-jointed

basalt masses formed below sea-level and in littoral cones formed above sea-level.

The productivity of the Jan Mayen volcanism seems to be around 3 times as high as that of the oceanic ridges, but slightly less than that of Iceland, if compared on basis of equal area. The average interval between eruptions on Jan Mayen is 100-133 years and the average volume of the erupted lava is 0.071 km^3.

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