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Quaternary landforms and deposits in southern Spitsbergen on the ground of photointerpretation

ABSTRACT: Results of geological interpretation of air photos from selected parts of southern Spitsbergen are presented. Quaternary and some older landforms and deposits distinguished during the photointerpretation are described on the basis of their discrimination features, as well as origin and spatial realtions. On this ground a code for interpretation of relief elements in polar areas was prepared. A geological interpretation of air photos completed by absolute datings of different deposits enabled to connect studied landforms with the Late Quaternary main glacial episodes. Sea and glacier extents in the northwestern Sörkapp Land, from the Wedel Jarlsberg Land Glaciation (Saale) to the Little Ice Age (Holocene) are presented.

K e y   w o r d s : Arctic, Spitsbergen Quaternary, photointerpretation, geomorphology.

Introduction

Land surface of Spitsbergen is under influence of different creative factors and for this reason photointerpretation and fieldworks were carried through on glaciers and in ice-free areas (Fig. 1). Interpretation of air photos enabled a simultaneous analysis and comparison of contemporary and ancient glacial relief, as well as correlation of distinguished landforms with glacial episodes and deglacial intervals in southern Spitsbergen. Coexistence of genetically different landscape elements allowed to reconstruct glacier and shoreline extents during the Late Quaternary.

In geological, geomorphological and glaciological studies of polar areas, interpretation of air photos is all the day's work. Long-lasting snow cover and impenetrable areas reduce duration and scale of fieldworks. First photogrammetric measurements in Spitsbergen were made in the early thirties by Zawadzki (1934) who prepared a topographic map of the northwestern Wedel Jarlsberg
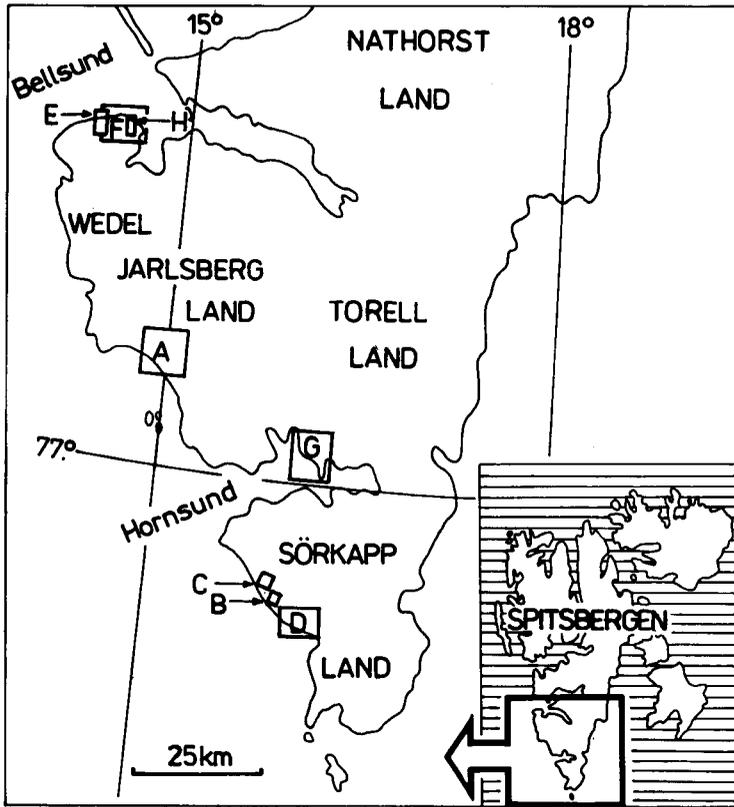
Fig. 1. Location sketch of studied areas

A — interlobal zone of Torellbreen (Szczęsny *et al.* 1985), B — surroundings of Kulmrabben (Lindner, Marks and Szczęsny 1986), C — Widerdalen (Szczęsny 1986), D — Hilmarfjellet region (Szczęsny Lindner and Marks 1987), E — Tjörndalen (Szczęsny 1987a), F — forefield of the Renardbreen, Scottbreen and Blomlibreen (Szczęsny *et al.* 1989), G — Treskelen region (Szczęsny, Lindner and Marks 1989), H — Calypostranda region (Nitychoruk, Ozimkowski and Szczęsny 1989)

Land* in scale of 1 : 50,000. Norwegian air photos of 1936 were used for preparation of topographic maps of Svalbard in scale of 1 : 100,000 (Norge, Topografisk map over Svalbard). They formed for a long time the basemap for geological and geomorphological mapping.

Terrestial and air photos are used at present in these disciplines where sketches, profiles and maps are needed as exampled by studies of glacier forefields (Szczęsny, Lindner and Marks 1989), raised marine beaches (Nitycho-

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* All geographical names in this paper correspond to the ones used on the Norge, Topografisk map over Svalbard, 1:100,000. The most common Norwegian names mean: fjellet and berget — mountain, toppen and tinden — top, ryggen — ridge, passet — pass, dalen — valley, breen — glacier, flyene — plain, bekken and elva — river, bukta and hamna — bay, fjorden — fiord.

ruk, Ozimkowski and Szczęsny 1987) or slope landforms and deposits (Jania 1982). Interpretation of air photos enables simultaneous identification, location and demarcation of most Quaternary landforms and deposits. The author focused on interpretation of recent glacial, glaciofluvial and marine features which could be rocognizable on air photos. Less attention was paid to slope and lacustrine deposits. Relations between landforms and glaciers, as well as morphology, lithology and tectonics of bedrock were also sought.

The whole work was done in the Institute of Geology, Warsaw University, as the continuation of previous investigations of Dr S. Ostaficzuk (Ostaficzuk, Marks and Lindner 1980, Ostaficzuk, Lindner and Marks 1982, 1986). Interpretation of air photos was completed with fieldworks in Spitsbergen in summers 1985 and 1986 during the scientific expeditions organized by the Jagiellonian University of Cracow and the Maria Curie-Skłodowska University of Lublin. This paper is a part of Ph.D. thesis (Szczęsny *unpubl.*) and presents results of the geological interpretation of air photographs from selected parts of southern Spitsbergen.

Outline of geological structure and relief of southern Spitsbergen

Spitsbergen is a unique area either from geographical or geological points of view. It is located in the northwestern part of the European continental shelf and separates the shallow Barents Sea in the east from the Atlantic in the west and the Nansen Basin of the Arctic Ocean in the north. In geological history of this area periods with completely different sedimentary environments occurred. Tectonics indicates connection with past events in northern Europe.

Rocks in Spitsbergen belong to two complexes: the consolidated pre-Quaternary bedrock and the loose Quaternary cover.

Bedrock. — Pre-Quaternary rocks are composed of 4 lithostratigraphic groups that discordantly overlie one another. The oldest Hecla Hoek Complex (Proterozoic — Middle Ordovician) is composed of shales, quartzites, dolomites, limestones, conglomerates, phyllites, tillites, amphibolites, greenstones and granitoids (Flood, Nagy and Winsnes 1971). The second, Paleozoic group of the Devonian, Carbonian and Permian is composed of shales, siltstones, sandstones with coal beds, conglomerates, breccias and limestones. The third group includes the Triassic, Jurassic and Cretaceous formations composed of sandstones, quartzites, conglomerates, shales and siltstones interbedded with thin limestone and coal beds. The Tertiary (Paleocene — Miocene) group is the youngest one and composed of conglomerates, sandstones, siltstones and shales with coal beds (Flood, Nagy and Winsnes 1971).

The present structure of Spitsbergen was formed during the Alpine Orogeny, probably in the Paleocene. It corresponds to the youngest phase of the Laramean Orogeny in the Alpine — Carpathian region (Birkenmajer 1972). This Tertiary

tectonic phase in Spitsbergen is called "the West Spitsbergen Orogeny" (Harland and Horsfield 1974) or "the Spitsbergenian Phase" (Birkenmajer 1972), and presumably connected with extension of the floor of the northern Atlantic.

Due to several stages of tectonic pushes from WSW and SW three main structural elements were formed. They are parallel to the continental margin and from SW to NE of Spitsbergen they are consequently: Western Block, Fold Belt and Forefield (Birkenmajer 1972). The Western Block is composed of the Hecla Hoek rocks folded during the Caledonian Orogeny and discordantly overlain by the Paleozoic and Mesozoic formations. Its specific block structure is created by two generations of faults of WNW-ESE and NE-SW directions (Birkenmajer 1972). The Fold Belt is composed of intensively folded Hecla Hoek formations, 2 to 5 times overthrusted on the Paleozoic and Mesozoic rocks (Birkenmajer 1972). The Forefield is formed of the Jurassic, Cretaceous and Tertiary formations. Rocks are inflected into a wide asymetric syncline with steep western limb and gently inclined eastern one. Formations of the Fold Belt are partly overthrusted on western limb of the syncline, generating secondary disturbances (Birkenmajer 1972).

Azimuths of strata are generally parallel to expansion of structures (NNW-SSE). Dips are from 80–90° (normal and reverse) within the formations of the Hecla Hoek Complex in the Western Block and the Fold Belt, to 5–8° in the Mesozoic cover of the Western Block and the Cainozoic formations of the Forefield.

Quaternary landforms and deposits. — Steep and narrow mountain ridges, often higher than 1000 m (Hornsundtind 1431 m a.s.l., Mehesten 1354 m a.s.l., Berzeliustinden 1205 m a.s.l.) and deeply incised valleys with glaciers form the characteristic landscape of South Spitsbergen. Valleys have been located presumably within the Tertiary depressions and remodelled during the Quaternary glaciations (Birkenmajer 1980).

Some valleys of the western seaside of the island are ice-free at present (*e.g.* Lisbetdalen) or glaciers exist in their upper parts only (*e.g.* Tjörndalen, Wiederdalen). However there are also the valleys which are completely filled with glaciers that reach coastal plains or even enter the sea (*e.g.* Vitkovskibreen, Renardbreen). Thickness of glaciers increases eastwards and northeastwards. Only the highest mountain massifs (*e.g.* Haitanna, Grimfjellet) penetrate through the glacier cover and form nunataks.

During the last 100 years intensive deglaciation (Fig. 2), resulted in abundance of crushed material derived from melting glaciers. Coarse debris has been deposited at glacier snouts in terminal, lateral and ground moraines which are generally still ice-cored moraines. Fine debris was transported by meltwaters and deposited in sandur fans. Apart from landforms connected with the contemporary and slighty older activity of glaciers, ancient lateral moraines, trimlines and roche moutonnées were noted on mountain slopes and on valley floors. They indicate different extents of glaciers in the past.
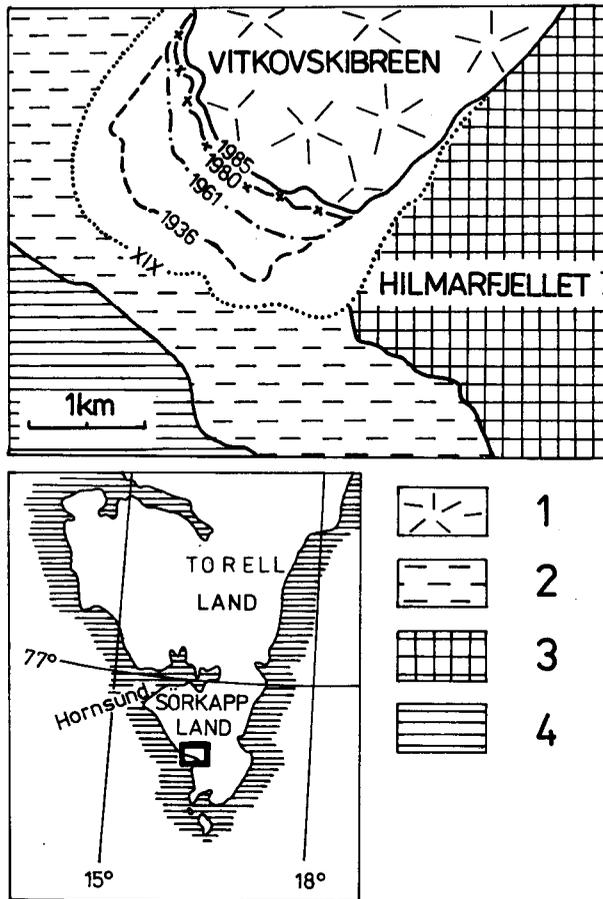
Fig. 2. Sketch of retreat of the Vitkowskibreen during the 20th century, adopted from Szczęsny,
Lindner and Marks (1987)
1 — glacier ice, 2 — raised marine beaches, 3 — mountain massifs, 4 — sea

Climatic conditions in Spitsbergen stimulate slope processes, especially on nunataks and in glacier-filled valleys. Rocks desintegrated by frost weathering have been transported downslope by mass movements and meltwaters. They formed rockfalls, taluses, alluvial fans, solifluction mantles, waste covers and nival moraines.

Along the western shore of Spitsbergen and in the fiords, a land strip between mountain massifs and a shoreline is occupied by a coastal plain from several dozen metres to 3–4 kilometres wide. The coastal plain is composed of raised marine beaches which are the evidence of vertical land and sea movements in the past. Measurements of altitude of raised marine beaches in different parts of Spitsbergen, supplemented with thermoluminescence (TL) and ^{14}C datings of deposits or remains of marine fauna and driftwood, allow to reconstruct rate and range of these movements. During the Late Quaternary the rate of land uplift

rapidly increased due to glacioisostatic release caused by deglaciation. However, amplitude of these movements is still the open question.

The highest raised marine beaches occur at 80–100 m a.s.l. in the southern Hornsund area (Kłysz and Lindner 1981), and reach 130 or even 160 m a.s.l. on southern coast of Bellsund (Szczęsny et al. 1989) where the uplift is greater. Some authors suggest a yet more mobile bedrock (Jahn 1959, Marcinkiewicz 1961, Stankowski 1981, Karczewski 1984). In their opinions the highest raised marine beaches in Spitsbergen are located up to 270 m a.s.l. or even higher. However, such flattenings at summits seem to be connected with pre-Quaternary erosive surfaces or tectonic shelves (Fig. 3). Such flattenings on the Karentoppen at up to 230 m a.s.l. were considered for raised marine beaches and described as "abrasional shelf cut out in the limestones of Hecla Hoek Formation; strata are
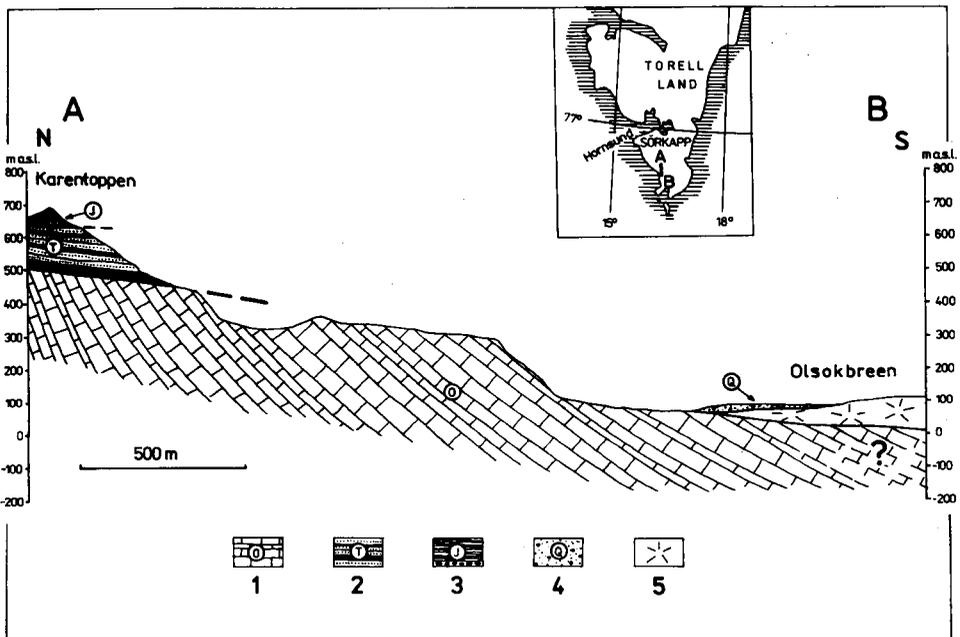
Fig. 3. Geological section through the Karentoppen
1 — limestones, Hornsundtind Limestone Formation (Ordovician), 2 — siltstones and shales Vardebukta Formation (Triassic), 3 — conglomerates and shales (Jurassic), gravel and till (Quaternary), 5 — glacier ice

inclined eastwards (40°), so origin of this shelf can not be structural "(Szupryczyński 1968b). Detailed investigations of the Karentoppen (Szczęsny 1988) proved the flattening to be undoubtedly a fragment of the pre-Triassic planation surface on which consequently conglomerates, sandstones, siltstones and shales were deposited (Fig. 3) during the Griensbachian (Flood, Nagy and Winsnes 1971). Arguments that this flattening is of marine origin, because marine pebbles were found there is correct, but these pebble are not of the Quaternary age and come from the conglomerate which started the Triassic sea transgression.

Relief of the studied western part of South Spitsbergen has been formed by erosion and accumulation, as well as by glaciofluvial, weathering and karst processes and depends on bedrock structure. Extension of main relief elements *i.e.* of mountain ridges and valleys, in NNW–SSE direction corresponds to azimuths of rock complexes, faults and overthrusts. Relief elevations are connected with more resistant bedrock formations, while depressions with the less resistant units — incomplement or intensively cracked in vicinity of faults.

Last geomorphological investigations in South Spitsbergen (Karczewski 1984, Karczewski *et al.* 1984, Jania and Szczypek 1987, Jania 1988) concentrated on separation of main morphogenetic landscape types and discrimination of characteristic groups of landforms within each type.

On the photogeological maps of Spitsbergen (Ostaficzuk, Marks and Lindner 1980, Ostaficzuk, Lindner and Marks 1982, 1986, Szczęsny *et al.* 1985, 1989, Szczęsny, Lindner and Marks 1987, 1989), genesis and lithology of deposits were criterions used to discriminate the Quaternary landforms.

Methodics

During geological and geomorphological investigations wide outlook on expansion and relations between different Quaternary landforms and deposits is necessary. Such analysis is possible after field identification and location of studied landforms, and after precise marking their boundaries on topographic maps. However, such work is sometimes difficult and time-consuming, especially in impenetrable mountains and on widespread coastal plains, devoid of characteristic landscape elements. Analysis of air photos make interpretation and location much easier. Transformed image allows preparation of topographic basemaps in useful scales and a simultaneous analysis of studied landforms in their real relations. It is especially important due to scancity of large-scale topographic maps of Spitsbergen. During geological and geomorphological fieldworks the Norwegian topographic maps in scale of 1 : 100,000 (Norge, Topografisk Map over Svalbard), or their photographic enlargements are usually used. But accuracy of the latter is not better than of the originals due to generated deformations; thus precise mapping, especially of small landforms is not possible. Also the topographic maps of the Hornsund area in scale of 1 : 25,000 (Barna and Warchoł 1987) are useless to fieldworks as no additional informations but the contour lines are on these maps.

Sometimes terrestial photogrammetry is used to geomorphological mapping (Jania 1982b, Lankauf 1982), but being considerably time-consuming, it could be used in very limited areas only. Terrestial panoramic photographs made by Horodyski, Kossobudzki and Musiał (1987) from mountain summits in the western Nördenskjold Land, continued an attempt to solve this problem. Such photos presented wide areas but boundaries of identified landforms were

manually drawn on topographic maps. This method seems to be therefore insufficiently precise, especially if preparing large-scale maps.

The method used by Stankowski (1987) appeared to be more precise. Quaternary boundaries marked on stereoscopic images were transferred by optical converter LUZ on a topographic basement, made by transformation of air photos with a use of a stereo plotter. However application of appliances of varying precision, as well as necessity of repeated transfers of boundaries from many photos, create undoubtful deformations.

Geological interpretation of air photos from Spitsbergen, made in the Institute of Geology, Warsaw University, seems to be free of most defects of the aforementioned methods. It is faster and easier than fieldworks and terrestial photogrammetry. In comparison with the combined methods it is more precise, as all prepared maps were done with the same instrument *i.e.* stereo plotter Topocart B (made by Carl Zeiss, Jena) which enables a simultaneous photointerpretation and drawing a map.

Photogeological maps (Szczęsny *et al.* 1985, 1989, Szczęsny, Lindner and Marks 1987, 1989 — areas A, D, F, G in Fig. 1), sketches (areas C, E in Fig. 1) and morphological sections (Fig. 19) were prepared with a use of Norwegian air photos in scale of 1 : 50,000, taken by Norsk Polarinstitutt in 1960, 1961 or 1970 (Pl. 1). The photos were transformed into photogeological maps in scale of 1 : 10,000 with a use of the set Topocart-Coordinatograph (stereoplotter — automatic plotting table). Detailed methodics of preparing these maps, and analysis of measurement accuracy were already published (Lindner *et al.* 1985, 1990).

Photogeological sketches were prepared with a use of stereoscope and enlarged by LUZ converter. Contour lines are absent, there are only boundaries of Quaternary landforms and deposits, as well as fluvial pattern (Figs 6 and 13). Of course sketches are not so precise as maps, but relations between studied landforms are real and therefore sketches are useful enough to genetic interpretations.

Code. — During interpretation of air photos discrimination and designation of distinguished forms are necessary. Classic diagnostic criterions proposed by manuals of photointerpretation (Gospodinov 1964; Ostaficzuk 1978; Ciołkosz, Miszalski and Olędzki 1978) as shape, phototone and texture of image could be used by the author. However, additional diagnostic criterion named "location" was brought into practice. Field observations indicated that landforms of similar appearance but of different origin are usually connected with closely specified areas. In fact a photointerpretation code for discrimination of Quaternary landforms and deposits in southern Spitsbergen was presented (Fig. 4).

Many similar codes have been constructed for different areas in the world (Gospodinov 1964, Zwiagielskij 1978). None of them was however prepared for polar areas, although photointerpretation in geological and geomorphological studies became a normal practice. All the codes were constructed as tables, in which characteristic features of different landscape elements are described. Such

Hilmarfjellet region on the air photo (S61:1248 E9) taken in 1961 by Norsk Polarinstaitutt, Oslo
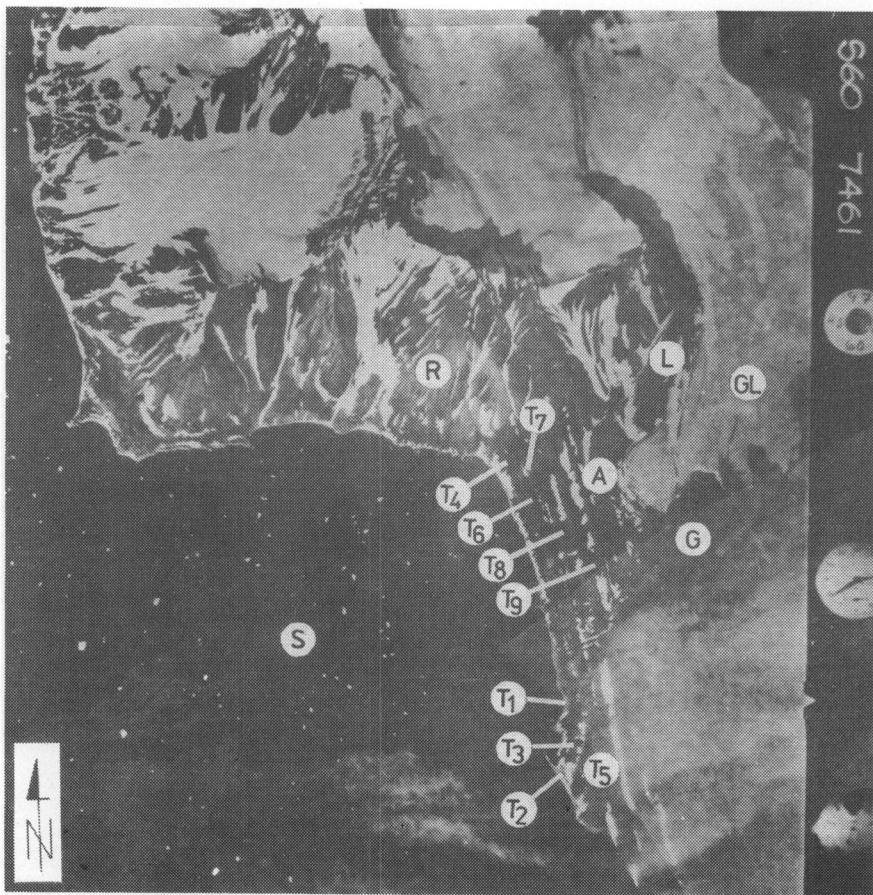
Treskelen Peninsula on the air photo (S60:1148 F9) taken in 1960 by Norsk Polarinstitutt, Oslo
R — rock outcrops partly with a waste cover, A — ancient lateral moraines, L — lateral moraines,
G — ground moraine, GL — glacier ice, T_{1-9} — raised marine beaches, S — sea

	No	LANDFORMS	COEXISTENCE (numbers from column 1)
SLOPE AND STRUCTURAL	1	rock outcrops	3,4,6,8,20,24,25
	2	klippes	4,20,23,24
	3	chutes	1,2,7,20
	4	waste covers	1,2,3,6,7,20
	5	solifluction mantle	4,11,20
	6	taluses	1,2,4,7,8,12,20
	7	alluvial fans	3,4,20,24
GLACIAL, FLUVIOGLACIAL AND NIVAL	8	ancient lateral and terminal moraines	1,6,12,13,20,23
	9	ground moraines	10,13–20,23
	10	fluted moraines	9,15–20
	11	ice-cored moraines	5,9,10,13–17,19–24,26
	12	nival moraines	6,8,13,20
	13	rock glaciers	9,11,12,15–17,20
	14	median moraines	9,11,15,16,20
	15	ablation moraines	9,10,11,13,14,16,20
	16	glacier ice	9,10,11,13–15,19–21
	17	kames and kame terraces	9,11,17–20
	18	eskers	9,17–20
	19	sandurs	9,11,16–21,23
	20	snow patches	1–27
	21	icings	11,16,18–20
MARINE	22	beach	20,23,23a
	23	raised marine beaches	2,8,9,11,19,20,22–24,26,27
	a	ancient storm ridges	11,20,22,23,23b
	b	depressions	1,25,11,20,23,23a,24
OTHER	24	edges	7,11,20,23
	25	sinkholes	1,20,23
	26	lakes	11,20,23,23b,24
	27	deposits of ephemeral lakes	11,20,23,23b,24

Fig. 4. Code for discrimination of Quaternary landforms and deposits on air photos from southern Spitsbergen
column 1 — list of landforms, column 2 — landform phototone, column 3 — form shape in plan (prolated, fan-shaped, round, shapeless) and in section (flat, convex, concave, uneven), column 4 — image texture (smooth, spotted, granular, striped, reticulate), column 5 — location of landforms (on valley axis, on a wall, at slope foot, on coastal plain), column 6 — coexistence o landforms

Fig. 5. Fragment of the photogeological map of the southern slope of Hyrnefjellet, adopted from
Szczęsny, Lindner and Marks (1989) — without contour lines
1 — mountain massifs with a waste cover, 2 — rock outcrops, 3 — structural features, 4 — lateral
moraines, 5 — raised marine beaches (altitude in m a.s.l.), 6 — present beach, 7 — alluvial fans,
8 — taluses, 9 — glacier ice, 10 — snow patches, 11 — lakes and streams, 12 — edges, 13 — shoreline
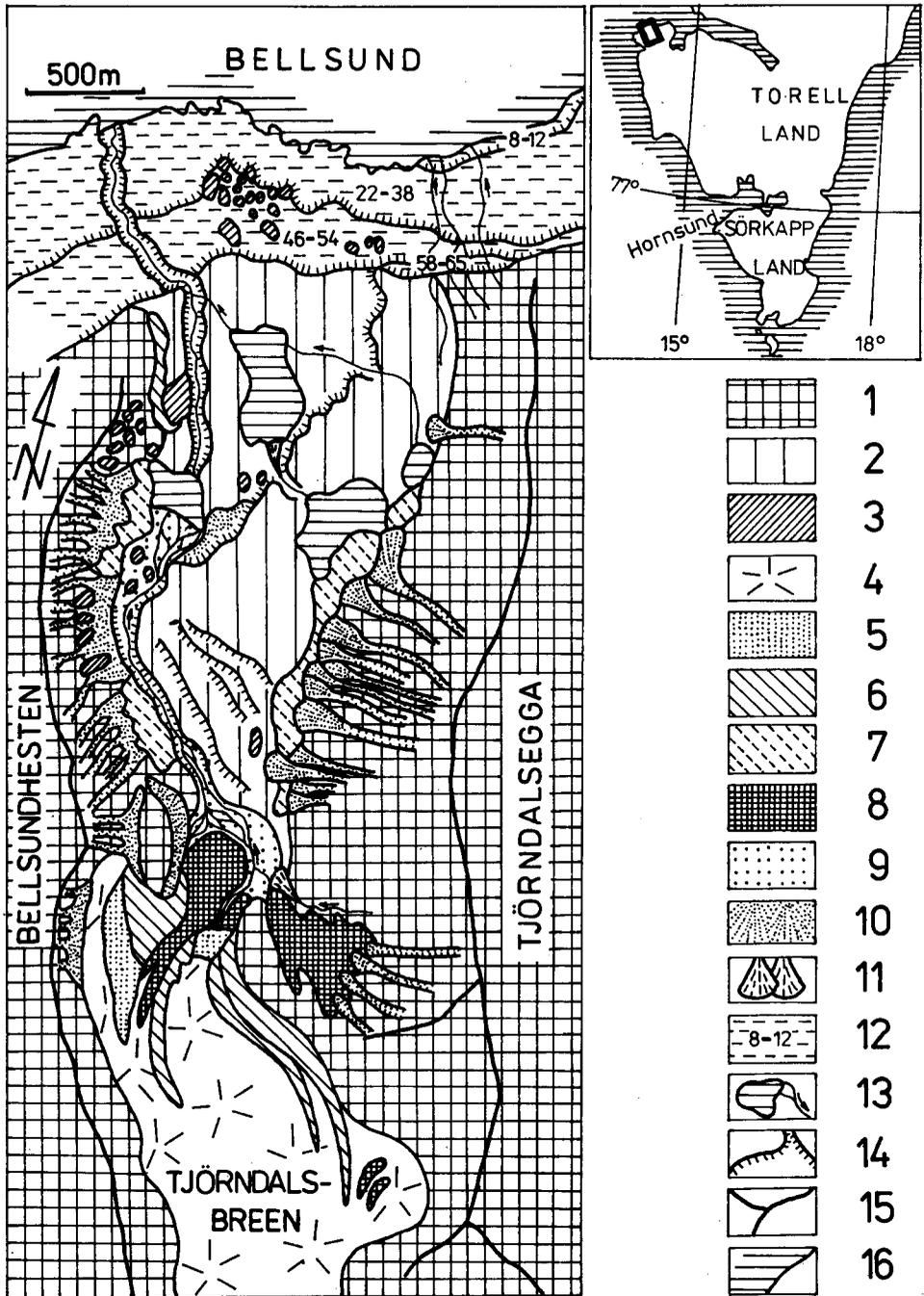
Fig. 6. Photogeological sketch of the Tjörndalen region, *after* Szczęsny (1987a)
1 — mountain masifs with a waste cover, 2 — valley floor, 3 — rock outcrops, 4 — glacier ice,
5 — ablation moraines, 6 — ancient terminal, lateral and median moraines, 7 — nival moraines on
the lateral moraines, 8 — ice-cored moraines and rock glaciers 9 — sandurs, 10 — taluses, 11
— alluvial fans, 12 — raised marine beaches (altitude in m a.s.l.), 13 — lakes and streams, 14 — edges,
15 — mountain crests, 16 — shoreline

presentation is undoubtedly rich in informations but at the same time out of practice due to laborious search for the most important informations. The code prepared by the author has a new graphic form, which seems to be more readable.

Photointerpretation of geological structure of pre-Quaternary bedrock

The pre-Quaternary bedrock in southern Spitsbergen is exposed partly on slopes of mountain massifs and on seashore plains. Due to intensive weathering, rock outcrops free of waste are rare. They exist only on narrow mountain crests and scarps where waste cannot persist. More resistant rocks are also exposed in elevations of valley floors where they survived intensive glacier erosion in the past. They have been covered for sure by ground moraines during glacier retreat but meltwaters easily removed a thin layer of glacial deposits and flat valley bottoms or roche moutones were exhumed (Fig. 6). Several rock shelves were abraded by sea on mountain slopes (Figs 9 and 12). At present they are covered with occasional nival and glaciofluvial accumulation what usually makes discrimination of abrasion and accumulation terraces on air photos difficult.

Klippes or their groups form specific rock outcrops in places with more resistant formations. They are convex elements in the field and of course on stereoscopic image either. On gently inclined mountain slopes klippes emerge in chains from under a waste mantle. In photointerpretation works these chains indicate composition of rock complexes (Fig. 5). Sometimes structural features that reflect bedding are visible on klippe surfaces (Fig. 12). Klippes are also common on raised marine beaches (Figs 6 and 9). They are fossil equivalents of contemporary skerries on abrasive platforms. In spite of their small sizes they are clearly visible on air photos due to the effect of vertical exaggeration. Marking every klippe is very important for further geological works because they are often the only places where lithologic observations and tectonic measurements are possible (*see* Ozimkowski 1989). Field observations and photointerpretation indicate that most klippes occur on abrasive terraces and are rare on accumulative ones. However no explicit criteria for discrimination of terrace origin seems at yet to be possible.

Texture of rock surfaces on air photos is usually due to their unevenness which is granular or spotted. Surfaces polished by glaciers are smooth while those cut by numerous narrow chutes are striped (Fig. 4). Wide chutes were marked on maps independently (*cf.* Szczęsny, Lindner and Marks 1989), due to their distinctness and characteristic discrimination attributes (Fig. 4).

Phototone differentiation of rock surfaces is extremal on air photos (Fig. 4). The phototones depend on lithology but considerably more on different illumination. Therefore, intensity of insolation makes the same rocks have frequently different phototones and vice versa. Comparisons are possible only for similarly inclined and illuminated surfaces. Last but not least many exposures

are in steepest fragments of mountain slopes which are in shadow or even "hidden" on studied air photos. In such case the next photos from the air raid series must be used.

The photointerpretation carried in southern Spitsbergen is not good enough to discriminate lithological complexes directly on air photos. Only general regularities are to be distinguished. Limestones and sandstones are usually lighter than shales or siltstones. Within metamorphic rocks even general relationships are not visible. However conclusions on lithology from morphology of mountain slopes and crests are possible, although results could be questionable. Many mountain slopes have been modelled by glacial erosion or by sea abrasion. In such cases modelling forces were so intensive that resistance variations of rocks seem to be meaningless and they are not visible on slopes. For example slopes of Bohliryggen (Bellsund) composed of tillite are similarly undercut as slopes of Würmbrandegga (Hornsund) composed of dolomite. Seeking differences are only visible on valley floors filled with small glaciers where thresholds and elevations are the evidence of more resistant formations (Fig. 6).

Relationships between lithology of abraded rocks and character of raised marine beaches are also unclear on air photos. Terraces in the Calypsostranda are similar to those in the Lyellstranda, although the first ones were cut in the Tertiary siltstones and sandstones, whereas the second ones in the Cambrian tillites. More klippes on tillitic terraces are the only difference.

A relief of southern Spitsbergen seems to be more closely connected with tectonics than with lithology. For example obsequent slopes are steeper than consequent ones (Lindner, Marks and Ostaficzuk 1986), narrow mountain crests occur in intensively folded areas and gently inclined beds favour presence of flat summit plains (Fig. 3).

Interpretation of tectonic features directly on air photos is an uneasy task. If monoclinal beds and large folds form horizons of klippes on mountain slopes and are visible as boundaries between zones of different phototone of waste or structural features which are equivalents of the intersection lines (Figs 5 and 12), then inference about faults are to be drawn only from geomorphological circumstances as rectilinear depressions filled with meltwaters (Lindner, Marks and Szczęsny 1986), deep canyons of glacial rivers incised in raised marine beaches (Fig. 6) and several meters high edges and shelves on mountain slopes (Szczęsny 1988). All such circumstances are indirect and therefore, a field confirmation is necessary.

The arising problems in photointerpretation of geological structure made the author look for other methods of remote sensing to be used. Thus, from topographic basemaps of photogeological maps in scale of 1 : 10,000 according to the Ostaficzuk's method (1975), maps of concentrated contour line were prepared. On the topographic maps, especially if in small scales, connections between relief and geological structure are usually unvisible due to generalization (Fig. 7A). On maps in large scales abundance of details make wanted connections
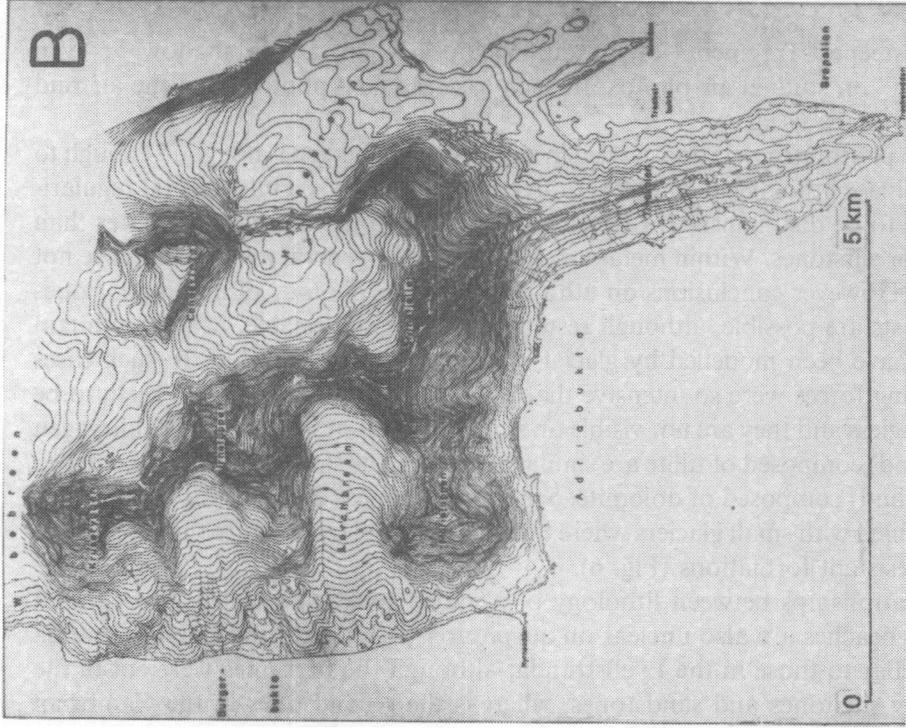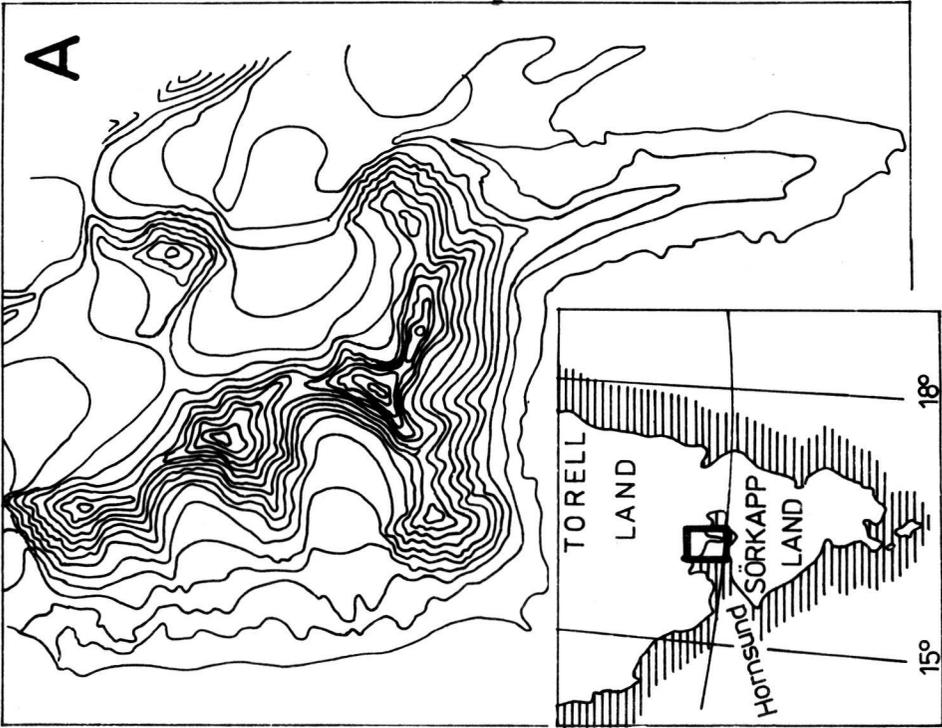
Fig. 7. Relief of the Treskelen area

A — contour lines from the geomorphological map of the Hornsund region, scale 1 : 75,000 (Karczewski et al. 1984), B — map with concentrated contour lines, scale 1 : 75,000, based on the photogeological map of the Treskelen-Hyrnefjellet-Kruseryggen area (Szczęsny, Lindner and Marks 1989)
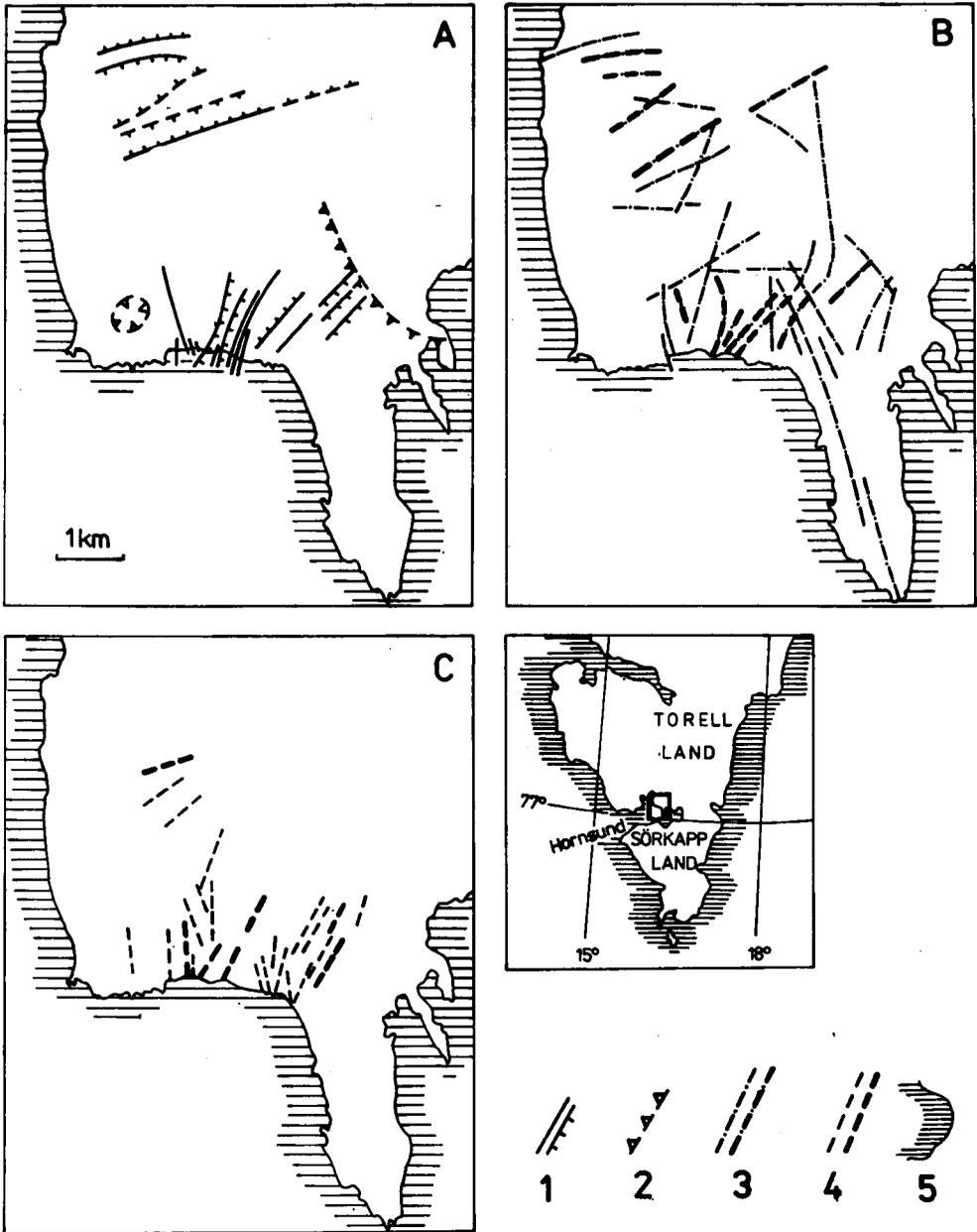
Fig. 8. Tectonic sketch of the Treskelen region based on: A — studies of Birkenmajer (1964a, 1964b, 1978a, 1978b), B — interpretation of map with concentrated contour lines (cf. Fig. 7C), C — interpretation of air photos
1 — vertical and inclined faults, 2 — overthrusts, 3 — structural features, 4 — lineaments (bold-faced lines indicate connection of structural features or lineaments with tectonic structures), 5 — shoreline

unclear. But photographical diminution of basemaps to a scale of 1 : 75,000 make it however similar to a radar image (Fig. 7B). The smallest forms independent on regularities of geological structure become unvisible. The others are visible as structural features similar to lineaments (*see* Szczęsny 1987b) and so they can be connected with tectonic dislocations. Connections betweeen structural features from maps of concentrated contour lines, lineaments interpreted directly on air photos and real tectonic features (Birkenmajer 1964a, 1964b, 1978a, 1978b) could be confronted with one another in the Treskelen area (Fig. 8). Comparison of location, direction and length of tectonic dislocations (Fig. 8A) with structural features (Fig. 8B) and lineaments (Fig. 8C) show that many dislocations are reflected in relief. It is especially visible in pattern of concentrated contour lines. Sense of structural features which are not parallel to distinguished faults or overthrusts could be interpreted in two ways: either they indicate unknown dislocations or phenomena of other origin. The method of concentrated contour lines is very useful for preliminary studies of geological structure of poorly known areas, in which strike of probable tectonic dislocations could be find.

Tectonic activity in southern Spitsbergen, especially induced by glacioisostatic rebound is not discussed in this paper as the author's studies are still continued in this subject. Preliminary interpretation of air photos indicates however that variation in intensity and amplitude of the youngest tectonic movements is greater than has been expected.

Description of Quaternary landforms and deposits in southern Spitsbergen

All Quaternary landforms and deposits recognized on air photos, and presented on photogeological maps and sketches (*see* Fig. 1) are described in this chapter. Each form is characterized by its origin and individual features described during fieldworks, supplemented with informations from bibliography and completed by analysis of air photos. Four groups of landforms and deposits were distinguished: slope landforms and deposits, glacial and nival landforms and deposits, marine landforms and deposits and landforms of other origin.

Slope landforms and deposits with structural features

This group is composed of mountain massifs with a waste cover, rock outcrops, solifluction mantles, alluvial fans, taluses and main chutes.

Waste covers. — Climatic conditions in Spitsbergen favour frost disintegration of rocks. Although medium annual temperature is relatively low (–7.6°C) and total precipitation only about 500 mm (*after* Czeppe 1966), weathering processes are very intensive due to frequent temperature variations around 0°C,

especially common from April to June and from August to October (Czeppe 1968). Chips of rocks detached by frozen water, roll down slopes and form waste covers (Fig. 9). Activity of weathering processes depends on lithology of rocks and especially on their fissuring. Although lithology and fissures are not visible on air photos, areas subjected by weathering can be shown, because waste covers are more widespread there. Detailed investigations on nunataks (Pękala 1980) indicate that medium rate of rock wall desintegration is equal 340–580 g/m^2 a year. Photointerpretation confirms field observations of Pękala (1980) that frost weathering is most intensive close to a snow line.
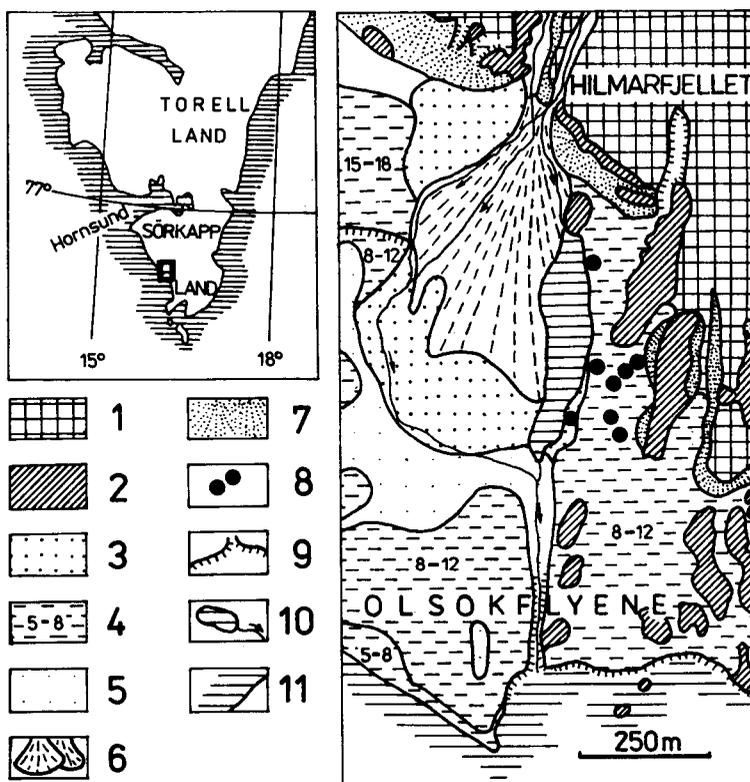
Fig. 9. Fragment of the photogeological map of the Olsokflyene area, adopted from Szczęsny, Lindner and Marks (1987) — without contour lines
1 — mountain massifs with a waste cover, 2 — rock outcrops, 3 — sandurs, 4 — raised marine beaches (altitude in m a.s.l.), 5 — valley and depression floors, 6 — aluvial fans, 7 — taluses, 8 — sinkholes, 9 — edges, 10 — lakes and streams, 11 — shoreline

Waste covers have grey to light grey phototone on air photos (Fig. 4) what depends on illumination. Connections between phototone and lithology of weathered rocks are occasionally visible *e.g.* summits of the Hilmarfjellet and Karentoppen (Fig. 3) covered with weathered Triassic shales and siltstones are
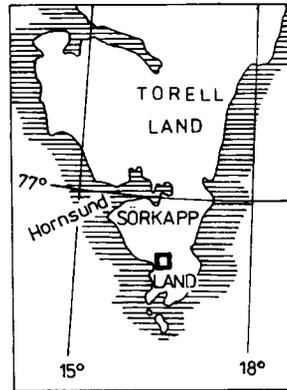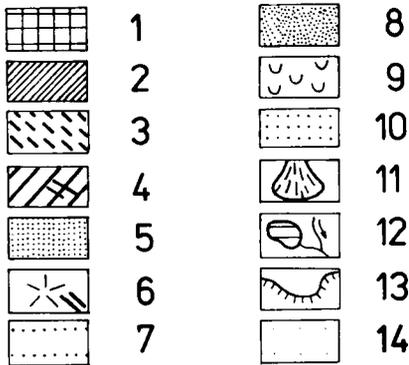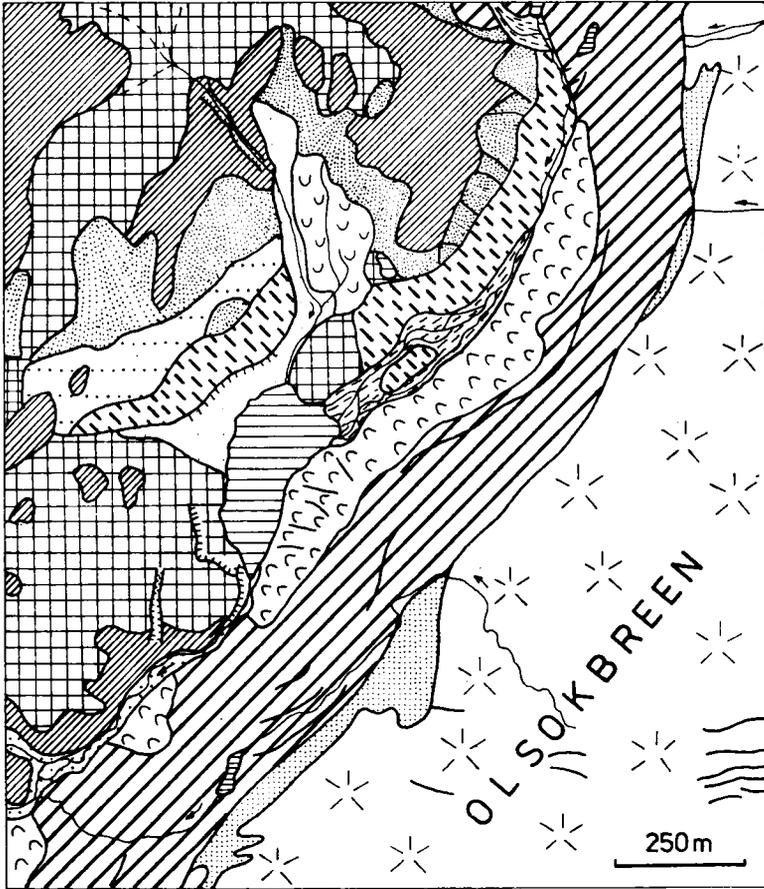
Fig. 10. Fragment of the photogeological map of the western margin of the Olsokbreen, adopted
from Szczęsny, Lindner and Marks (1987) — without contour lines
1 — mountain massifs with a waste cover, 2 — rock outcrops, 3 — ancient lateral moraines,
4 — ice-cored moraines with structural features, 5 — ablation moraines, 6 — glacier ice with
structural features, 5 — ablation moraines, 6 — glacier ice with crevasses, 7 — protalus ramparts and
nival moraines, 8 — taluses, 9 — solifluction mantle, 10 — sandurs, 11 — alluvial fans, 12 — lakes
and streams, 13 — edges, 14 — valley and depression floors

distinctly darker than slopes covered with chips of Ordovician limestones. Texture of waste cover surfaces is usually granular, sometimes smooth (Fig. 4) and depends on debris size.

Waste can be transported downslope by gravity and other factors, creating different landforms.

Solifluction covers. — In Spitsbergen a water-saturated waste creeps on inclined surfaces which are impenetrable due to periglacial presence of permafrost and coherent rocks. Melting of snow consumes all delivered thermal energy (Czeppe 1968) and therefore meltwater cannot sink into a still frozen substrate. Saturated loose material moves downslope. Solifluction is most intensive at the turn of spring and summer *i.e.* in June (Czeppe 1968), during rapid melting of snow. Uppermost layers of permafrost start thawing after disapperance of snow and maintain solifluction during the whole summer, although intensity of this process gradually decreases.

Solifluction occurs mainly on slopes of ice-cored moraines (Figs 10, 14 and 17), ice core of which forms an impervious horizon. On air photos solifluction covers have the same phototone as surfaces of ice-cored moraines because they are composed of the same material. Only a more rough surface and striped texture of solifluction zones discriminate these areas (Fig. 4). Fabric of ice-cored moraines often visible on their surface, is usually hidden under solifluction covers.

Small solifluction tonques are also observed on high and steep edges of raised marine beaches (Szczęsny *et al.* 1989). Results of photointerpretation confirm Czeppe's opinion (1966) that slopes of ice-cored moraines are the only place where solifluction processes are active at present. Solifluction tongues and covers exist also on slopes of mountain massifs but they were active during climatic warming at the beginning of the Holocene (Czeppe 1966). These tonques are dead now, and that is why their phototones and textures on air photos are similar to the ones of taluses, some alluvial fans and small rock glaciers. Solifluction covers happen therefore to be interpreted on air photos as waste covers.

The other solifluction phenomena *i.e.* stone ridges (*see* Jahn 1961), due to their small sizes cannot be distinguished on analyzed air photos in a scale of 1 : 50,000.

Taluses. — Taluses are very frequent in Spitsbergen. They are formed in front of deep chutes and rock chimneys, along which debris is transported downslope, mainly by snow avalanches. Most taluses are located around glacier snouts at altitudes of 100–300 m a.s.l. (Fig. 11). Fieldworks indicate that frost weathering and avalanches are the most active in this zone.

Shape of taluses on air photos is simple or multiple due to ovarlapping, especially in their lowest parts (Figs 6 and 10). Their dimensions vary considerably: maximum length of 500 m and width of 150 m were observed (Fig. 10). Inclination of talus surfaces varies form 25° to 45°. Longitudinal profiles are straight, concave, convex or complex what depends on substrate configuration
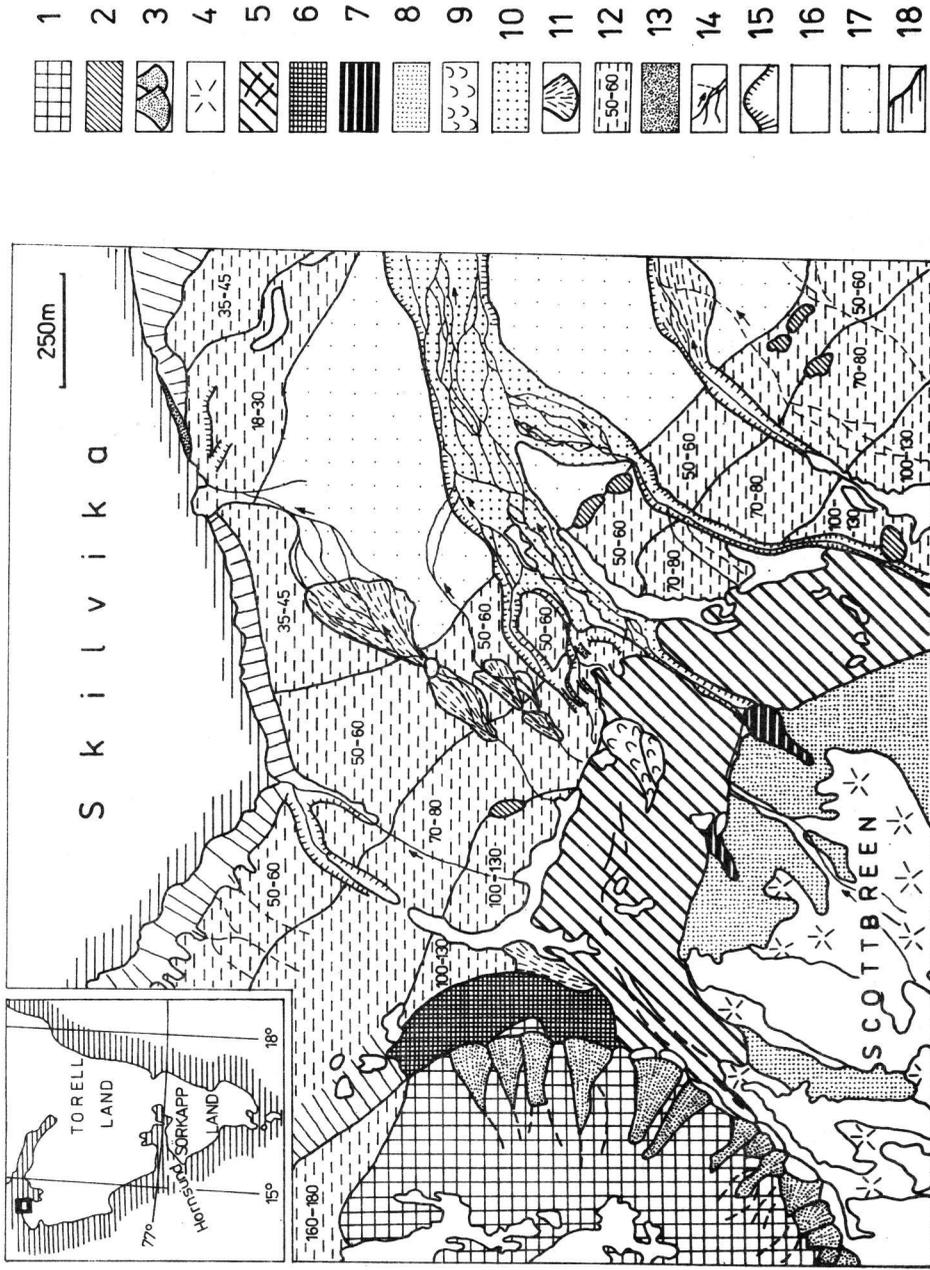
Fig. 11. Deception Island: A — in 1929 (*after* Kendall, *in* Barrow (1831); B — in 1957–8 (*after* Hawkes 1961); C — in 1968 (Brit. Antarct. Territory, topographic map, 1:200,000, Sheet W 62 60); D — in 1988
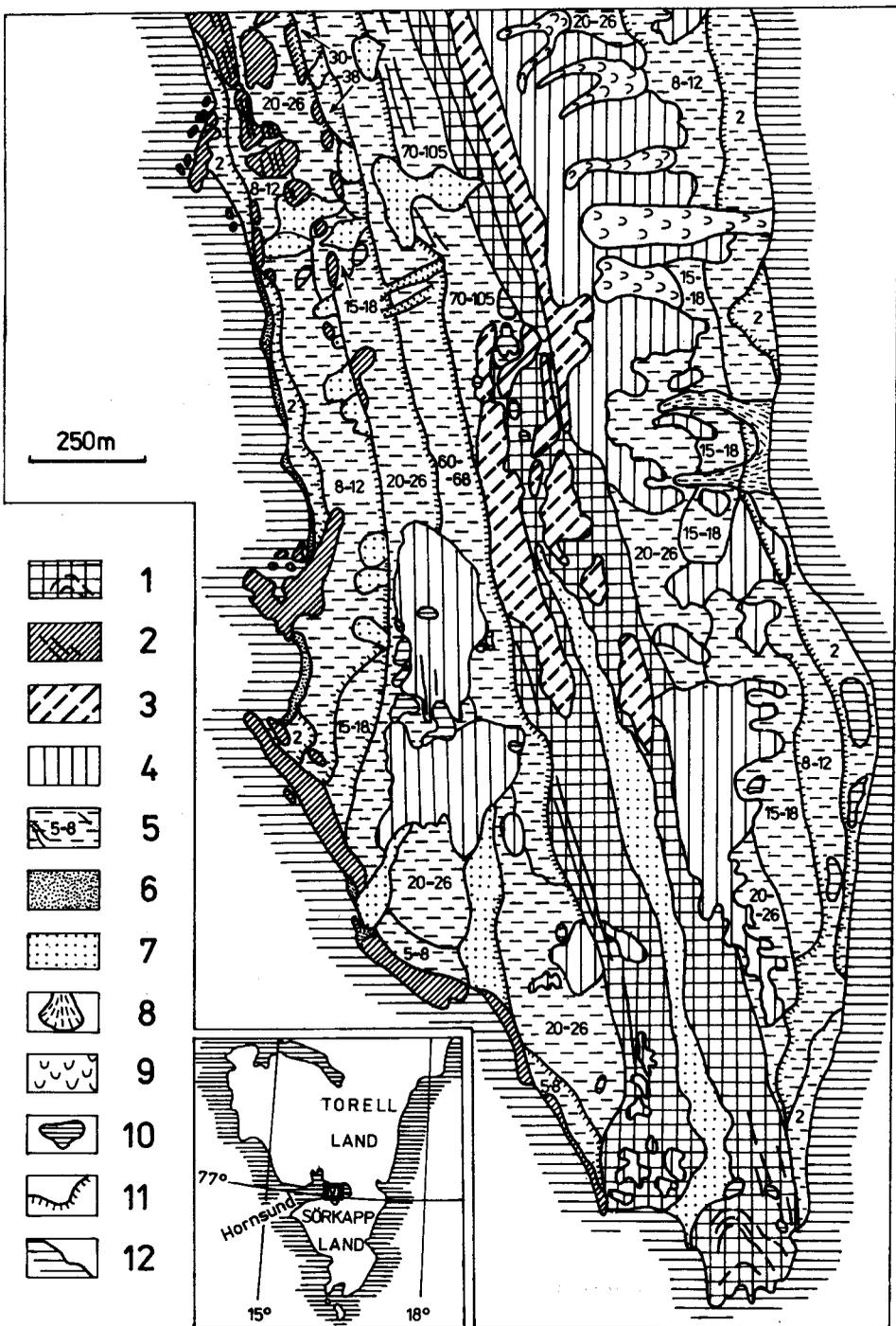
Fig. 12. Fragment of the photogeological map of the southern part of Treskelen Peninsula, adopted from Szczęsny, Lindner and Marks (1989) — without contour lines

1 — mountain massifs with a waste cover and structural features, 2 — rock outcrops with structural features, 3 — ancient lateral moraines, 4 — ground moraines, 5 — raised marine beaches with ancient storm ridges (altitude in m a.s.l.), 6 — present beach, 7 — sandurs, 8 — alluvial fans, 9 — solifluction mantle, 10 — lakes, 11 — edges, 12 — shoreline

downslope *e.g.* uncroaching of taluses upon a glacier or their undercutting by waters. Complex profiles of taluses seem to be typical for the Arctic zone (Klimaszewski 1981). Detailed morphogenetic classification of taluses was presented by Nitychoruk and Dzierżek (1988).

Phototones of active taluses are usually light (Fig. 4) because their surfaces are vegetation-free. Phototones darker than the normal ones indicate over-growing by mosses *i.e.* inactivity of such taluses. Texture of taluses on air photos is granular, especially in their lowest parts (Fig. 4) generated by fractional differentiation of rock debris downslope. Coarse debris (blocks up to 2 m in diameter) is concentrated in lowermost parts of cones. Narrow furrows are occasionally incised in taluses by mud and debris flows.

Present shapes of taluses in Spitsbergen were formed during the Little Ice Age (Nitychoruk and Dzierżek 1988). Most intensive recent activity of these forms is observed in May and June (Pękala 1980).

Alluvial fans. — Alluvial fans are formed due to rapid deposition of clastic material transported by meltwaters. In studied areas of southern Spitsbergen alluvial fans occur mainly on raised marine beaches, at foot of terrace edges or mountain slopes (Figs 5, 9 and 11). The fans are composed of washed debris from waste covers or from pebbles of marine terraces. Clastic material transported by meltwaters along chutes and other erosive cuts is deposited at their outlet. Alluvial fans develop therefore mainly during snow melting at the beginning of summer (Dutkiewicz 1967).

On air photos alluvial fans have characteristic shapes, light phototones and striped textures due to existence of the numerous erosive channels (Fig. 4). They are usually concave in longitudinal profile. Lowest parts are distinctly less inclined (5°) than the upper ones (30°). On air photos alluvial fans can be interpreted by mistake as taluses if different location and texture are not taken into account (Fig. 4).

Glacial and nival landforms

This group of landforms is composed of ancient lateral moraines, ground moraines (partly fluted), ablation moraines, nival moraines, kames, eskers, compact glacier ice with crevasses, terminal and lateral ice-cored moraines, rock glaciers, sandurs, icings and snow patches.

Ancient terminal and lateral moraines. — Landforms and aggregations of deposits interpreted as ancient terminal and lateral moraines occur far from the present glaciers on mountain slopes, in valleys and on raised marine beaches. They form chains of separated ramparts (Figs 6, 10, 12 and 15), the longest of which (1 km long) was distinguished on the Treskelen Peninsula (Pl. 2). Ramparts that do not form chains are interpreted as remains of older glacial episodes.

On photogeological maps ancient moraines occur on southern slopes of Hilmarfjellet and Karentoppen (Fig. 10) and on the Treskelen Peninsula (Figs 12 and 19; Pl. 2). In the Hilmarfjellet-Karentoppen region the ancient moraines were distinguished at altitudes of 80, 120–150 and 230–240 m a.s.l. Moraines at highest altitudes indicate extents of Vitkovskibreen and Olsokbreen during the Wedel Jarlsberg Land Glaciation and the lowermost moraine was formed during the Sörkapp Land Glaciation (Lindner, Marks and Pękala 1987). Ancient moraines at altitudes 40 and 80 m a.s.l. on the Treskelen Peninsula are the traces of the Hyrnebreen standstills after the Little Ice Age. Ancient moraines are also presented on photogeological sketches of Tjörndalen (Fig. 6) and Wiederdalen (Fig. 13), where they were formed during glacial stages of the Sörkapp Land Glaciation (Szczęsny 1987). On air photos ancient moraines are distinctly convex (Fig. 4). They are several metres (Szczęsny, Lindner and Marks 1989), even to 50 m high as indicated by field measurements (Szupryczyński 1968b). Surfaces of moraine ridges are uneven and resemble sometimes the overlapping bulges. Irregularities are however considerably smaller than on ice-cored moraines.

Phototones of ancient moraines are usually dark whereas texture on air photos is granular and sometimes spotted (Fig. 4). Moraine ridges are composed of coarse and angular material. Ridge surfaces are often covered with large blocks.

Discernment of ancient lateral and terminal moraines is sometimes difficult. They are similar to nival moraines and subslope rock glaciers which are the features of different origin, although located in the same places (Fig. 4). Classification criteria for these landforms have not been explicit for a long time (cf. Czeppe 1966, Szupryczyński 1968b, Baranowski 1977) until the latest studies (Lindner and Marks 1985; Dzierżek and Nitychoruk 1987).

Possibile overlapping of different processes, should be taken into consideration e.g. the ancient lateral moraine in the Tjörndalen is partly covered with taluses (Fig. 6). Thus, in case of ancient moraines the analysis of air photos is mainly useful for location of these landforms. Genetic interpretations must be very careful and arising doubts can be dispelled by comparison of photointerpretation results with field observations.

Ground moraines. — Ground moraines in Spitsbergen cover only small areas in vicinity of glaciers. On studied air photos they were distinguished in forefields of Vitkovskibreen (Fig. 14), Lorchbreen and Hyrnebreen (Figs 12, 18 and 19; Pl. 2), Renardbreen (Fig. 15) and Wiederbreen (Fig. 13). They form isolated patches on raised marine beaches (Fig. 12), valley floors (Fig. 13) and sandurs (Fig. 15).

According to the Price's (1973) model a ground moraine, is composed of two layers, the upper of supraglacial and the lower of subglacial origin. Clayey-sandy material with gravel and boulders makes surfaces of ground moraines flat on air photos, with smooth or spotted textures and dark phototones (Fig. 4).

Fluted moraines form a specific type of ground moraines. They have distinct striped texture on air photos (Fig. 4), generated by the numerous parallel furrows
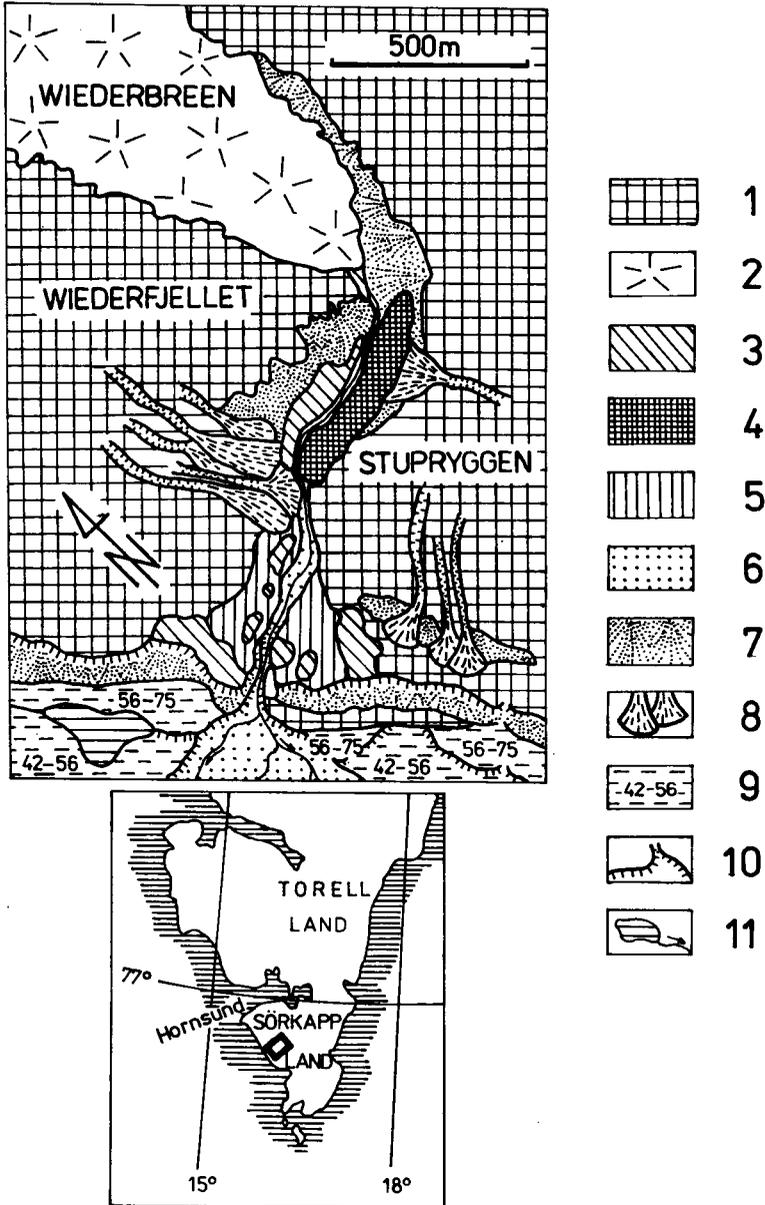
Fig. 13. Photogeological sketch of the Wiederdalen region, after Szczęsny (1986)
1 — mountain massifs with a waste cover, 2 — glacier ice, 3 — ancient terminal and lateral moraines,
4 — rock glaciers, 5 — ground moraine, 6 — sandurs, 7 — taluses, 8 — alluvial fans, 9 — raised
marine beaches (altitude in m a.s.l.), 10 — edges, 11 — lakes and streams
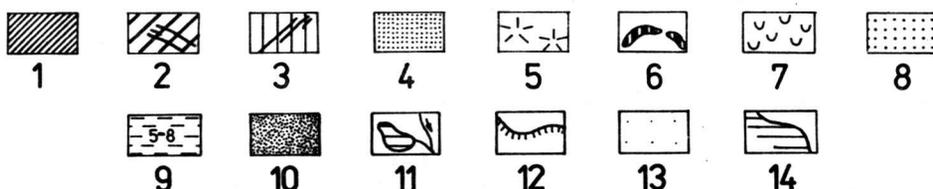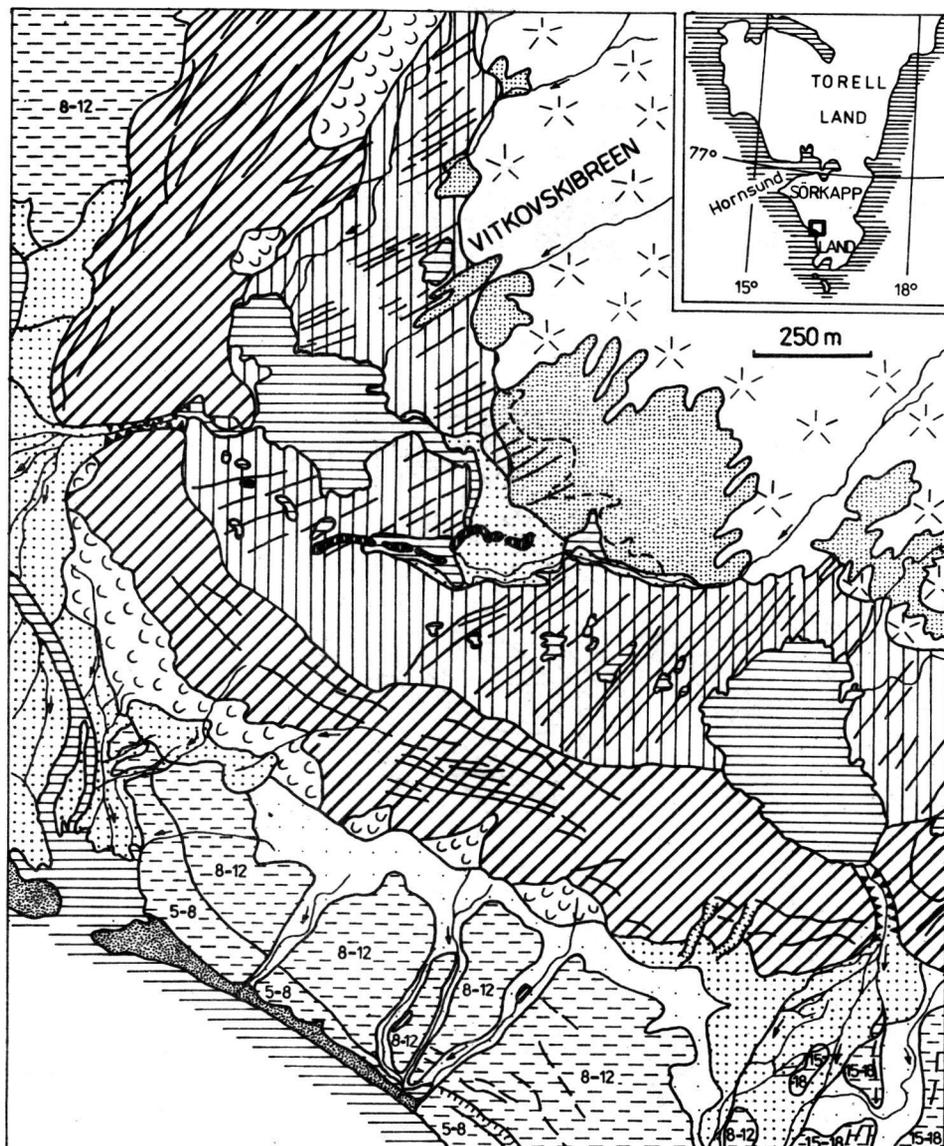
Fig. 14. Fragment of the photogeological map of the Vitkovskibreen forefield, adopted from
Szczęsny, Lindner and Marks (1987) — without contour lines
1 — rock outcrops, 2 — ice-cored moraines with structural features, 3 — ground moraines partly
fluted, 4 — ablation moraines, 5 — glacier ice, 6 — gravel-sandy ridges, 7 — solifluction mantle,
8 — sandurs, 9 — raised marine beaches (altitude in m a.s.l.), 10 — present beach, 11 — lakes and
streams, 12 — edges, 13 — valley and depression floors, 14 — shoreline
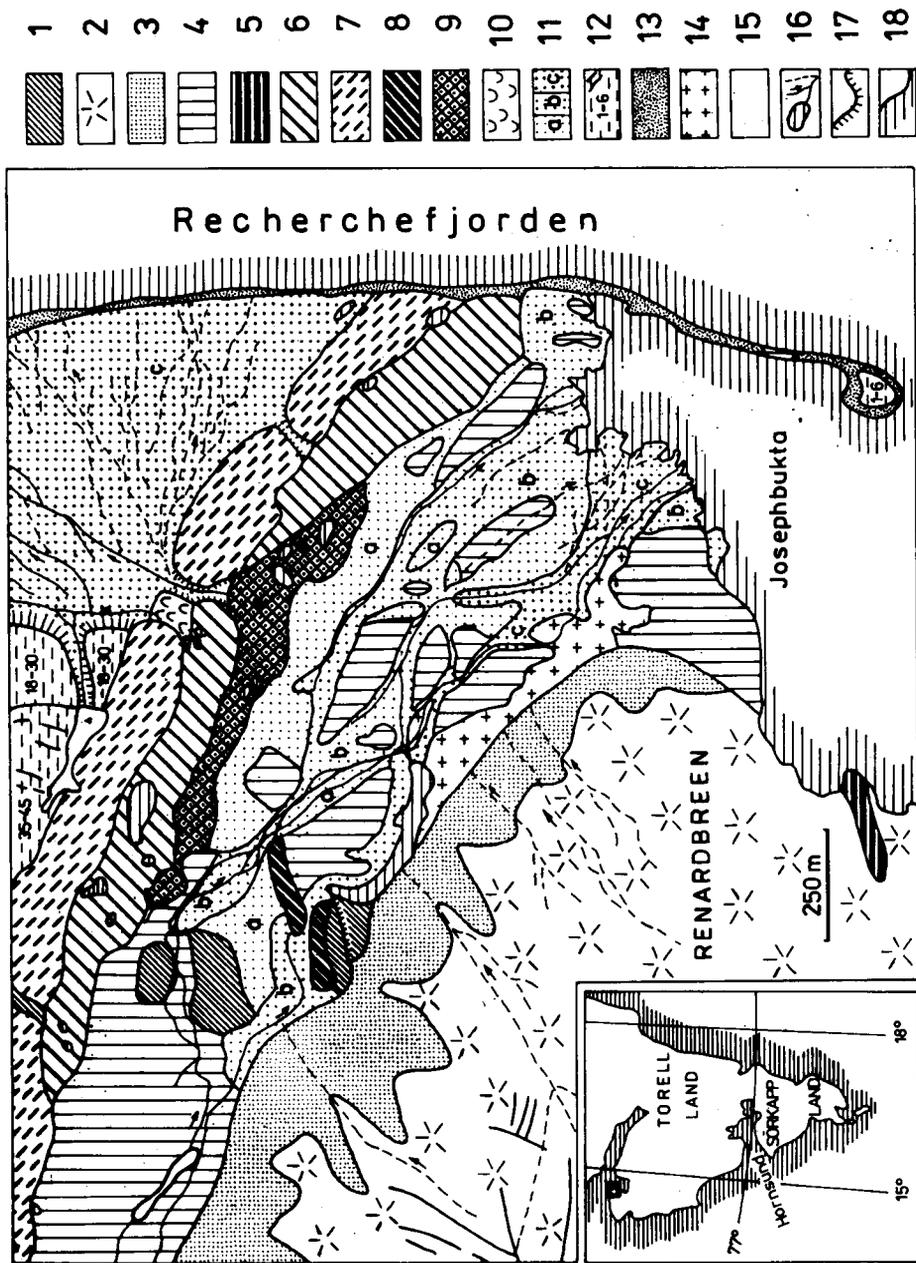
Fig. 15. Fragment of the photogeological map of the Renardbreen forefield, adopted from Szczęsny *et al.* (1989) — without contour lines
1 — rock outcrops, 2 — glacier ice, 3 — ablation moraines, 4 — ground moraine, 5 — median moraines, 6 — ice-cored moraines, 7 — ancient lateral moraines, 8 — eskers, 9 — kame teraces, 10 — solifluction mantle, 11 — sandurs: a — older, b — younger, c — youngest, 12 — raised marine beaches with ancient storm ridges (altitude in m a.s.l.), 13 — present beach, 14 — icings, 15 — snow patches, 16 — lakes and streams, 17 — edges, 18 — shoreline

and ridges, conformable to direction of glacier movement. Other photointerpretation criteria are the same as for typical ground moraines (Fig. 4). Fluted moraines were observed on air photos from forefields of Vitkovskibreen (Fig. 14) and Renardbreen (Fig. 15).

According to the hitherto conceptions (described in detail by Merta 1989) the characteristic relief of fluted moraines resulted from squeezing of basal morainic material into crevasses at glacier foot. Thus fluted moraine was considered for an imprint of a glacier base. Observations of Merta (1989), among others in Renardbreen forefield, univocally indicate that crests on morainic surface are parallel to linear ablation depressions on termini of glacier snouts and are partly filled with supraglacial material. In this case relief of fluted moraines forms rather a negative of a source glacier surface.

Analysis of air photos confirms the model of Merta (1989) as connection of strips of ablation moraine and of directions of crests on the moraine surface seems clear (Fig. 14). Intensive deglaciation makes areas covered with fluted moraines gradually vaster (Fig. 2, *see also* Merta 1989).

Ground moraine surfaces are sometimes very diversified, with pyramides and pinnacles (Szupryczyński 1968b) but such ground moraines were not found on any studied air photo.

Due to their occurrence within intramarginal zones of glaciers, the studied ground moraines are to be connected with deglaciation after the Little Ice Age (Fig. 20).

Ice-cored moraines. — Characteristic but unvisible on air photos feature of ice-cored moraines is a compostion of their interior. It is composed predominantly of ice, covered with a thin mantle of morainic material that has melted out from glacier ice. In southern Spitsbergen such structure is typical for all recent terminal and lateral moraines, as well as for rock glaciers formed during the Little Ice Age.

On air photos ice-cored moraines have prolated or arc shapes (Fig. 11). Occasionally they are the predominant relief elements on coastal plains (Fig. 14) and within deglaciated valleys (Fig. 6). The highest ice-cored moraines in studied areas are 40–50 m high, however forms up to 100 m are known (Szupryczyński 1968b). Ice-cored moraines can be simple (Fig. 11) or complex, as on a glacieret on slope of Gråkallen where moraine looks like several overlapping bulges (*see* Ostaficzuk, Lindner and Marks 1986). Melting of ice cores creates small depressions on moraine surfaces that are often filled with meltwaters. In course of time depressions become larger, making relief more and more diversified while a moraine surface gets lower. Melting of ice favours covering material to be saturated with water and solifluction covers on rampart slopes are formed (Fig. 10). Final melting of ice core results in disappearance of ridges and thin hummocky moraine remains only (Szupryczyński 1968b).

Phototones of ice-cored moraines are usually dark and texture on air photos is granular, spotted or striped (Fig. 4). Mineral material that covers these forms, is of

Fig. 16. Fragment of the photogeological map of the Björnbeinflyene region, adopted from Szczęsny,
Lindner and Marks (1987) — without contour lines
1 — mountain masifs with a waste cover, 2— rock outcrops, 3 — ice-cored moraines with structural
features, 4 — ground moraines, partly fluted, 5 — sandurs, 6 — raised marine beaches with ancient
storm ridges (altitude in m a.s.l.), 7 — valley and depression floors, 8 — alluvial fans, 9 — taluses,
10 — edges, 11 — lakes and streams, 12 — present beach, 13 — shoreline

different grain sizes and large boulders often occur within a loamy matrix. Presence of boulders generates a granular texture on air photos whereas a spotted structure is caused by neighbouring fine- and coarse-grained deposits. On surfaces of ice-cored moraines structural features are to be distinguished during photointerpretation. They make a striped image (Figs 14 and 16) as consist of shallow furrows which seem to reflect crevasses or sliding surfaces within an ice core.

Shape, phototone and texture of ice-cored moraines on air photos are similar to the ones of rock glaciers but their location is usually quite different (Fig. 4). Photointerpretation does not allow to distinguish push moraines among ice-cored ones as it is impossible to see their inner structure on air photos. The former are composed of mixed marine, glaciofluvial and glacial deposits, pushed by advancing glacier. Push moraines in Torellbreen area (Szczęsny et al. 1985) were distinguished on the basis of field observations by Pękala. In his opinion the ice-cored moraine of Renardbreen (Fig. 15) is also a push moraine (Pękala 1987).

Nival moraines. — Intensive frost weathering in Spitsbergen favours development of waste, mainly on the mountain slopes. Then the waste is dislocated down due to gravity and waste covers are formed. Transport by snow, mainly by snow avalanches, leads to formation of taluses on slopes and of nival moraines at their foot (Lindner and Marks 1985), named also the subslope ramparts (Karczewski, Kostrzewski and Marks 1981).

On air photos nival moraines are easy to distinguish. They form ramparts, even a few kilometres long, several metres wide and 20–30 m high, located at foot of mountain slopes: in the valleys (Fig. 6) and on raised marine beaches (Fig. 11). Narrow depressions, often filled with snow, separate ramparts from rocky mountain walls. Such depressions allow to distinguish nival moraines and ancient lateral moraines. Surfaces of nival moraines are uneven and often mantled with the lowermost parts of taluses (Fig. 6) being composed mainly of coarse debris. Nival moraines indicate grey phototones and granular textures on air photos (Fig. 4).

Nival moraines are the first stage (Lindner and Marks 1985; Dzierżek and Nitychoruk 1987) in development of subslope rock glaciers.

Rock glaciers. — Conception of rock glaciers is new in the Spitsbergen bibliography. Such forms were defined as ancient lateral moraines (Jahn 1959), nival moraines (Czeppe 1966), slope moraines (Baranowski 1977), subslope ramparts (Karczewski, Kostrzewski and Marks 1981) or ice-cored moraines (Szczęsny 1986). Rock glaciers have been defined lately (Lindner and Marks 1985, Dzierżek and Nitychoruk 1987) as large waste agglomerations with ice core. Frozen interior could be formed from compact or intergranular ice which joins rock splinters. Melting of ice makes rock debris as well as a whole rampart move slowly.

On air photos rock glaciers have dark phototones and distinctly granular, sometimes spotted texture (Fig. 4). Depending on location 3 types of rock

glaciers were distinguished *i.e.* morainic, cirque and subslope ones (Dzierżek and Nitychoruk 1987). Relief of morainic rock glaciers and their composition are similar to the ones of ice-cored moraines. They are convex landforms with rough surfaces, usually located near glacier snouts. They are several metres high and several hundred metres long. Cirque rock glaciers exist in small depressions or flattenings on mountain slopes, high above valley floors. They are small, with ice cores hidden under thick covers of rock debris. Overlapping bulges often occur on their terminal parts. These two types of rock glaciers are easy to distinguish on air photos due to their characteristic features. They were noted on slopes of Tjörndalsegga (Fig. 6) and Wijkanderberget (Szczęsny *et al.* 1989).

Subslope rock glaciers develop from nival moraines. Freezing and melting of snow, delivered by avalanches together with rock debris, generate intergranular ice. Loading by rock debris makes ice plastic and fragments or even the whole landforms start to move away from mountain slopes. Such rock glaciers can be hardly distinguished on air photos as evidences of their movement are badly needed. The latter are to be found only during fieldworks or by comparing air photos from different times. If no field observations are done, these features should be rather described as ice-cored moraines partly transformed into rock glaciers, as on the photogeological map of the Treskelen area (Szczęsny, Lindner and Marks 1989).

Rock glaciers are the evidence of slow deglaciation and intensive developement of frost weathering and slope processes (*see* Dzierżek and Nitychoruk 1987).

Median moraines. — Median moraines are visible on air photos as long and narrow features on glacier ice. They extend from several tens (Fig. 11) to several thousand metres (Ostaficzuk, Lindner and Marks 1982), starting from ice margins upglacier. Median moraines divide glaciers into individual lobes.

Median moraines are formed when a glacier is constantly supplied with rock debris. There are 3 types of median moraines according to Szupryczyński (1968b). The first one is formed by confluence of lateral moraines of two connecting glaciers. Moraines of the second type start downglacier nunataks, and of the third type are formed of subglacial material at glacier snouts. Median moraines occur only on some glaciers in the studied areas. They belong mainly to the first and third type, of the above mentioned classification. Median moraines on the Torellbreen (Fig. 17) and on the Hyrnebreen (Szczęsny, Lindner and Marks 1989) were formed by junction of lateral moraines. Longitudinal structural features independent on crevasses were distinguished on several moraines (*e.g.* Tanngardmorena of Torellbreen). They act therefore as morainic suture, formed along junction of lateral moraines. The second type of median moraines cannot be univocally interpreted as it starts sometimes downglacier a nunatak and at the same at junction of lateral moraines. For example Torellmorena starts in shadow of Raudfjellet but also at contact of two lobes of
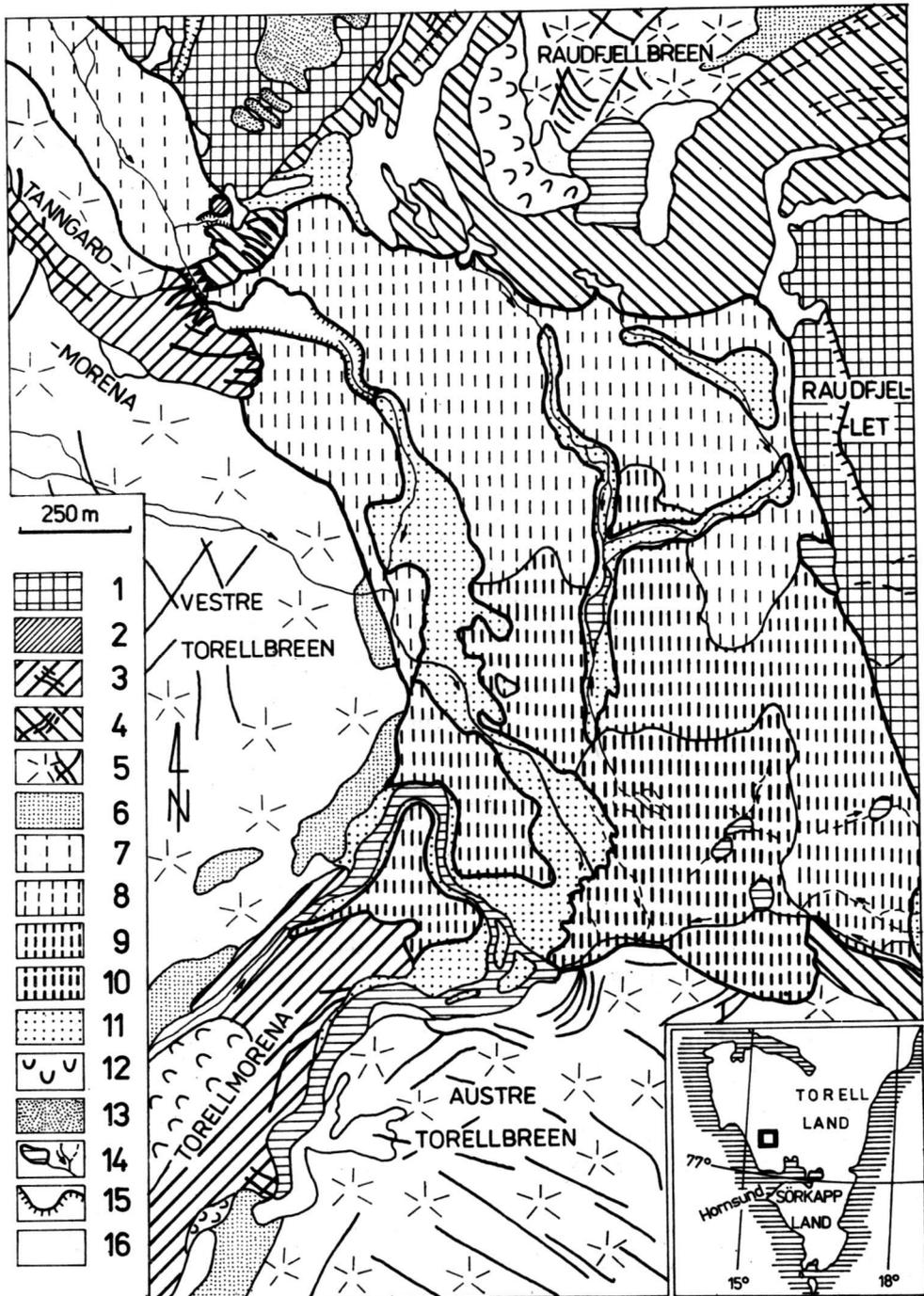
Fig. 17. Fragment of the photogeological map of the interlobal zone of Torellbreen, adopted from
Szczęsny *et al*. (1985) — without contour lines

1 — mountain massifs with a waste cover, 2 — rock outcrops, 3 — median moraines with structural
features, 4 — lateral and terminal ice-cored moraines with structural features, 5 — glacier ice with
crevasses, 6 — ablation moraines, 7 — oldest lake deposits, 8 — older lake deposits, 9 — younger lake
deposits, 10 — youngest lake deposits, 11 — sandurs, 12 — solifluction mantle, 13 — taluses,
14 — lakes and streams, 15 — edges, 16 — snow patches

the Torellbreen *i.e.* Westre Torellbreen and Austre Torellbreen (Szczęsny *et al.* 1985).

Median moraines of the third type were distinguished only on the Scottbreen and Renardbreen (Figs 11 and 15). They exist on terminal parts of glacier snouts. On the air photos of 1960 they were only several tens of metres long what means that these landforms are very young.

On air photos median moraines have dark or very dark phototones contrasting with light surface of ice (Fig. 4). Texture is usually granular in lower parts of moraines and smooth in their upper parts. Larger forms have texture similar to the one of ice-cored moraines *i.e.* spotted and striped, especially if solifluction processes are active. Different texture on air photos is connected with lithological variation. Gravel-sandy deposits prevail in morainic covers but in some parts they are enriched in clay. Sometimes thin moraines have striped structure due to fissures in underlying ice (Fig. 4). Median moraines are the largest near glacier fronts because ablation processes are the most active there. The largest forms were up to 30 m high and 400 m wide (Fig. 17). No median moraines were noted along longitudinal axes of glaciers what suggests widely varying quantity of ice that flows within individual lobes.

Ablation moraines. — In studied areas of southern Spitsbergen ablation moraines were distinguished on surfaces of all glaciers (Figs 10, 11, 14, 15 and 18). Their presence is connected with emerging of englacial debris due to melting of ice. According to Jahn (1954, *after* Szupryczyński 1968b) rock debris melts out or is transported upwards along sliding surfaces.

Analysis of air photos indicates that melt-out debris is concentrated mainly on glacier terminus in irregular patches with characteristic strips upglacier (Fig. 14). Ablation moraines have dark-grey phototones and smooth texture (Fig. 4). Crevasses in glacier ice are usually visible through a thin morainic cover, composed mainly of clay, sand and gravel. Boundaries of ablation moraines are not sharp and on the photogeological maps they have therefore approximate positions.

Ablation moraines are also composed of material delivered along sliding planes. Such process is usually predominant up-glacier and resulting features are less extended than the previously described ones. On air photos they form dark and narrow stripes on glacier ice. On photogeological maps individual stripes are ignored, whereas their concentrations have been generalized.

Sizes of ablation moraines depend on quantity of rock debris dispersed in ice, so at the same time on activity of weathering processes in surrounding mountain massifs. Probable connections exist between development of ablation moraines and microclimate, as well as bedrock lithology and tectonics what needs however studies in the field.

Glaciers. — Glaciers are the most widespread landscape element in southern Spitsbergen. Compact glacier ice which is penetrated only through tops of highest mountain massifs, covers central part of the studied area up to 500

m a.s.l. Only western coast of southern Spitsbergen, coasts of fiords and some valleys (e.g. Lisbetdalen) are ice-free. Three types of valley glaciers were distinguished. Glaciers of the first type flow out the valleys, cross coastal plains and reach the sea (Fig. 15). Glaciers of the second type flow out the valleys and form ice-cored moraines on coastal plains (Figs 11 and 14). The third type includes the glaciers, snouts of which occur in uppermost parts of the valleys only (Figs 6 and 13). Detailed classification of glaciers and analysis of glacial processes in southern Spitsbergen were presented by Jania (1988).

On air photos of southern Spitsbergen glaciers have various shapes, from wide covers to prolated tonques, and varying relief. Some fragments are completely flat but on the others there are also domes and depressions. Phototones of Spitsbergen glaciers are very light. Texture is smooth, striped or reticulate (Fig. 4; Pl. 1) what depends on presence and a type of crevasses and changes even within very small distances. Occurrence of crevasses is connected mainly with relief of bedrock, so they concentrate over elevations or thresholds. Calving glacier snouts are intensively fissurred (Fig. 20).

Drainage pattern forms together with crevasses a texture of glacier ice. During summer glacier surfaces are subjected to intensive ablation and meltwaters form commonly very complex outflow systems. They are parallel, dendritic or concentric and depend on glacier relief. Meltwater streams often deliver water to depressions where ephemeral lakes are formed (Szczęsny, Lindner and Marks 1987). Development of drainage pattern evidently depends on occurrence of crevasses. Supraglacial streams exist only in those parts of glaciers which are free of crevasses. In intensively fissured parts of glaciers, streams disappear in fissures like on the Austre Torellbreen (see Szczęsny et al. 1985). Besides crevasses and meltwater channels, glacier ice is combined usually with ablation, median, terminal and lateral moraines. Ice surface is covered locally by taluses and snow patches. All these features are described separately in this paper.

Kames and kame terraces. — Kames form usually small regular, round hummocks in glacier forefields. Kames are formed during deposition of fine debris in depressions between dead ice blocks and for this reason they are interpreted as indicators of aerial deglaciation (Szupryczyński 1968b). Kames can be supra-, en- or subglacial in origin (Jewtuchowicz 1962) but such discrimination seems impossible on air photos. Kames are composed of stratified gravel and sand with varying bed thickness. Sandy beds are generally thicker than gravel ones.

On air photos kames were distinguished in forefield of a small glacier on western slope of Urnetoppen (Fig. 18). Kames on air photos are convex and have dark phototones and granular texture (Fig. 4).

Kame terraces were distinguished in forefield of Renardbreen, on the inner side of lateral moraine (Fig. 15). Among the photointerpretation criteria, location and prolated shape from the significant differences between kame terraces and kames (Fig. 4). Analysis of air photos enabled to locate these
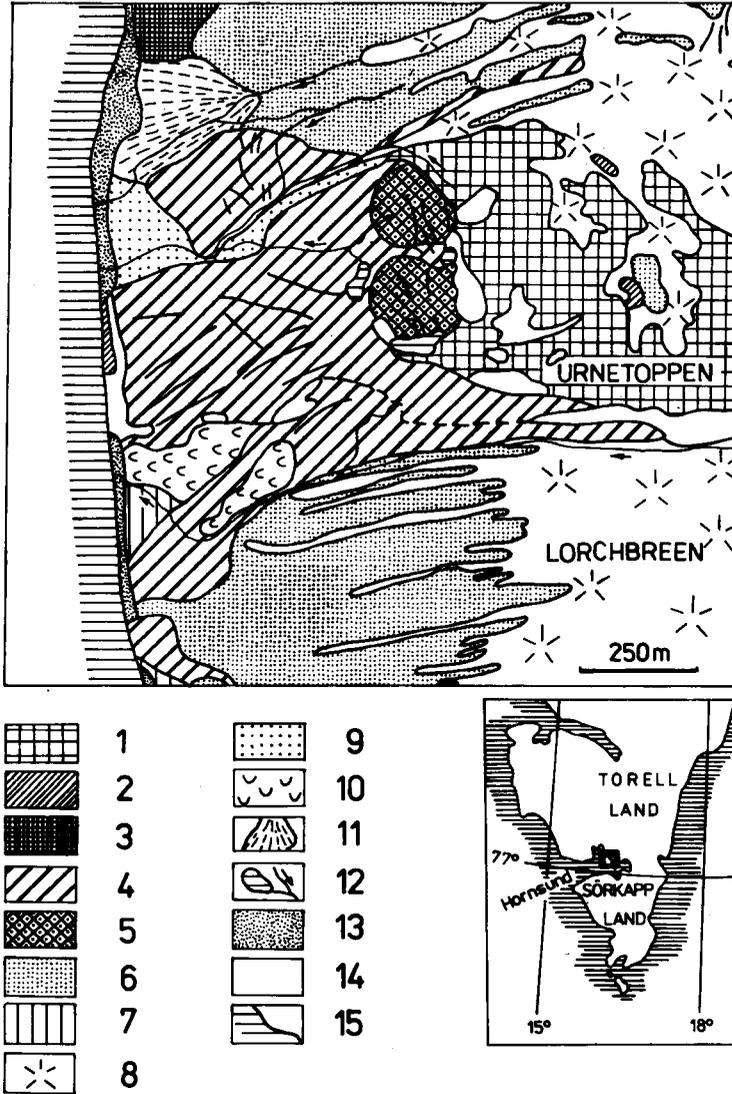
Fig. 18. Fragment of the photegeological map of the Urnetoppen region, adopted from Szczęsny, Lindner and Marks (1989) — without contour lines

1 — mountain massifs with a waste cover, 2 — rock outcrops, 3 — rock glaciers, 4 — terminal and lateral ice-cored moraines, 5 — kames, 6 — ablation moraines, 7 — ground moraine, 8 — glacier ice, 9 — sandurs, 10 — solifluction mantle, 11 — alluvial fans, 12 — lakes and streams, 13 — beach, 14 — snow patches, 15 — shoreline

landforms but their identification could be done during fieldworks. Kame terraces are formed by meltwaters between glacier margin and moraine rampart or mountain slope. However, Cegła and Kozarski (1977) indicate a role of icings in development of such forms.

Eskers. — On Spitsbergen eskers are rather small in comparison with similar forms from other areas of the Arctic (*see* Jewtuchowicz 1962 and Szupryczyński 1963) and their shapes are not as diversified as it could be possible. Eskers are composed of sands and sometimes of coarse gravels. Deposits are diagonally stratified due to deposition in narrow channels.

Eskers were distinguished on air photos only in forefield of Renardbreen (Fig. 15). They form straight ridges, about 200 m long and 2–3 m high. Distinguished eskers are located in glacier axis and perpendicularly to a contemporary ice margin. Eskers in the Renardbreen forefield are located on ground moraine and they are therefore of en- or supraglacial origin. On air photos phototones of eskers are grey and similar to phototones of ground moraine but their texture is smooth (Fig. 4).

Smaller and winding esker-like ridges were found in forefield of Vitkovskibreen (Fig. 14) but they have been presumably formed with participation of icings (*cf.* Cegła and Kozarski 1977).

Sandurs. — In southern Spitsbergen sandurs occupy either small areas between glacier snouts and terminal moraines (Fig. 14) or occur outside terminal moraines. The latter are very limited because glacier fronts are generally close to a sea. On studied photos of southern Spitsbergen, ancient sandurs without any connection with contemporaty glaciers were also distinguished (Szczęsny, Lindner and Marks 1989). They are the evidence of older glacial episodes when glaciers were more extensive than at present.

Sandurs form flat or slightly convex areas in glacier forefields and are composed of numerous overlapping fans (Fig. 15). The latter consist of sands and gravels deposited by glacial rivers. According to Jewtuchowicz (1962) accumulation of sandurs is connected mainly with rapid melting of glaciers what happens even several times a year. Sandurs are then flooded with water and their surfaces are smoothed by deposition of sand and gravel transported from terminal moraines, waste covers, taluses, etc. During moderate melting of ice, superficial runoff changes into linear one and erosion predominates.

Phototones of sandurs are usually light but older fans are distinctly darker due to progressive overgrowing by vegetation. Texture of sandurs is usually striped (Fig. 4). Fan-shaped outflow systems generate striped texture on air photos and traces of ancient channels are preserved occasionally (Fig. 17).

Dead ice blocks are often buried within sandur deposits. After melting of ice numerous depressions are formed in sandur surface (Price 1973). But this kind of "pitted" sandur has not been found on air photos of studied areas. Photointerpretation indicates that participation of icings in active sandurs is doubtless.

Icings influence outflow systems as well as erosion and accumulation within stream channels.

Snow patches. — Presence of snow patches in summer (when air photos are usually taken) depends on local climatic conditions and relation to a snow line. Air photos made too early or too late in summer when non-melted or fresh snow occurs are useless. On interpreted air photos snow cover was different in individual areas: very limited in the Hilmarfjellet region (Szczęsny, Lindner and Marks 1987) and widespread on the Wijkanderberget (Szczęsny *et al.* 1989). Snow patches were distinguished mainly in summit parts of mountains and within chutes and depressions on their slopes. On coastal plains they occur at foot of terrace edges. Up-glacier snow patches mask crevasses and drainage pattern.

On air photos snow patches are very light, smooth, shapeless and flat features (Fig. 4). Only snow avalanches are slightly convex, rough and darker, and their texture is granular due to inclusions of mineral debris.

Demarcation of areas covered with snow is important for field reconnaissances. Besides interpretation problems, snow patches are important morphogenetic features (Czeppe 1966, Baranowski and Pękala 1982). Snow and especially snow-debris avalanches are a main erosive factor on rocky walls. They also transport mineral material which can be deposited in taluses or nival moraines. Snow patches are water reservoirs, feeding nival streams during at least a part of summer (Fig. 11).

Icings. — Icings are to be considered as type of superficial glaciation in morainal zones of subpolar glaciers. They develop due to freezing of meltwaters which ascend through sandurs. In Spitsbergen maximum thickness of icings equal 4 metres was noted by Baranowski (1977). The icings disappear when air temperatures are above the melting point for a long time.

On air photos icings were distinguished in the interlobal zone of Torellbreen (Szczęsny *et al.* 1985) and in the forefield of Renardbreen (Fig. 15). Icings on air photos are very similar to snow patches due to smooth texture, irregular shape and very light phototones, only slightly darker than the ones of snow (Fig. 4). However, interpretation of icings on air photos is not really difficult as they occur only on sandurs and close to glacier margins.

Icings are formed probably also in forefields of other glaciers in Spitsbergen. Their absence on studied air photos arises presumably from the time when photos were taken *i.e.* decline of summer. Icings exist mostly at the beginning of summer, like those observed by the author in July 1986 in forefield of the Scottbreen. Occurrence of winding ramparts within intramorainal zone of the Vitkovskibreen (Fig. 14) seems to be connected with deposition of mineral material in the winding channels between patches of incings (*cf.* Cegła and Kozarski 1977). Some fragments of ice-cored moraines are composed probably of icing patches which were covered by glaciofluvial deposits (Fig. 14).

Analysis of air photos not only confirms occurrence of icings but also suggest

their participation in development of other landforms in glacier forefields. Repeated air photos could be very useful for studies of icings migrations in time and of their influence on changes of sandur relief.

Marine landforms and deposits

This group is composed of present beach and raised marine beaches with structural features.

Present beach. — Contemporary beaches in southern Spitsbergen develop only in these coast fragments which are protected from waves and where sea currents enable deposition. In southern Spitsbergen beaches are composed of sand and gravel, sometimes containing organic lamine (Szczęsny 1989). Beaches are usually narrow, up to several metres and not higher than 1.5 m a.s.l. They are from several hundred metres long within small bays to several kilometres, like on the western coast of the Recherchebreen (Szczęsny *et al.* 1989).

On air photos beaches are visible as narrow and light strips with flat surfaces and smooth texture (Fig. 4). They occur along a coastline, down edges of the lowest raised marine beach (Fig. 14). Sometimes boundary between a beach and the first raised marine terrace is unclear, like in the Calypsostranda (Szczęsny *et al.* 1989) where both these young landforms have the same phototones. The raised marine beach is darker only in places overgrown by vegetation. In such cases presence of ancient storm ridges constitute the main discrimination criterion. On a present beach fragments of a single contemporary storm ridge are to be distinguished, while on a raised beach — several generations of such ridges are visible.

A present beach often encloses small shallow lagoons. Such phenomenon is connected with sea currents which transport mineral material along a coast. In lagoons freshwater delivered by meltwater streams and glacial rivers mixes with sea water that inflows through narrow inlets during flood tides. Inlets are easily distinguished on air photos due to sharp contrast between phototones of beach and water (Figs 14 and 16). Sometimes also wide bays, like Josephbukta, are being closed by spits (Fig. 15). This 750 m long spit seems to be very fresh as occurs in the area which was covered by the Renardbreen at the turn of 19th and 20th centuries (*see* Wharton 1896). Glacier retreat initiated the processes that smooth a shoreline (*see* Marsz 1987). Material from the abraded lateral moraine of the Renardbreen is successively deposited in mouth of a shallow bay and forms a spit (Fig. 15).

Raised marine beaches. — Raised marine beaches are the most characteristic elements of a seashore in southern Spitsbergen. They form several shelves, separated from each other by steep edges (Figs 6 and 19) and are from several metres (Fig. 12, PL. 2) to several hundred metres wide (Fig. 11). Abrasive and accumulative raised marine beaches were distinguished. The abrasive ones are cut in mountain slopes composed of pre-Quaternary rocks. The accumulative
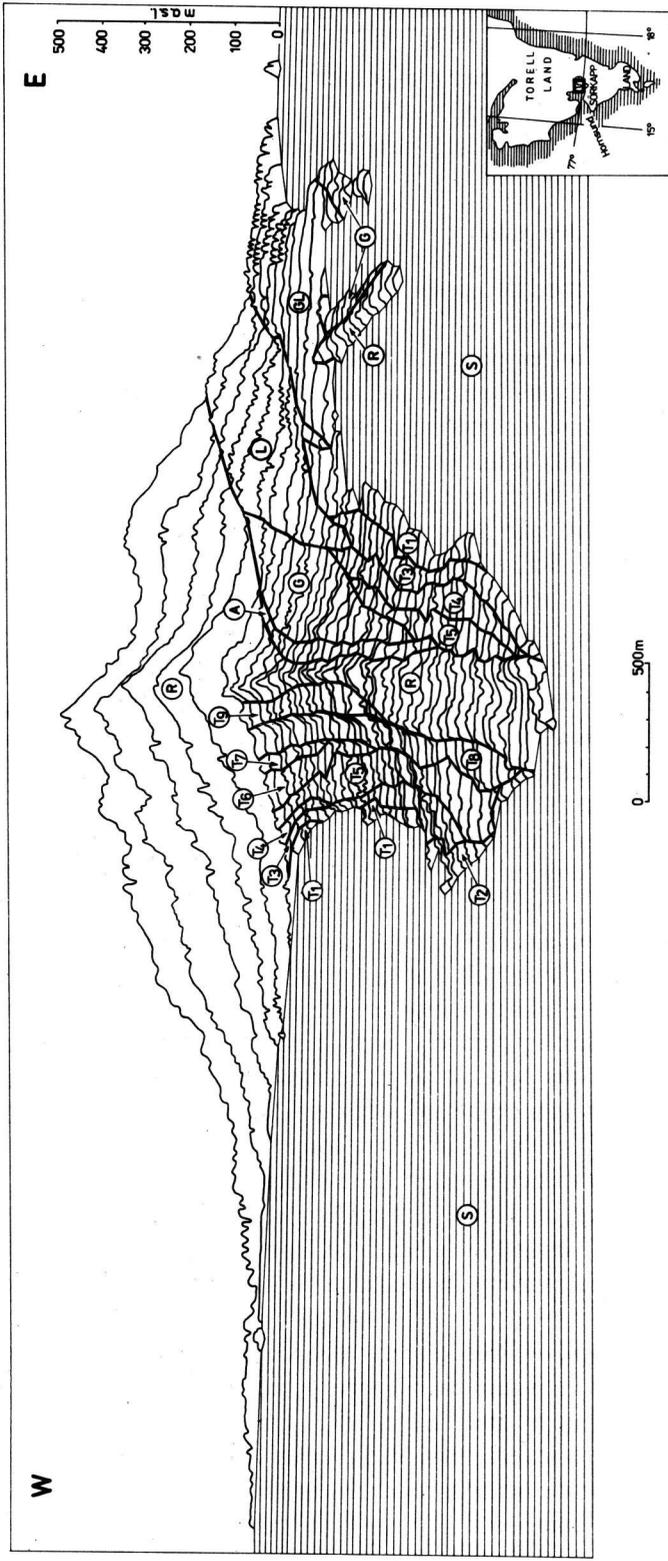
Fig. 19. Block diagram composed of concentrated morphological profiles across the Treskelen Peninsula

R — rock outcrops, partly with a waste cover, A — acient lateral moraines, L — lateral moraines, G — ground moraine, GL — glacier ice, T_{1-9} — raised marine beaches, S — sea

terraces are composed of sand and gravel, sometimes interbedded with organic matter, and often disturbed by frost processes (Szczęsny 1989). Shape and location of raised marine beaches are so characteristic that phototones and texture of image form only the secondary criteria in photointerpretation. However, phototone and texture are varying (Fig. 4), because their development was influenced by different fine landforms like klippes, ancient storm ridges, depressions or karst forms.

Studies of the raised marine beaches and especially measurements of their altitudes play an important role during cinsiderations of intensity and extent of glacioisostatic uplift of Spitsbergen. Owing to outstanding distinction of raised marine beaches, such measurements could be made with use of air photos and with sufficient accuracy (Nitychoruk, Ozimkowski and Szczęsny 1989).

Shelves distingushed on slopes of mountain massifs at altitudes over 150 m a.s.l. are many a time similar to raised marine beaches (Fig. 3) but on their surfaces there are no landforms which are typical for Quaternary marine terraces. Doubts in interpretation of such landforms were already discussed.

Ancient storm ridges. — Storm ridges are connected with a supralittoral zone where wave energy is dispersed, and clastic and organic material is deposited (Szczęsny 1989). Contemporary storm ridges in Spitsbergen are over 2 metres high and occur along a coastline. On air photos in scale of 1:50,000 they are usually unvisible, because they have the same phototones and texture as the present beach (Fig. 4). Furthermore, beaches are so narrow that even stereoscopic vertical exaggeration does not allow to distinguish storm ridges on a stereoscopic model. Only in places where beaches become wider, storm ridges could be marked on their surfaces.

Completely different situation concerns raised marine beaches. Ancient storm ridges are the most clear relief elements there (Fig. 16). Presence of storm ridges generates characteristic striped texture on air photos (Fig. 4). Light stripes on photos reflect ridges while dark ones — depressions between individual ridges. Different phototones are due to lithology. Ridges are composed of coarse pebbles, unfavourable for water retention and vegetation. On the other hand wet depressions filled with fine material form a very comfortable place for mosses and lichens.

On surfaces of raised marine beaches several or a dozen or so, generations of ancient storm ridges occur (Fig. 16). They indicate sea level variation during land uplift. Datings of deposits locate variations of sea extent in time. For example sudden deflection of ancient storm ridges on the marine beach 15–18 m a.s.l. on the Björnbeinflyene (Fig. 16) indicates that about 8–10 ka BP a bay existed in this area. Ancient storm ridges enter under the contemporary snout of Vitkovskibreen (Fig. 14). Therefore this glacier occupied a considerably smaller area at the beginning of the Holocene.

Depressions. — Location of ancient storm ridges is occasionally connected with depressions on raised marine beaches. On air photos they are concave and of

various dimensions: from 20 × 20 m on the Björnbeinflyene to 2200 × 700 m on the Calypsostranda (Figs 11 and 16). They are prolated or irregular. Depressions on air photos have dark phototones, darker than surface of marine terraces, and a smooth texture (Fig. 4). Such phototones are generated by increased moisture, favourable for overgrowing by vegetation. Some depressions are filled with meltwaters from nival streams.

Depressions on raised marine beaches are often surrounded by ancient storm ridges, parallel to margins of depressions (Figs 9 and 16). Such phenomena occur on accumulative terraces and can be explained in different manner. One possibility connects development of such depressions with deposition of floating sea ice on a beach (Marsz 1987). Deposited ice patches could therefore protect beach from action of waves. In places where sea ice was deposited, there are melt-out pits that interrupt storm ridges. Such interpretation can explain only the origin of the smallest depressions visible on air photos.

Point of view presented by Lindner and Marks (1989) is an explication of Marsz's opinion (op. cit.). Depressions are the traces of icebergs that anchored during land uplift and were buried by mineral deposits of just generated beach. After ice melting, depressions surrounded by storm ridges were exposed. Because most such depressions developed on the marine beaches 8–12, 15–18 and especially 20–24 m a.s.l., Lindner and Marks (1989) believe that development of depressions was synchronous with more intensive calving of glaciers that occurred during climatic warming. According to this point of view, even extensive depressions could be formed.

The above interpretations seem controversial. If Marsz's (1987) opinion can be applied straightforward to small depressions, interpretation of Lindner and Marks (1989) calls for further explanations. It is difficult to understand how icebergs, 90% volume of which sinks in water, could be preserved long enough to influence development of storm ridges in a supralittoral zone. Also growing of storm ridges behind the icebergs i.e. in places protected form waves, is questionable. Moreover, if sea or iceberg ice was buried by beach deposits, then after its melting remains of ancient storm ridges should be found on bottoms of depressions. Unfortunately, no signs of them have been noted there.

However, interpretaion of a very extensive depression on the Calypsostranda (Fig. 11) is quite different. Disposition of raised marine beaches is a clue to this question. Across a sheashore the following marine landforms were distinguished: present beach, 1–6, 18–30, 35–40, 18–30, bottom of depression, 35–45 and 50–60 m a.s.l.. It indicates that this depression formed a bottom of an ancient sea bay. Due to land uplift the bay lost connection with a sea and became, firstly a lagoon and then a lake. Detailed study of the bay contour is not possible at present as its northern part does not exist. Changes in disposition of sea currents have activated lately the abrasive processes and a small bay Skilvika, was formed (Fig. 11).

Most depressions on abrasive marine terraces cut in carbonate rocks are undoubtedly of karst origin.

Landforms and deposits of different origin

This group is composed of landforms and deposits of different origin: edges, depressions, sinkholes and caves. Set of landforms in this group is individual for each map.

Edges. — On photogeological maps all types of edges were put together into a single group of landforms, irrespective of the forming factor. On seashore the edges separate raised marine beaches from one another (Figs 6, 12 and 16) and occur along ravines in marine terraces incised by glacial rivers (Figs 6 and 9) but primarily often connected with rejuvenated tectonic dislocations (Lindner, Marks and Szczęsny 1986). Fracturing of rocks favours intensive erosion in such places (Szczęsny 1987a).

Edges were also distinguished on mountain slopes. They are located on valley slopes and are parallel to valley axes. They have been presumably formed by glacial erosion (Fig. 6). Edges are also marked on photogeological maps as limits of main chutes (Figs. 6, 11 and 13).

Due to vertical exaggeration all edges are the most distinct elements of relief on stereoscopic images. This effect is intensified by a rectilinear outline of edges and their independence on shape of undercut forms. Phototones of edges sharply contrast with phototones of surrounding landforms due to different illumination (Fig. 4). Texture of edges is usually smooth, except from those parts on which different forms exist e.g. solifluction covers (Szczęsny et. al. 1989). The lowest edges recognized on air photos in scale of 1:50,000 were 1 m high, while the highest — up to 30–40 m (Fig. 6).

Karst landforms. — Several karst landforms were located and described in southern Spitsbergen by Pulina (1977) and Lindner and Kłysz (1989). They were: canyons, sinkholes, uvalas, karst pits, vaucluse springs, caves, rock niches, karst furrows and several microforms. Main problems during interpretation of karst landforms on air photos arise from insufficient knowledge of bedrock lithology and dimensions of the forms. Only the largest landforms as sinkholes and uvalas are recognizable.

Sinkholes in the Sörkapp Land were distinguished only on the Olsokflyene (Fig. 9). They exist on raised marine beaches 15–18 and 8–12 m a.s.l., cut within the Ordovician limestones of the Hornsundtind Limestone Formation (Szczęsny 1988). Diameters of sinkholes do not exceed 5 m and they are 2–4 m deep. Such dimensions are hardly to be recognized on available air photos in scale of 1 : 50,000 but owing to vertical exaggeration of stereoscopic model they are clear enough. Phototones of sinkholes are very dark (Fig. 4).

Karst forms described by Pulina (1977) as uvalas were interpreted on air photos as depressions but their origin could not be defined more precisely. Some uvalas are similar to iceberg melt-out depressions. The latter exist however on accumulative raised marine beaches. Unfortunately, photointerpretation criteria so far are not sufficiently univocal for discrimination of terrace origin and bedrock lithology, and field observations are necessary.

Karst pits and vaucluse springs are easily distinguished on air photos, although they have small dimensions. They occur in places where dark streams suddenly disappear or appear on lighter surfaces (Szczęsny, Lindner and Marks 1987).

Caves and other small karst features are usually invisible on air photos. Cave inlets are too small or are shut out by rock walls. Location of caves on the photogeological map of the Hilmarfjellet region (Szczęsny, Lindner nad Marks 1987) was possible due to field observations.

Deposits of ephemeral lakes. — Ephemeral lakes are common in South Spitsbergen. They were distinguished on all photogeological maps. In western South Spitsbergen such lakes often exist in depressions on raised marine beaches (Fig. 16). In spring and summer depressions are filled with water from melting snow and glacier ice. Transport efficiency of meltwaters considerably decreases downslope and on flat and extensive marine terraces. That is why only the finest material is deposited in tundra lakes (Figs 9 and 16). Lake deposits are visible only on these photos which were taken after drying up or draining. Lithology of lake deposits favours water retention and on air photos they have very dark phototone and smooth texture (Fig. 4).

However, deposits of ephemeral lake in the Raudfjellet area (Fig. 17) have light phototones and spotted texture (Fig. 4). They cover bottom of triangulate depression between slope of Raudfjellet and lobes of the Austre and Vestre Torellbreen. Specific spotted texture is generated by numerous, several metres high pyramids. Meltwater fills partly this depression in springs, being dammed by glacier ice and impermeable bedrock. Vicinity of steep and intensively weathered slopes of Raudfjellet intensively delivers coarse debris. That is why phototones of lake deposits are light — similar to the ones of waste covers (Fig. 4). Drainage of the lake occurs after melting of snow which dams outflow channels in glacier crevasses. When possible, outflow is very rapid and lasts several tens of hours only (Pękala *pers. comm.*). Impetuously flowing waters erode bottom deposits what is especially intensive at the end of draining. Repeated filling and emptying of the depression, as well as changing outflow direction and aerial weathering generate an outstanding relief of lake deposits. Interpretation of air photos enabled to distinguish 4 generations of lake deposits. Each generation indicates different relief, phototones and extents (Fig. 17). Younger deposits have lighter phototones, more rough surface and cover gradually smaller area what manifests that volume of infilling water decreases. Such phenomenon is probably due to more numerous outflow channels because during the last several dozens of years a continued climatic warming (Fig. 20) could not result in smaller feeding with meltwaters.

Small ephemeral lakes exist on ice-cored moraines (Fig. 14) but their existence is extremely short, due to permanent relief changes caused by melting of ice core. For this reason contemporary or ancient lake deposits of this kind cannot be distinguished. On the other hand discrimination of such deposits from morainic ones is not possible either.

Development of relief and Quaternary deposits in southern Spitsbergen on the ground of photogeological analysis

Collecting of data concerns usually location of deposits, their origin and age. Interpretation of air photos provides a lot of important, although mostly superficial informations in the first two subjects. Inner structure of landforms remains usually undetectable. Interpretation of air photos enables to define age relations between adjacent landforms. Photointerpretation can be helpful in selecting areas for paleogeographical studies and sampling for ^{14}C and TL datings.

In studies of Spitsbergen, changes of sea level and influence of glaciers on relief during the Quaternary are the most important questions. On the ground of photogeological maps and sketches (Fig. 1) attempt of correlation of distinguished landforms with glacial and deglacial episodes was done (Fig. 20), completed with datings of deposits from the studied and adjacent areas.

Examined Quaternary landforms were connected with main glacial events in southern Spitsbergen (Lindner, Marks and Pękala 1987). The known chronostratigraphical scheme of this area starts with the Torellkjegla Interglacial (Mazovian, Holstein), followed by the last two Pleistocene glaciations (Fig. 20). The older one is defined as the Wedel Jarlsberg Land Glaciation and is composed of two glacial episodes, being equivalents of the Warta and Odra Glaciations in Poland, Saale in western Europe, Moscow and Dnieper in Russia and Illinoian in North America. During the younger glaciation, defined as the Sörkapp Land Glaciation, 4 glacial stages were distinguished. The Sörkapp Land Glaciation is an equivalent of the Wisła (Weichsel, Waldai) Glaciation in Europe and of the Wisconsin Glaciation in North America. The Sörkapp Land and the Wedel Jarlsberg Land glaciations are separated by the Bogstranda (Eemian, Mikulino, Sangamon) Interglacial (Fig. 20).

During the Holocene three glacial episodes were distinguished: Grönfjorden, Revdalen (Magdalenefjorden *after* Szupryczyński 1968a) and Little Ice Age. Chronostratigraphical reconstruction of Quaternary landforms and deposits distinguished on air photos of southern Spitsbergen was done separately for glacial and slope landforms, and for marine landforms. Chronostratigraphical correlation is completed by paleogeographical sketches (Fig. 21), on which changes of sea level and of glacier extents during main glacial episodes are presented.

Glacial and slope landforms

Wedel Jarlsberg Land Glaciation. — The oldest glacial and slope landforms interpreted on air photos are of the Wedel Jarlsberg Land Glaciation age.
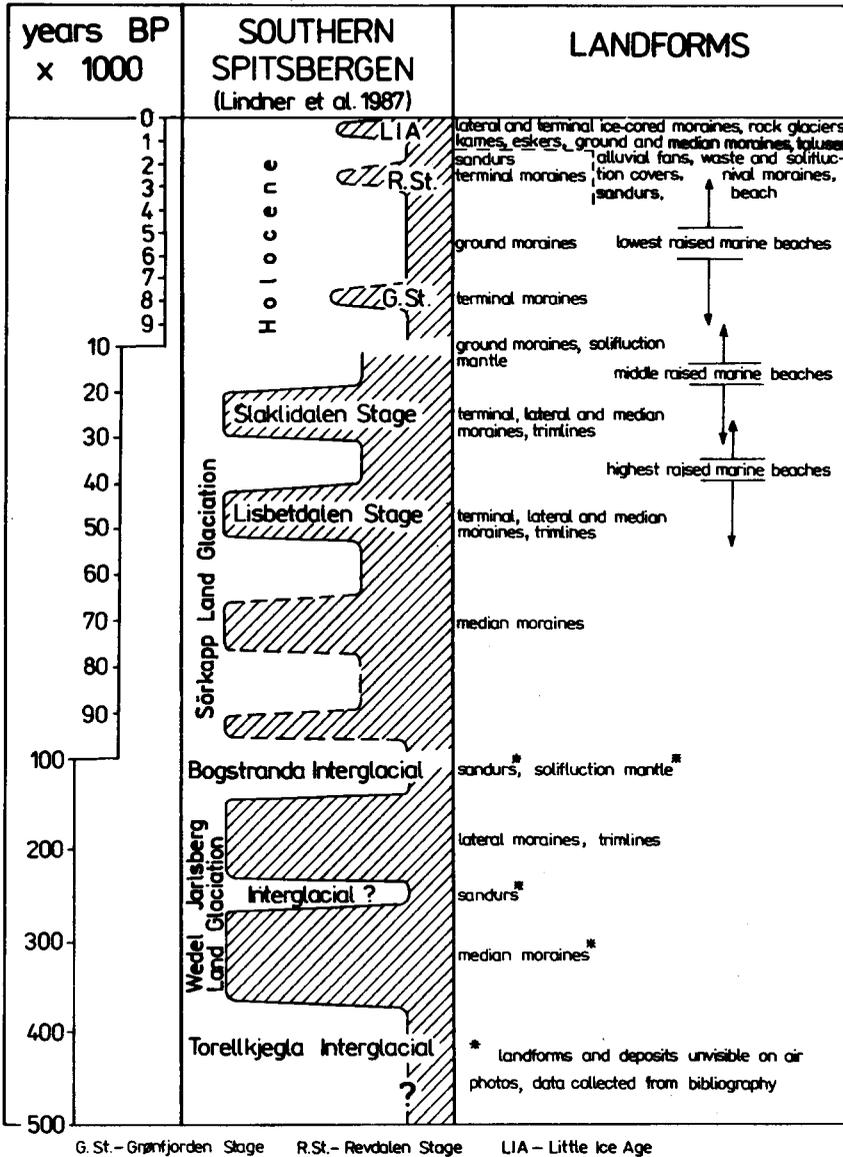
Fig. 20. Correlation of main landforms with glacial episodes and deglacial intervals in southern Spitsbergen

Remains of this glaciation were discovered only on slopes of the highest mountain massifs. On slopes of Hilmarfjellet and Karentoppen ancient lateral moraines at 230–240 and 110–140 m a.s.l. were distinguished (Fig. 10). Deposits of similar moraines on slopes of Stupryggen and Gavrilovfjellet (northwestern Sörkapp Land) at about 80 and 100 m a.s.l. were dated at 141 ka and 217 ka BP, *i.e.* correspond to the younger part of the Wedel Jarlsberg Land Glaciation
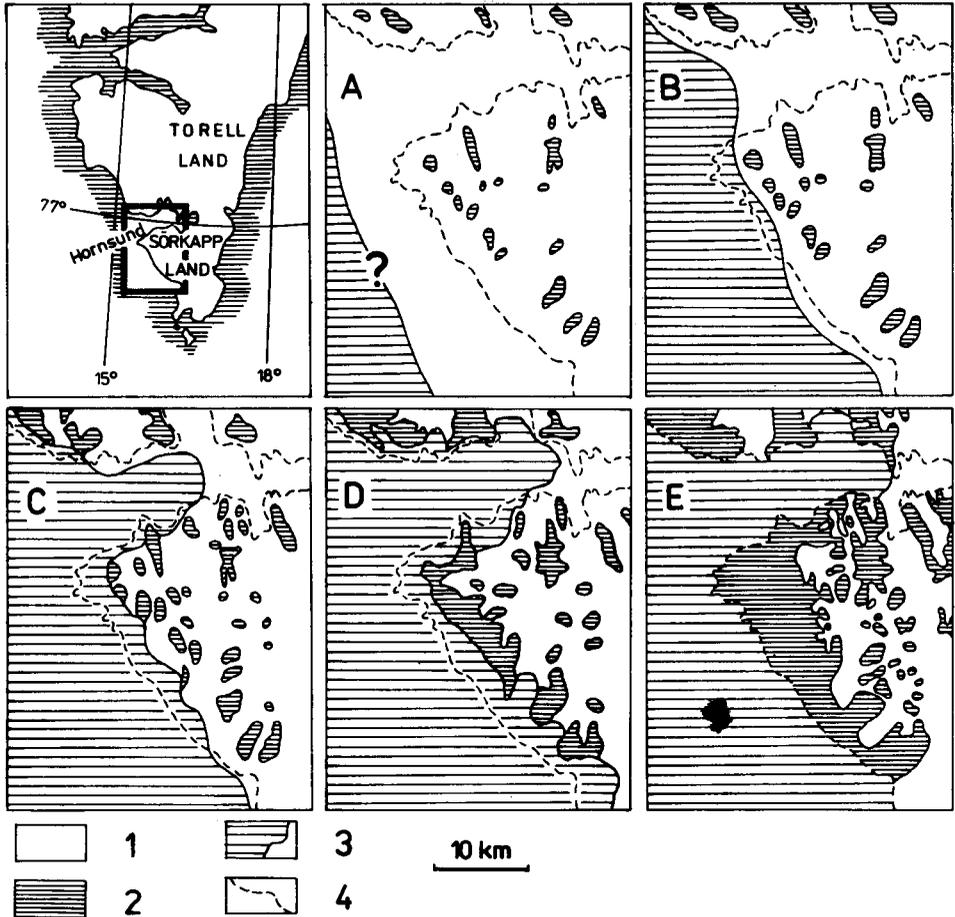
Fig. 21. Extents of glaciers and shorelines in western Sörkapp Land during the Middle and Late
Quaternary
A — Wedel Jarlsberg Glaciation, B — older stage of the Sörkapp Land Glaciation, C — younger
stage of the Sörkapp Land Glaciation, D — turn of the Pleistocene and the Holocene,
E — Little Ice Age
1 — glaciers, 2 — ice-free areas, 3 — sea extent, 4 — contemporary shoreline

(Butrym *et al.* 1987). Ancient lateral moraines and trimlines at similar altitudes
on valley walls in western Sörkapp Land (*see* Ostaficzuk, Lindner and Marks
1982, 1986, Szczęsny Lindner and Marks 1987) indicate that nearly the whole
southern Spitsbergen was covered by glaciers during the Wedel Jarlsberg Land
Glaciation (Fig. 21A). Glaciers reached their maximum in this time and thus, no
signs of the older Quaternary glaciations could have been preserved. During the
Wedel Jarlsberg Land Glaciation glaciers coalesced with one another at valley
outlets and floated in the sea (Fig. 21A). That is why landforms and deposits of
extramorainal zones of this age are so rare. Tills within the Torellmorena (Fig.

17) could be studied in the field (Lindner, Marks and Pękala 1987) and TL dated at 313 ka, 284 ka and 229–187 ka BP, *i.e.* correspond to both glacial episodes of the Wedel Jarlsberg Land Glaciation (Fig. 20). Tills are separated by glacio-fluvial sands, TL dated at 220–190 ka BP.

Bogstranda Interglacial. — Deposits of this age were not distinguished on any studied air photos. They are however, known form outcrops. Within the Torellomorena (Fig. 17) there are glaciofluvial sands, TL dated at 161 ka and 143 ka (Lindner, Marks and Pękala 1987). Climatic warming favoured development of slope processes in the Bogstranda (Fig. 20). They were dated at 143 ka BP (*op. cit.*).

Sörkapp Land Glaciation. — Landforms and deposits of the Sörkapp Land Glaciation are more frequent than the older ones. During this glaciation four glacial stages were distinguished (Lindner, Marks and Pękala 1987). The oldest stages of the Sörkapp Land Glaciation were distinguished on the ground of TL datings of tills from the Torellmorena (Fig. 17) at about 73 ka BP (Lindner, Marks and Pękala 1987).

Geological interpretaion of air photos enables to interpret landforms of the two, surely the youngest stages. In the Slaklidalen there are trimlines at 10 and 40 m above valley bottom which are ascribed to the Sörkapp Land Glaciation (Lindner, Marks and Ostaficzuk 1986). A bottom of the nearby, considerably smaller Wiederdalen (Fig. 13) hangs about 40 m above a seashore plain, probably corresponding to the lower trimline of the Slaklidalen. Presence of undisturbed threshold at valley mouth presumably indicates that terminal part of the Wiederbreen floated during the younger stage of the Sörkapp Land Glaciation and erosion of this small glacier considerably decreased. Similar thresholds are also noted in the Tjörndalen and Blomlidalen, northern Wedel Jarlsberg Land (Fig. 6; Szczęsny *et al.* 1989).

Remains of ancient lateral moraines occur on valley floors and slopes at 70–80 m a.s.l.. Tills of such moraines were TL dated in the Lisbetdalen at 47 ka and 22 ka BP (Butrym *et al.* 1987). They confirm existence of at least 2 glacial stages during the Sörkapp Land Glaciation (Fig. 20). The lowest ancient lateral moraine on the Hilmarfjellet, at 80 m a.s.l. could be also formed in that time (Figs 10 and 20).

Glacier extents during the Sörkapp Land Glaciation were smaller than during the Wedel Jarlsberg Land Glaciation (*see* Figs 21A and 21B). If during the oldest stages of the Sörkapp Land Glaciation glaciers could coalesce at valley outlets (Fig. 21B), then in the younger stage they occupied a smaller area and became isolated from one another (Fig. 21C). Most glaciers seem to be tidewater glaciers in the present seashore area. In the valleys completely deglaciated now, glacier fronts formed ice bays at valley mouths.

Turn of Pleistocene and Holocene. — Climatic warming after the Sörkapp Land Glaciation (Fig. 20) was accompanied by rapid retreat of glaciers (Fig. 21D). Their snouts withdrew into the valleys as confirmed by presence of raised

marine beaches in the glacier forefields *e.g.* of the Vitkovskibreen (Fig. 16) and the Olsokbreen (Szczęsny, Lindner and Marks 1987). Ancient storm ridges on the beach 15–18 m a.s.l. (ascribed to the beginning of the Holocene) and on the beach 8–12 m a.s.l. (dated in Hornsund at about 8 ka by Birkenmajer and Olssson, 1970) enter under the glacier snouts. This fact clearly indicates that deeply incised bays existed in valleys that are at present again filled with glaciers. During rapid glacier retreat ground moraines were formed, patches of which still exist *e.g.* in the Slaklidalen (Ostaficzuk, Lindner and Marks 1986). On seashore plains in forefields of the Wiederbreen (Szczęsny 1986) and the Vitkovskibreen (Szczęsny, Lindner and Marks 1987) extensive sandur fans were simultaneously formed.

Holocene. — During the Holocene three glacier advances occurred (Fig. 20). During the oldest, Grönfjorden Stage, glaciers did not get out of the valleys. Terminal moraines were formed on a threshold in the Wiederdalen (Fig. 13) and in the mouth of the Slaklidalen (Ostaficzuk, Lindner and Marks 1986). After the following warming when glaciers retreated leaving ground moraines in the Wiederdalen (Fig. 13), next glacier advance of the Revdalen Stage occurred (Fig. 20). During this second cold episode extents of glaciers were commonly smaller than during the previous stage, what is indicated by location of corresponding terminal moraines (Figs 6 and 13; Ostaficzuk, Lindner and Marks 1986). During a successive interstadial several generations of sandur fans were deposied in glacier forefields *e.g.* in front of the Wiederbreen (Szczęsny 1986).

Landforms and deposits of the last glacial stage *i.e.* the Little Ice Age are the most common. Ice cover was less extensive than during the Revdalen Stage. Glacier extents (Fig. 21E) are marked by terminal and lateral ice-cored moraines located in mouths of large valleys (Figs 11, 14 and 15) or in upper parts of small valleys (Figs 6 and 13). Median moraine at contact of Vestre and Austre Torellbreen was formed (Fig. 17). Small glacierets on slopes of Urnetoppen (Fig. 18), Tjörndalsegga (Fig. 6) or Gråkallen (Ostaficzuk, Lindner and Marks 1986) were activated and then they transformed into rock glaciers. At contact of glaciers and ice-cored moraines kames and kame terraces could be formed (Figs 15 and 18). According to Nitychoruk and Dzierżek (1988) most taluses, waste covers and nival moraines were developed (Figs 6, 11 and 15) during the Little Ice Age (Fig. 20).

Transformations of relief of southern Spitsbergen after the Little Ice Age are connected with intensive deglaciation (Fig. 20). Ramparts along the Treskelen Peninsula (Figs 12 and 19) indicate glacier standstills between the maximum extent of the Hyrnebreen during the Little Ice Age and today. During the last 100 years glacier fronts retreated even several hundred meters from ice-cored moraines (Fig. 3). Extensive areas became deglaciated and mantled with ground moraines (fluted ones included). Within intramorainal zones eskers (Fig. 15) and sandurs (Figs 14 and 15) have been deposited. On glaciers median and ablation moraines have been also formed (Figs 11, 14 and 15). On ice-cored moraines and

edges of marine terrraces solifluction processes developed (Figs 10 and 14; Szczęsny *et al.* 1989). Outside the ice-cored moraines sands and gravels of youngest sandur fans have been deposited (Figs 14 and 15). Mountain slopes were subjected to weathering. Most taluses and alluvial fans have been still developing (Figs 11 and 15).

Landforms and deposits of marine origin

Measurements of altitudes of raised marine beaches play a main role in studies of sea influence on relief of Spitsbergen. Boundaries and altitudes of raised marine beaches can be precisely defined with use of air photos (Figs 9, 12–15 and 19). In fact variations of sea level in the past can be determined (Fig. 21), although their rate cannot be easily evaluated due to scancity of absolute datings. Development of raised marine beaches is connected with glacioisostatic rebound of the earth crust after deglaciation. Although time of bedrock reaction cannot be precisely established, land uplift and resulting development of marine terraces seem to be connected with climatic warming (Fig. 20).

Accuracy of dating (Olsson and Blake 1962) and influence of tectonics must be taken into consideration in studies of raised marine beaches. For this purpose a subdivision of raised marine beaches into three groups (*cf.* Kłysz and Lindner 1981) *i.e.* low (1–19 m a.s.l.), medium (20–69 m a.s.l.) and high (above 70 m a.s.l.) seems suitable. Altitudes of raised marine beaches distinguished by the author from measurements on air photas are presented (Fig. 22). Dating of terraces was possible by comparison of their altitudes with ^{14}C datings of mollusc shells and driftwood from marine deposits. Most low terraces were dated at 2.5–10 ka BP: the terraces below 5 m a.s.l. are dated at 2.5–10 ka BP, the terrace 8–12 m a.s.l. at 7–10 ka BP, and the terrace 15–18 m a.s.l. at 8–10 ka BP. Medium terraces are generally dated at 8.5–55 ka BP: the terrace 20–26 m a.s.l. at 8.5–22 ka BP, the terrace 30–38 m a.s.l. at 9–25 ka BP, the terrace 42–56 m a.s.l. at 10–25 ka BP, and terrace 58–65 m a.s.l. at 35–55 ka BP. High terraces are dated at 10–55 ka BP.

No universal scheme of connections between altitude and age of raised marine beaches can be presented for any place of Svalbard yet. The high and the highest medium terraces were formed generally during the older stages of the Sörkapp Land Glaciation (Fig. 20). Most of the medium terraces were formed at the end of the Sörkapp Land Glaciation, while the low terraces were formed during the Holocene (Fig. 20). The oldest accessible dates indicate probably the time when due melting of glacier ice resulted in first ice free fragmens of a seashore. Simultaneous glacioisostatic uplift of Svalbard has been initiated. A lot of dates around 10 ka BP consider the raised marine beaches, development of which is connected with increasing tectonic activity at the turn of the Pleistocene and the Holocene. On the other hand a great variation in age of terraces at the same altitudes indicates that land uplift occurred at different rates, connected with block structure of the bedrock, especially in western Spitsbergen.
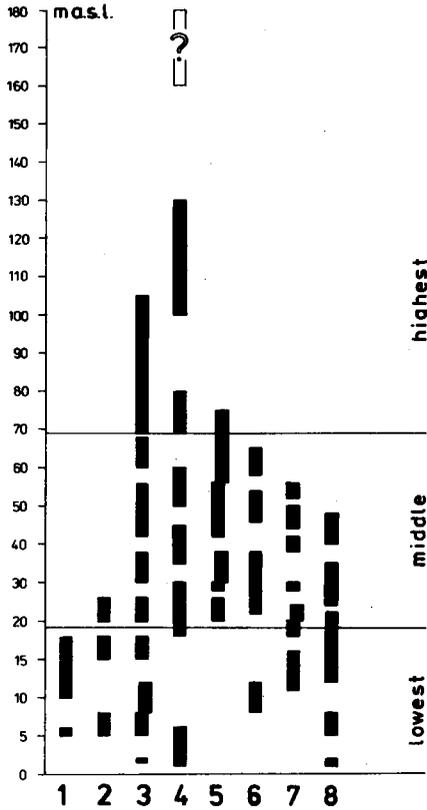
Fig. 22. Altitudes of the raised marine beaches measured on air photos from the studied areas
1 — interlobal zone of the Torellbreen (Szczęsny et al. 1985), 2 — Hilmarfjellet area (Szczęsny, Lindner and Marks (1987), 3 — Treskelen region (Szczęsny, Lindner and Marks 1989), 4 — Calypsostranda (Szczęsny et. al. 1989), 5 — Wiederdalen forefield (Szczęsny 1986), 6 — Tjörndalen forefield (Szczęsny 1987a), 7 — Kulmstranda, 8 — Breinesflya

        Results of the studies prove that most elements of the contemporary relief are very young. Nearly 90% of slope, glacier and marine landforms were formed during the Holocene and most of them during and after the Little Ice Age. These numbers indicate unusual dynamics of endo- and exogenic processes in development of land surface and in the same time — destruction of earlier landscape.

Conclusions

        Photogrammetric transformation of air photos into photogeological maps of Spitsbergen with application of home made basemaps, was done for the first time in the polar areas (Fig. 1). Systematic research allowed to improve methodics of

geological interpretation of air photos. Results confirm utility of this method in studies of the landforms and deposits in the Arctic.

On the ground of photointerpretation, Quaternary landforms in selected areas of southern Spitsbergen could be located and marked. For most landforms qualification of their origin was possible but occasionally fieldworks were needed to clarify doubts that arised during photointerpretation. Diagnostic criteria as phototone, shape, texture and location were used in photointerpretation of studied landforms and deposits. Each distinguished form was defined with its characteristic features. On this ground a photointerpretation code applied for discrimination of relief elements directly on air photos was prepared (Fig. 4). This code is the first one for the Svalbard area and probably also for other polar areas. It has a new readable graphic form. This proposition is a step to prepare a numerical code for discrimination of geological and geomorphological elements visible on air photos (see Mastella and Wesołowski 1989).

Results of photointerpretation allowed to define relations between slope, glacial and marine landforms and deposits. Completing these informations with absolute datings gave occasion to arrange distinguished forms in a chronological order (Fig. 20). Contemporary relief of southern Spitsbergen is an effect of intensive deglaciation after the last glacial episode. Most distinguished landforms developed during and after the Little Ice Age (600–100 years BP). Most older forms have been destroyed or remodelled due to endo- and exogenic processes. Ancient lateral moraines on slopes of the Hilmarfjellet are the oldest distinguished landforms. They seem to have been formed during the younger stage of the Wedel Jarlsberg Land Glaciation (Fig. 20). Similar forms from the nearby Stupryggen were dated at 217 ka BP (Butrym et al. 1987).

Together with age arrangement of studied landforms, paleogeographical interpretation was made (Fig. 21). Changes in sea level and of glacier extents from the Middle Pleistocene to the Little Ice Age were reconstructed in the northwestern Sörkapp Land. Rate of glaciers retreat and in the same time enlarging land areas due to glacioisostatic uplift of southern Spitsbergen are presented.

The author's studies indicate that possibilities given by air photos to remote sensing of Spitsbergen have not been fully applied yet. Construction of maps with concentrated contour lines acted towards development of research methodics for polar areas. Comparison of structural features interpreted on maps of concentrated contour lines with lineaments from air photos and with tectonic dislocations distinguished in the field prove distinct connection between these elements (Fig. 10) and seems to be very useful during preliminary geological studies. Blockdiagrams of concentrated profiles (Fig. 19) arise useful to find changes in altitude and inclination along extensive landforms as raised marine beaches and river terraces, which are the evidence of recent tectonic activity.

On the ground of carried examinations of Quaternary landforms and deposits, further studies can be projected. Other part of Spitsbergen are to be

covered with photogeological maps, profiles, maps of concentrated countour lines and blockdiagrams of concentrated profiles. Analysis of such materials would enable to organize field investigations. Fieldworks should focus on selected profiles and sampling of deposits for absolute datings. Geodetic measurements in areas with contemporary tectonic activity are also badly needed. Such complex investigations would create the basis for full and reliable interpretation of relief development and of neotectonic influence.

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Streszczenie

Po raz pierwszy na obszarach polarnych — na Spitsbergenie zastosowano metody fotogrametrycznego przetwarzania zdjęć lotniczych (pl. 1–2) w celu sporządzenia map form rzeźby i osadów czwartorzędowych na własnych podkładach hipsometrycznych. Systematyczne prace w tym zakresie zaowocowały 7 arkuszami mapy fotogeologicznej południowego Spitsbergenu w skali 1 : 10 000, przy czym 4 z nich powstały przy współudziale autora (fig. 1). Doskonalona w kolejnych opracowaniach metodyka analizy fotointepretacyjnej, zmierzająca w kierunku sporządzania map tego typu została opisana w odrębnych opracowaniach (Lindner i in. 1985, 1990). Wyniki tej analizy w pełni potwierdzają jej użyteczność w badaniach form rzeźby i osadów czwartorzędowych na obszarach polarnych. Na podstawie interpretacji zdjęć lotniczych południowego Spitsbergenu rozpoznano, okonturowano oraz zaznaczono na mapach lub szkicach (fig. 2–3, 5–6 i 9–18) obszary występowania różnego typu osadów czwartorzędowych, jak również niektórych elementów rzeźby starszego podłoża. Zajęto również stanowisko wobec genezy większości z nich a także wzajemnych związków pomiędzy poszczególnymi formami i osadami. Stosowane podczas prac analitycznych kryteria rozpoznawcze posłużyły do sporządzenia klucza fotointerpretacyjnego (fig. 4). Przedstawiono na nim po raz pierwszy dla obszarów

polarnych, cechy wyróżniające wszystkie interpretowane elementy rzeźby starszego podłoża oraz formy rzeźby i osady czwartorzędowe. Dobrane one zostały w taki sposób, aby umożliwiały w miarę jednoznaczne rozpoznanie analizowanych form i osadów na zdjęciach lotniczych.

Wyniki znanych z literatury i przeprowadzonych przez autora prac fotointerpretacyjnych i fotogrametrycznych, wykorzystujących zdjęcia lotnicze do zdalnego badania powierzchni Ziemi, umocniły autora w przekonaniu o ciągle niepełnym wykorzystaniu tych prac w badaniach geomorfologicznych i geologicznych. Próbą rozszerzenia metodyki badawczej, zwłaszcza w studiach tektonicznych, na pozbawionych pokrywy roślinnej obszarach polarnych, jest propozycja konstrukcji map zagęszczonych poziomic z własnych podkładów topograficznych (fig. 7) oraz blokdiagramów z zagęszczonych profili morfologicznych (fig. 19.). Porównanie na polu testowym przebiegu struktur linijnych widocznych na mapach zagęszczonych poziomic oraz lineamentów odczytanych ze zdjęć lotniczych z dyslokacjami zlokalizowanymi podczas badań terenowych (fig. 8) wykazało dużą zbieżność. Stosowanie tego typu metod wydaje się być celowe we wstępnych pracach geologicznych dla wyznaczenia prawdopodobnego przebiegu dyslokacji.

Opracowane zdjęcia lotnicze, dzięki wiernemu i niezgeneralizowanemu odwzorowaniu wszystkich elementów rzeźby analizowanych obszarów, dostarczyły również danych pozwalających na wstępne interpretacje paleogeograficzne niewielkich obszarów południowego Spitsbergenu w czwartorzędzie. Prześledzenie zależności przestrzennych pomiędzy formami rzeźby i osadami czwartorzędowymi rozpoznanymi na zdjęciach lotniczych pozwoliło na uszeregowanie ich w kolejności powstawania (fig. 20, 22). Uzupełnienie tych informacji zaczerpniętymi z literatury wynikami datowań próbek osadów umożliwiło ustalenie bezwzględnych relacji wiekowych pomiędzy osadami lodowcowymi i zboczowymi oraz morskimi, a także określenie ich prawidłowości rozwojowych. Najstarszymi, rozpoznanymi na zdjęciach lotniczych formami rzeźby południowego Spitsbergenu, okazały się stare moreny boczne zachowane na zboczach Hilmarfjellet (fig 10), będące odpowiednikami takich form na Stupryggen, wydatowanych na 217 000 lat (Butrym i in. 1987). Większość analizowanych czwartorzędowych elementów rzeźby południowego Spitsbergenu uformowana została podczas Małej Epoki Lodowej (600–100 lat temu) lub po jej zakończeniu.

Dzięki analizie fotointerpretacyjnej zaistniała możliwość syntetycznego ujęcia zmian paleogeograficznych na znacznie większym obszarze południowego Spitsbergenu. Rekonstrukcją objęto zachodnią i północną część Sörkapp Land oraz południową część Wedel Jarslberg Land, od plejstocenu po dzień dzisiejszy. Graficznym wyrazem tej syntezy są szkice paleogeograficzne tego obszaru (fig. 21), na których odtworzono zasięgi lodowców i przebieg linii brzegowej w czasie zlodowacenia Wedel Jarlsberg Land, dwóch stadiałów zlodowacenia Sörkapp Land, a także na przełomie plejstocenu i holocenu oraz podczas Małej Epoki Lodowej. Ilustrują one tempo zaniku lodowców oraz przyrastanie obszarów lądowych na skutek glaciizostatycznego podnoszenia południowego Spitsbergenu.