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Extent and Regional Differentiation of Glacio-Isostatic Shoreline Variation in Spitsbergen*

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Abstract: The various causes of land-uplift in Svalbard, traces of which are found up to 100 m and higher above sea level, are discussed. A method of identifying terrace sediments by means of morphometry and statistical comparison tests is demonstrated. The marine terraces in a profile from Bellsund to Freemansund are compared and described, and the former ice thickness is determined from the ice-scour limit. The land-uplift is considered to be an old epirogenic lift tendency later modified by glacio-isostatic movement.

Zusammenfassung: Fragen nach den verschiedenen Ursachen der Landhebung in Svalbard, deren Spuren bis mehr als 100 m über NN reichen, werden diskutiert. Eine Methode zur Identifikation der Terrassensedimente mittels Morphometrie und statistischen Vergleichstests wird vorgeführt. Für ein Profil vom Bellsund zum Freemansund werden die marinen Terrassen vergleichend beschrieben und die ehemalige Eismächtigkeit anhand der Schliffgrenze bestimmt. Die Landhebung wird als eine alte epirogene Hebungstendenz gewertet, der die glazial-isostatische Bewegung modifizierend aufgeprägt wurde.

1. ELEVATED SHORELINES IN SPITSBERGEN

A characteristic feature of the relief on Spitsbergen and the other islands of Svalbard is the occurrence of elevated shorelines on the coasts (Fig. 1). Some of these are wide, definitely marine terraces with a thick sediment cover, others are only narrow cliff lines or rock terraces, found well over 100 m above the present shore and whose marine origin is not proved (Fig. 2). The evidence of changing levels of land and sea has often been investigated in Svalbard (BÜDEL, 1960, 1968; SCHYTT, HOPPE, BLAKE & GROSSWALD, 1967; SEMEVSKIJ, 1967; TROITSKIY et al., 1975; etc.).

In spite of detailed research in various areas the question has not yet been settled as to the respective importance of each of the different causes:

— is this an endogenously caused uplift, or an exogenously caused sea-level variation?
— is it an epirogenic movement, an after-effect of orogenesis, whose activity is shown by the adjustment of Tertiary and older strata, by neotectonic faults and by subrecent volcanism?
— is it a glacigenous movement, due to the formation and disappearance of one or more large arctic ice sheets during the Pleistocene ice ages?

Today, land-uplift in Svalbard, unlike that in Scandinavia, has come to an end. On many exposed coasts of the archipelago active cliff formation shows that the coasts are retreating. This is due to the worldwide rise in sea-level of about 1—2 mm/a as a result of generally higher temperature and other developments of the ocean floors.

In the 19th century JAMIESON (1882) had already linked the occurrence of beach terraces with the development of the ice cover. NANSEN (1922) applied these views to Spitsbergen, and BÜDEL (1977: 45) emphasized again the role of glacial isostasy as the decisive cause of raised shorelines in Spitsbergen. Locally, two effects overlap. Water from melting ice sheets causes a worldwide rise in sea level. Compared with the maximum global glaciation of the last ice age 18000 years ago, glacio-eustatic trans-

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gression measures about 100 m (EMBLETON & KING, 1975: 168). Regionally, ice-relief causes land-uplift, which is at first an elastic reaction. It is generally assumed that the pressure of ice sheets thicker than 1000 m causes compensation currents in the subcrust, resulting in a gravity deficiency. After the disappearance of the ice burden, this deficiency leads, with a time lag, to glacio-isostatic uplift of land, amounting to up to a third of the original, regionally varying ice thickness, according to differences in density (WOLDSTEDT, 1961: 295; EMBLETON & KING, 1975: 175).

Fig. 1: Series of beach ridges in Spitsbergen 5 km E of Langneset with view SW over Van Mijenfjord to Bromelldalen; on the southern fjord coast in the background is the main level, the 20 m beach terrace. (Photo: STÄBLEIN, August 1968).

Abb. 1: Strandwallserien in Spitzbergen 5 km östlich Langneset mit Blick nach SW über den Van Mijenfjord gegen das Bromelldalen; an der südlichen Fjordküste im Hintergrund das Hauptniveau, die 20 m Strandterrasse. (Foto: STÄBLEIN, Aug. 1968).

2. DATING OF SHORELINES AND COASTAL UPLIFT CURVES

The chronological development of this postglacial process was reconstructed for Svalbard by means of radiocarbon dates. Whale bones, driftwood and shells found in the marine terrace sediments (SCHYTT et al., 1967) were ^{14}C dated, together with a key horizon, especially widespread in the north, of pumice deposited on the former shorelinse and due to a volcanic event occurring 6500 years ago (BIRKENMAJER, 1958).

Corresponding diagrams by SEMEVSKIJ (1967), SCHYTT et al. (1967) show that uplift started earlier in the western part of Spitsbergen, and the upper marine limit shows less uplift than in the east of the archipelago (Figs. 1 and 7). In the west uplift occurred rapidly at first and then more and more slowly; further to the east uplift was more regular. The height above present sea level does not represent the entire amount of uplift, the eustatic sea-level rise must be added.

3. REGIONAL DIFFERENTIATION

Within this general framework, I should now like to describe observations made in the central part of Spitsbergen from Bellsund with Van Mijenfjord and Van Keulenfjord as far as Freemansund in SE Svalbard. Special attention will be given to

— the identification of marine terraces
— the reconstruction of ice thickness
— terrace division,

and the regional mechanism of movement will be considered. Our investigations follow up those by BÜDEL (1960, 1968), WIRTHMANN (1962, 1964, 1976) and GLASER (1968), carried out in the sixties within the framework of the Stauferland Expedition, which I also took part in (cf. BÜDEL 1972, 1977: 42—47; STÄBLEIN 1969).

Fig. 2: Recent cliff, beach terraces in 3 levels (8, 20, 47 m) and accordant structural terraces on the north coast of Van Keulenfjord near Strandvollsletta. (Photo: STÄBLEIN, August 1968).

Abb. 2: Rezentes Kliff, Strandterrassen in drei Niveaus (8, 20, 47 m) und akkordante Strukturterrassen an der Nordküste des Van Keulenfjordes bei Strandvollsletta. (Foto: STÄBLEIN, Aug. 1968).

3. 1 *Series of beach ridges*

The present shore shows series of ascending beach ridges (Fig. 1) at suitable sites in bays and at parts of the coast where ice has prevented wave action. Differences in age, increasing with height, are often also indicated by differences in colour. Like BÜDEL (1962: 343) we can distinguish a „white, green and brown series" (Fig. 7). The light colour of the bottom series, up to 4 m above sea level, is intensified by a considerable quantity of bleached driftwood. The green series contains shore pools and is covered by a humid tundra with succulent green mosses. In the W the series extends up to 15 m, in the E to about 40 m above sea level. Weathering has already browned the pebble surface of the higher beach ridges and the vegetation changes according to drier habitat conditions. This brown series rises in the W up to 37 m above sea level; corresponding levels in the E reach 60 m.

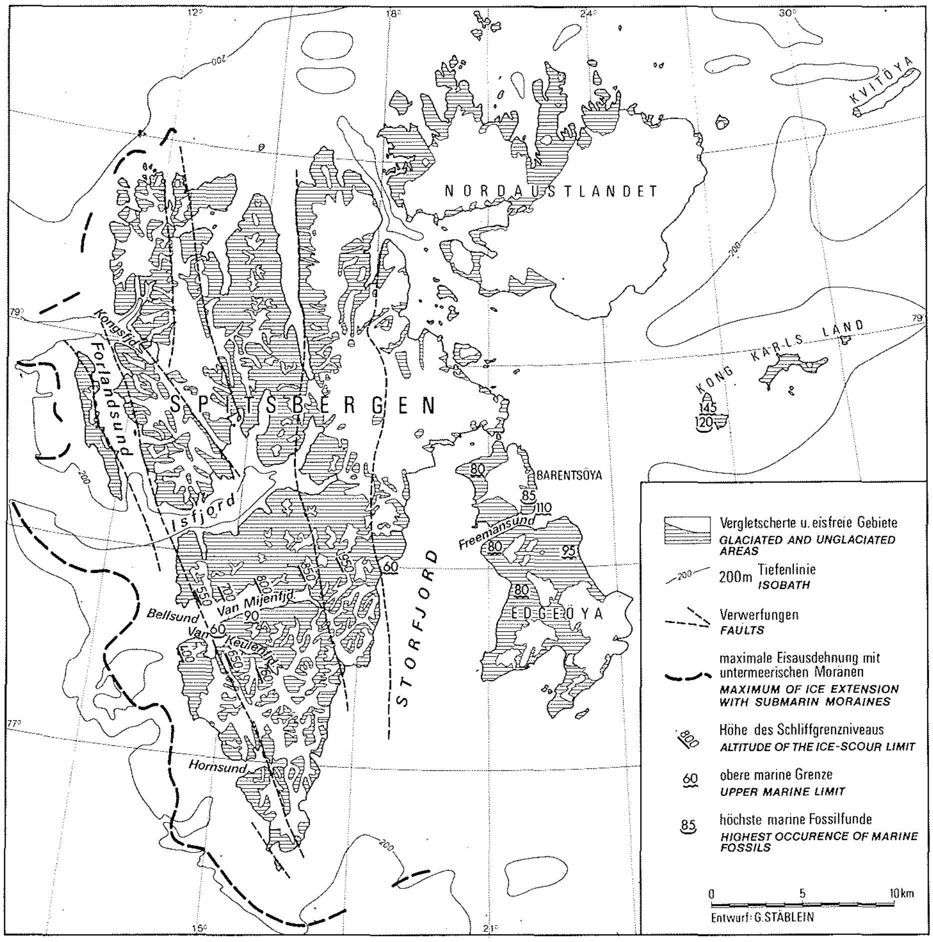

Fig. 3: Glaciation limit in Spitsbergen, ice-scour limits and upper marine limit from Bellsund to Kong Karls Land.

Abb. 3: Vereisungsgrenze Spitzbergens, Schliffgrenzhöhen und obere marine Grenze vom Bellsund bis Kong Karls Land.

3.2 *Main level, cliff and bar terraces*

In the Bellsund area the 20 m terrace is particularly broad (Fig. 4), a sign that the sea-level remained active at this level for an especially long time (cf. Fig. 7). There follow terrace remnants at different heights up to 60 m above sea level. These often end in a fossil cliff. In almost all medium-sized valleys, prominent terrace bars occur at about 85 m (Fig. 5). The bar does not occur in some of the large valleys.

These bars consist of coarse pebbles up to 20 cm in diameter in a sandy groundmass. Marine traces could not be found in the W but were clearly visible in the bar terraces in the E (BÜDEL, 1968: 1). The formation of the bars must have been a complex geomorphological process, taking place at different periods. We assume that the bars originated as glacially compressed valley fills, which were previously deposited fluvially like deltas, and, after compression, were levelled off to a lateglacial marine terrace by 85 m sea level, which prevailed in different regions at different times. Since, to some extent, glaciers were still flowing in the larger valleys at this time, bar terraces could not be formed there.

3. 3 *Structural slope-steps or higher marine terraces?*

On the slopes terraces occur even higher, over 250 m above sea level. Often their non-horizontal position, concordant with the rock basement, shows that they are structural

Fig. 4: Calypsostranda and Scottbreen with Renardodden and Cape Lyell S of Bellsund (view to SW). Beach terraces partly on ice-scoured bedrock with pebbles of the shoreline up to 80 m, above on the mountain flanks to the W (photo, right) of Scottbreen a pronounced ice margin terrace at 110—130 m. (Photo: Norsk Polar Institutt, 1936).

Abb. 4: Calypsostranda und Scottbreen mit Renardodden und Kap Lyell südlich des Bellsunds (Blick nach SW). Strandterrassen z. T. auf glazial geschliffenem Anstehenden mit Brandungsgeröll bis 80 m, darüber an den Bergflanken westlich (rechts im Bild) des Scottbreen markante Eisrandterrasse in 110 bis 130 m Höhe. (Foto: Norsk Polar Institutt 1936).

slope-steps and not marine terraces. At Bellsund we found marine evidence only up to 60 m, and at Freemansund the marine limit was set at 110 m (BÜDEL, 1977: 45). On the Kong Karls Land Islands, the marine limit was established at 145 m (BÜDEL, 1968: 7) (cf. Fig. 1).

Pebbles are still frequently found on the higher slope-steps. Some of them could come from weathered conglomerates (GLASER, 1968: 4; STÄBLEIN, 1969: 128). The question often remains open: are the pebbles pebbles of the shoreline or not? To answer this question we used morphometry and test statistics (cf. STÄBLEIN, 1970, 1972).

The recent shore gives us the norm for typical shoreline pebbles. In shape they are clearly distinguishable from the pebbles of a glaciofluvial river bed. If the frequency distribution of the roundness values of a sediment is compared with the frequency

Fig. 5: N coast of Edgeöya on Freemansund in SE Svalbard, view W over Storfjord. Beach terraces up to 60 m, rising eastward; above, structural terraces and in the valley exit remnants of the bar series at 70 m. (Photo: Norsk Polar Institutt, 1936).

Abb. 5: Nordküste der Edgeöya am Freemansund in SE-Svalbard, Blick nach W über den Storfjord. Strandterrassen bis rd. 60 m, nach E zu ansteigend; darüber Strukturterrassen und in den Talmündungen Reste der Riegelserie um 70 m. (Foto: Norsk Polar Institutt 1936).

distribution of indisputably shoreline pebbles (Fig. 6), the Kolmogorov-Smirnov test decides whether the two distributions differ significantly or not. The decision is based on the fact that if the supremum of both the curves, i. e. the greatest distance, is greater than the valid critical value of the test based on the required level of significance according to a theoretical probability function, there is a significant difference. If the supremum is smaller, both distributions of the shape index show no significant differences, i. e. they are similar in shape. This means that the coarse sediment which was compared with the shoreline pebbles is with high probability also shoreline pebbles. With this method of identification, lithological differences must be considered and only corresponding samples should be compared. With this method it was possible to identify a terrace as a marine form although there were no definitely marine fossils such as shells or whale bones and only shoreline pebbles occur.

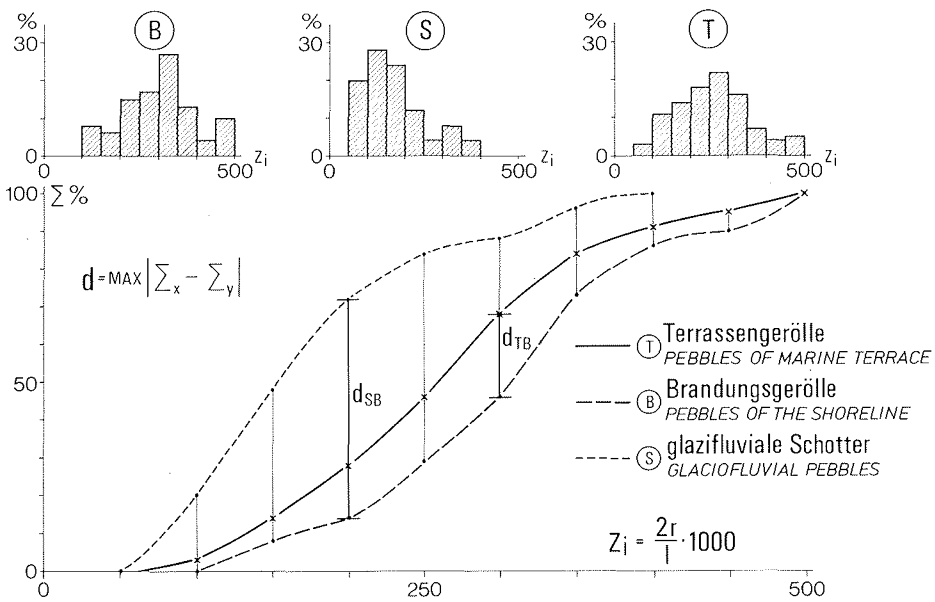

Fig. 6: Morphometric diagrams of pebble samples (sandstone 2—15 cm ϕ) from Van Keulenfjord; sample T marine terrace at Strandvollsletta, sample S highwater bed in Ulladalen, sample B recent beach in eastern Van Keulenfjord. Test value d_{xy} greatest distance between two compared cumulative curves of %-frequencies; critical value of the test D = 23.05 for samples of 100 pebbles and with a level of significance of 99% (SACHS, 1972: 228). As d_{SB} = 58 and d_{TB} = 22, the samples T and B do not differ significantly, following the Kolmogorov-Smirnov test; samples S and B, however, are significantly different as regards roundness index z.

Abb. 6: Morphometrische Diagramme von Geröllproben (Sandsteine 2—15 cm ϕ) vom Van Keulenfjord; Probe T marine Terrasse an der Strandvollsletta, Probe S Hochwasserbett im Ulladalen, Probe B rezenter Strand im östlichen Van Keulenfjord. Testgröße d_{xy} größter Abstand zweier verglichener Summenkurven der %-Häufigkeiten; Testsschranke D = 23,05 für Proben von je 100 Geröllen und mit einer Sicherheitswahrscheinlichkeit von 99% (SACHS 1972: 228). Da d_{SB} = 58 und d_{TB} = 22, unterscheiden sich nach dem Kolmogorov-Smirnov-Test die Proben T und B nicht signifikant; die Proben S und B jedoch sind signifikant unterschiedlich bzgl. des Zurundungsindex z.

3.4 *Ice margin terraces*

As well as structural slope-steps a further feature is found, particularly in the Bellsund area. These forms are not beach terraces, in spite of a similarity of shape. They are pronounced steps at a height of 120—100 m, sloping down westwards and rising towards the valleys. In places (e. g. Cape Lyell, Fig. 4) such steps in the bedrock are glacially formed into ice-scour steps and spread with moraine material. The present form is a lateglacial ice margin phenomenon from a period of ice retreat during only low regional glaciation. TROITSKIY et al. (1975) classified this as a marine terrace and thus spoke of a marine terrace at 120 m here at Bellsund.

3. 5 *Terrace diagram and regional comparison*

A comparison of observations shows that the elevated shorelines in the Bellsund and Freemansund areas are similarly structured, but the corresponding terraces reach greater heights in the E. The upper marine limit in the E is 110 m (according to ^{14}C dates this was the sea level 11.000 years ago). In the W, in the Bellsund area, it is probably 90 m but up to now only 60 m could be proved. According to the climatic conditions at the time of their origin, the various terrace series vary as to the dominance of the fossil molluscs, marine snails and shells, as has been proved in detail for the Isfjord area (FEYLING-HANSSEN, 1955, 1965a).

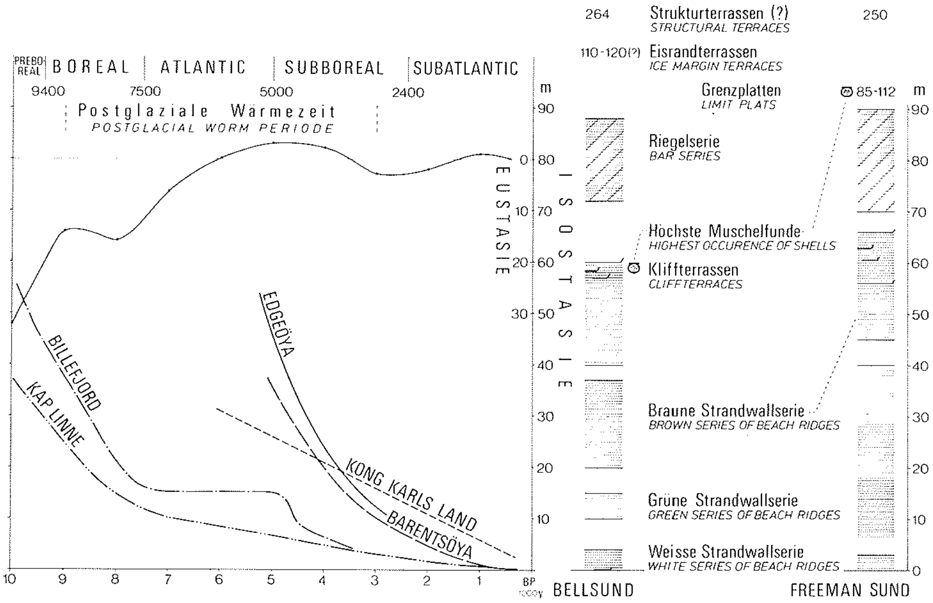

Fig. 7: Series of beach terraces at Bellsund and Freemansund compared to curves of eustasy and isostasy (after FAIRBRIDGE, 1961, quoted from EMBLETON & KING, 1975: 169; SCHYTT et al., 1967; SEMEVSKIJ 1967b; BÜDEL, 1968 and own surveys).

Abb. 7: Strandterrassenserien am Bellsund und Freemansund im Vergleich zu Kurven der Eustasie und Isotasie (nach FAIRBRIDGE 1961, zitiert nach EMBLETON & KING 1975: 169, SCHYTT et al. 1967, SEMEVSKIJ 1967b, BÜDEL 1968 und eigenen Aufnahmen).

JAHN (1959) has found terrace structures in Hornsund which correspond to those at Bellsund. He too does not settle the question of the origin of the top levels above 65 m which contain pebble layers but no conclusive marine evidence. The comparative morphometric tests suggested above could perhaps help here (cf. JAHN, 1968).

A comparison with results from FEYLING-HANSSEN (1965b) from the Bille- and Sassenfjord in the inner Isfjord area proves interesting because of the available absolute ^{14}C dates (cf. Fig. 7). An analogous age to the Bellsund terraces seems probable. The curve of uplift shows the eustatic transgression, which, particularly in the postglacial warm period (Atlantic 7500—5000 years b. p.) led to a temporary standstill in coastal development. Isostatic land-uplift and eustatic sea-level rise took place fairly regularly during this period.

Especially remarkable is the age of the 84.5 m terrace of the Billefjord, which was dated at 21300 b. p. Prior to this dating, it had been assumed that ice pressure was then still effective. This supports the view that at least some parts of central Spitsbergen were ice-free at this time and that the uplift tendency began earlier than the last ice relief. LAVRUSHIN (1967) interpreted OLSSON & BLAKE's (1962) ^{14}C dates of 35 to 40000 years b. p. for beach terraces on Nordaustlandet as an indication of a mostly ice-free interstadial.

The presence of end-moraines (see, for example, the striking examples in the Bellsund area near Collinderodden on Van Mijenfjord) also suggests regionally varying, repeated ice reliefs and, as a result of glacial re-advances, new and considerable ice burdens. During such stages the elevated shorelines sank again. Regionally pronounced stages were distinguished for the Billefjord ("Billefjord stage") and for Bellsund ("Bellsund stage") on the basis of Pleistocene sediments (SEMEVSKIJ, 1967a). So the glacigenous part of the land uplift should not be regarded as just the result of the deglaciation of a large Barents Sea ice-sheet (a hypothesis last put forward by HUGHES et al. (1977)). Younger glacier oscillations, as BÜDEL (1960) deduced from observations in the Freemansund area, have also led to regional shoreline variations. This is supported by the studies carried out in northern Spitsbergen by BOULTON & RHODES (1974), who pointed to the effects of lateglacial oscillations there.

Cliff formations on the west coast and in SE Svalbard — e. g. on the coast of Axelöya in Bellsund or on the west coast of Edgeöya (cf. WIRTHMANN, 1964; GLASER, 1968: 18) — show that land-uplift does not take place today. It is conceivable that the present land subsidence is a last lagging reaction of the powerful glacial re-advance in the 19th century. Most of the individual glaciers show no older moraines apart from the terminal moraines from this most recent advance. The present-day glaciers have thus reached their Holocene maximum stage (STÄBLEIN, 1969). In many places, these recent glacier advances passed over postglacial beach terraces which had been deposited in an ice-free area. In comparison, the glacier burden must have been considerably less during the postglacial warm period than today.

4. ICE-SCOUR LIMIT AND MAXIMUM ICE THICKNESS

It is difficult to establish by direct means the extent of former ice burden in the Freemansund area, because the completely scoured form of the just under 500 m low plateaux shows that the ice cap must once have been very much thicker (Fig. 5).

In the Spitsbergen fjords in the W, the mountains (sometimes higher than 1200 m) clearly show an ice-scour limit, the extent of earlier erosion by the ice masses flowing westward through the fjords (Fig. 4). In southern Nordenskjöld-Land the top ice line rises from 400 m at the entrance to Bellsund to 550 m at Ingeborgfjellet and 780 m at Litledalsfjellet, reaching 800 m at Liljevalchfjellet. In accordance with the glacier snout form, familiar to us from recent glaciers, we must assume that Pleistocene ice can have extended only a few kilometres beyond the west coast of Spitsbergen (Fig. 3). This was proved in the last years by the existence of submarine moraines on the flat shelf off Spitsbergen (LIESTØL, 1972).

5. THE MECHANISM OF LAND-UPLIFT MOVEMENT

Contrary to this established increase in ice burden from W to E, land uplift in the W, particularly in the area of Bellsund and its hinterland, does not vary. Here, the marine terraces run predominantly horizontally, parallel to the current sea-level along the fjord coasts which notch 70 km inland. It is only beyond the big N-S striking, structure determining faults and the Storfjord groove further E that the uplift of the comparable levels is greater and increases eastwards, corresponding to the increased ice burden.

This suggests the conclusion that uplift did not occur as a regionally differentiated continuous process that can be reproduced accurately by interpolated isobases, as in the case of the postglacial domal uplift of the Fennoscandic shield. Whilst W of Svalbard Spitsbergen with its Caledonian-consolidates basement reacted blockwise to the ice-burden, the geologically more continuous southeast was buckled according to the varying pressure.

6. CONCLUSIONS

To return to our original question of how great a share should be attributed to the various causes of the regionally differentiated shoreline displacements:

Observations to date indicate that uplift in Svalbard was not just a glacio-isostatic process but also the elastoplastic endogenous reaction of the earth's crust to exogenic stress through Quaternary ice burden and ice relief, which modifies an older epirogenic uplift tendency and is due to the neotectonic plate development in the area (cf. SEMEVSKIJ, 1976). — This thesis is supported by a comparison with Greenland, where we carried out similar research on land uplift (STÄBLEIN, 1975). In Greenland, the extent of postglacial coastal development which is documented by marine evidence is similar, although the Greenland ice sheet still exists today and postglacial ice relief is presumably on the whole less than in Svalbard, where the ice-age Barents Sea ice-sheet as such has disappeared. The causes of longterm uplifts must be older than the ice age and are to be found in postorogenic shield development. Regional differentiation indicates that upper Quaternary land-uplift was only temporarily more or less reduced by probably several phases of ice retreat and advance with regionally varying glaciation.

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