The Norwegian strandflat – a geomorphological puzzle

HANS HOLTEDAHL

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The strandflat between Karmøy and Bodø has been geomorphologically analysed, primarily on the basis of constructed hypsographical curves. By this method, height conditions and the maturity of the strandflat have been estimated. The general level of the strandflat is to a great extent related to the Late Weichselian marine limits along the coast from Karmøy to Frøya/Hitra, indicating a formation, closely connected to glacial isostasy, but with increasing maturity, reaching a maximum in the Smøla island area. Along the Helgeland coast, there is great discrepancy in height between the high Late Weichselian marine limits and the level of the low, and very mature, partly submerged strandflat. The horizontality of the Helgeland strandflat, and the peripheral parts of the strandflat farther south, must be due to denudation during stages of crustal stability, i.e. during interglacials or interstadials. The strandflat is polycyclic, and remnants of higher levels are present close to the backwall in many areas, and also at some distance inside the fjords. The strandflat was most likely formed in Late Pliocene/Pleistocene times, i.e. during the last 2.57 Ma. It is thought to be a product of glacial erosion, marine erosion and subaerial weathering, where frost processes have played an important part. Conditions similar to the Late Weichselian must have been particularly favourable for the strandflat-forming processes. The pre-strandflat palaeo-surface has been reconstructed, and in some coastal areas where it nearly coincides with the present strandflat surface, the strandflat may represent an exhumed pre-Jurassic surface.

H. Holtedahl, Department of Geology, University of Bergen, N-5007, Bergen, Norway.

Introduction

When H. Reusch, in 1894, introduced the term 'strandflat' for the very special landscape which exists along great stretches of the Norwegian coast, and discussed its origin, it caused great interest among geologists and geographers. A number of contributions appeared, especially during the first part of this century, and opinions with regard to origin and genesis varied greatly. However, much of this work was, of course, hampered by the lack of quantitative data.

With present quantitative data available, and modern knowledge of different aspects of Cenozoic geology, it is now possible to exclude some of the earlier hypotheses, and arrive at a better understanding of the strandflat's formation.

It is difficult precisely to define the strandflat, but it is an uneven and partly submerged rock platform extending seawards from the coastal mountains. Where well developed, the strandflat consists of numerous low islands, skerries, shallow sea areas and a low rock platform that often abuts against a steep slope. Often the strandflat can be seen as a rim of low land lying around islands and peninsulas. Some of the islands, often with a remote seaward position, have central parts rising above the strandflat to altitudes of several hundred metres.

The Norwegian strandflat is mainly developed between Stavanger and Magerøya in Finnmark (Fig. 1A). Its width varies between 50 and 60 km on the Helgeland coast and the northern parts of the coast of Møre, to more or less zero in the Stadt area (Holtedahl 1959). Its inner boundary is defined by a sharp change of slope (knickpoint), but it can also be more diffuse, where the strandflat continues more gradually into the hinterland. The outer boundary of the submerged strandflat is also somewhat arbitrary, often limited by the 20 or 40 m water depth contour. At a depth of 60–100 m, slopes lead down to the main, more even continental shelf. The boundary between slope and shelf generally coincides with the boundary between the old crystalline basement rocks and younger Mesozoic sediments.

Previous literature dealing with the strandflat focused on two main problems: time of formation, and processes involved.

Reusch (1894) regarded marine abrasion to be the main process responsible for its formation, and assumed a preglacial age. Other authors, including Davis (1899), J. H. L. Vogt (1900), Rekstad (1915) and Johnson (1919) all supported the role of marine abrasion. Subaerial denudation, producing a base levelled plain in the peripheral parts of the Scandinavian landblock, was suggested by Ahlmann (1919). Somewhat similar thoughts were expressed by Evers (1941, 1962), who believed that the strandflat was part of a polycyclic piedmonttreppe system, formed by subaerial processes. A polygenetic origin of the strandflat was also invoked by Møller & Sollid (1973) in their treatment of the geomorphology in Lofoten and Vesterålen.

The 'paleic surface' was discussed by Gjessing (1967). He emphasized that the pre-existence of a palaeo-landscape, with mature landforms approaching sea level, would enhance the effect of the different strandflat-forming agencies, while Büdel (1978) saw the strandflat

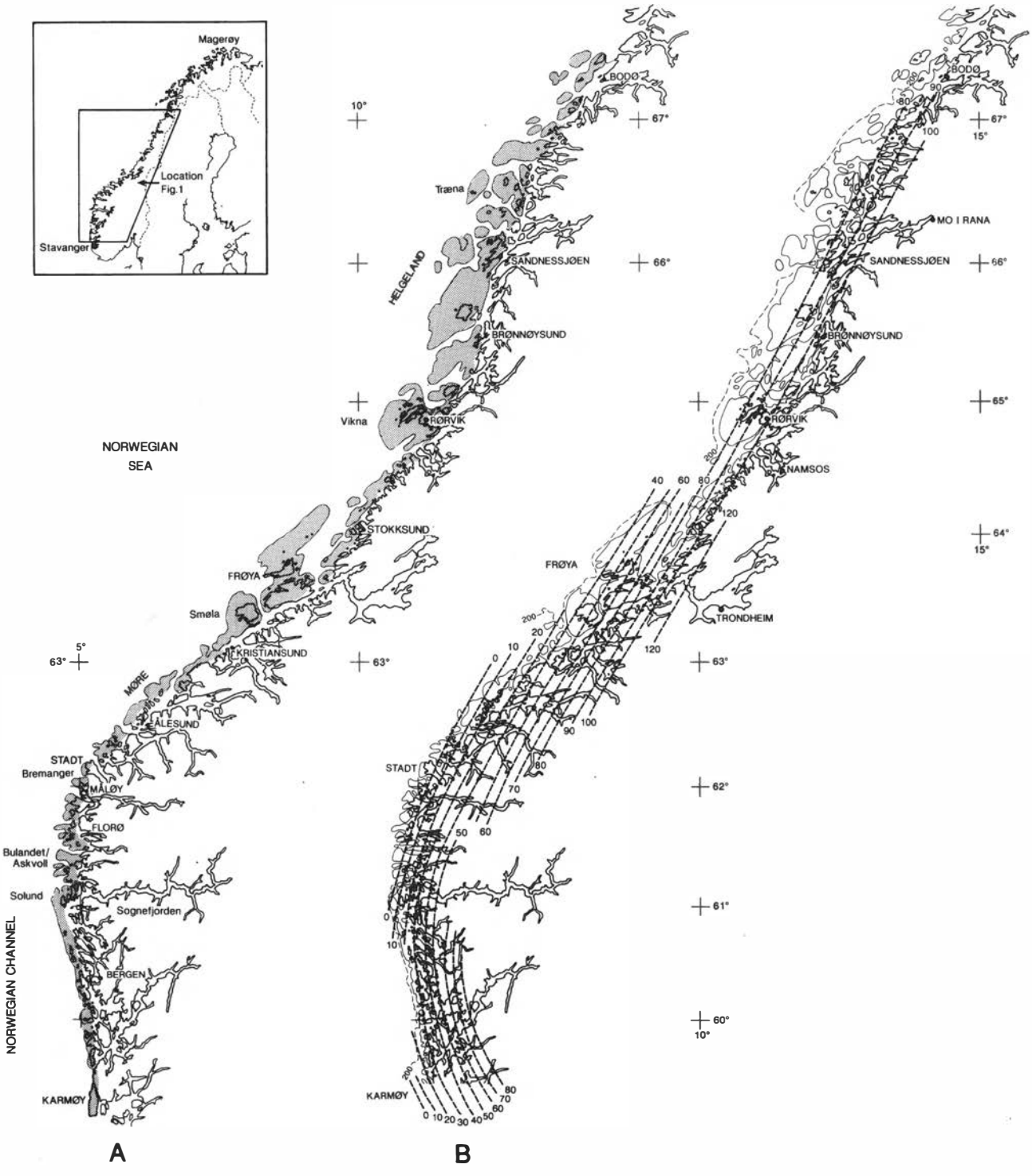


Fig. 1. A: Map showing the strandflat area (shaded) investigated. B: Late Weichselian (Younger Dryas) isobases along the coast of western Norway between Karmøy island and Bodø. Compiled from various sources, including *Nationalatlas for Norge* (1987).

as an etch-plain ('Rumpffläche'), with inselbergs mainly developed by processes in a tropical climate.

Asklund (1928) thought that strong, pre-Cretaceous and Cretaceous chemical deep weathering and subsequent marine abrasion were responsible for the formation of a 'strandflat' in western Sweden, and that the Norwegian strandflat had a similar origin.

Nansen (1904, 1922), very much influenced by his experiences in Arctic regions, discussed the strandflat in the light of frost weathering along sea cliffs, and removal of the material and planation by sea ice and wave abrasion. Sea-ice erosion and frost shattering were also emphasized by Larsen & Holtedahl (1985).

The effect of glaciation, especially local glaciation, was stressed by O. Holtedahl (1953) and Dahl (1947); as did Strøm (1938), even though Strøm held that marine abrasion had developed the strandflat on the northwestern coast of Lofoten, facing the northern parts of the Norwegian Sea.

Klemsdal (1982) correctly pointed out that the literature on the strandflat reflects a change from emphasizing one or two processes, to a combination of several processes. The present writer, in several works dealing with the Møre area (H. Holtedahl 1955, 1959, 1960a, b), held the view that glacial erosion, by coastal cirque glaciers, as well as by the inland ice, marine abrasion, and, not least, frost weathering, contributed to the origin of the strand-flat.

Summarizing the literature, certain points of importance should be emphasized:

- The typical strandflat is developed in areas which are presently, or have previously been, glaciated.
- The island of Andøya, in northern Norway, with its U. Jurassic/L. Cretaceous down-faulted rocks, is part of the strandflat.
- The strandflat must have developed after the main (Tertiary) uplift of the Scandinavian landmass.
- A dissection of the previous peripheral land mass by fjords and sounds has taken place prior to the action of the various strandflat-forming processes.
- Changes in sea level, due to glacioisostatic and eustatic movements, have been of great importance for the development of the strandflat.

Present investigations

As previously mentioned, former work dealing with the Norwegian strandflat has been hampered by the lack of detailed maps, thereby precluding an adequate geomorphological analysis. Also, a great deal of the literature, (with the exception of Ahlmann 1919 and Nansen 1904, 1922), deals with a geographically limited area.

With the availability of better maps, e.g. mostly with a 1:50,000 scale and a contour interval of 20 m, and a 1 km grid system (Topographic Main Map Series, Statens Kartverk), it became feasible to make a geomorphological analysis of the strandflat between Karmøy in the south to the town of Bodø in the north (Fig. 1A, B). Along this area of the coast three types of strandflats could be defined: (1) the area between the island of Karmøy and Stadt in the south, fringing the eastern part of the Norwegian Channel, and with a north–south running coastline, to some extent parallel to the Late Weichselian isobases, (2) the area between Stadt and the island of Frøya, where the coast has a more northeasterly direction, intersecting the isobases, and (3) the region between the Frøya island and the town of Bodø, representing the strandflat of northern Trøndelag and Helgeland, where the coastline trend and the Late Weichselian isobases more or less coalesce. The two northern areas face the Norwegian Sea, with a well-developed continental shelf. Most of the strandflat areas were visited in the field.

In the Møre area, where the present author's previous studies were carried out, maps in the scale of 1:5000, and a contour interval of 5 m (Economic Map Series, Statens Kartverk) were also utilized.

In all, 74 maps of 1:50,000 scale were analysed, constituting 34 zones of 15 minutes latitude. In areas where the strandflat was narrow, a zone was covered by one map sheet; in others, two or three map sheets were necessary to cover the area from the inner coast to the most seaward skerries. The map-sheet names and zone numbers later referred to are presented in Table 1.

Only areas with elevations less than 100 m a.s.l. and submerged areas down to −20 m water depth were analysed. In each square a value for the maximum heights, expressed by the middle value between the highest contour interval and the next, was given, i.e. if the highest contour is 20 m, the height is expressed as the middle value between 20 m and 40 m = 30 m. Or if the highest point inside a square is shown by a number, the height is similarly expressed by the middle value of the respective contour interval (Fig. 2).

This simplification only gives an approximate measure of the area of the strandflat, as only squares with elevations of less than 100 m were counted, and therefore many areas with a combination of strandflat and higher land were omitted. On the other hand, squares with only a few submerged skerries surrounded by deep water were counted as strandflat.

Table 1. Numbers refer to map sheet, or zones of map sheets, covering the strandflat.

1. Skudesneshavn (Karmøy)
2. Utsira, Haugesund
3. Bømlo, Sveio
4. Slåtterøy, Fitjar
5. Marstein, Austevoll
6. Fjell
7. Herdla
8. Fedje, Mongstad
9. Utvær, Solund
10. Bulandet, Askvoll
11. Ytterøyane, Florø
12. Bremanger
13. Stadt
14. Fosnavåg
15. Vigra, Brattvåg
16. Ona, Hustad
17. Hustadvika, Bremsnes, Kristiansund
18. Silsingodden, Smøla, Skardsøya
19. Veiholmen, S. Frøya, Hitra
20. Sula, N. Frøya
21. Froan, Halten, Stokksund
22. Somstadflesa, Osen
23. Villa, N. Flatanger
24. Nordøyan, Vikna
25. Sklinna, Leka, Austra
26. Høgbraken, Horsvær, Brønnøysund-Velfjord
27. Bremstein, Vega
28. Nordvær, Skåla, Tjøtta
29. Floholmen, Skipbåtsvær, Sandnessjøen
30. Træna Fyr, Lovunden, Lurøy
31. Træna, Selvær, Rødøy
32. Myken, Bolgvær, Meløy
33. Grønna, Fugløyvær, Gildeskål
34. Tennholmen, Helligvær, Bodø

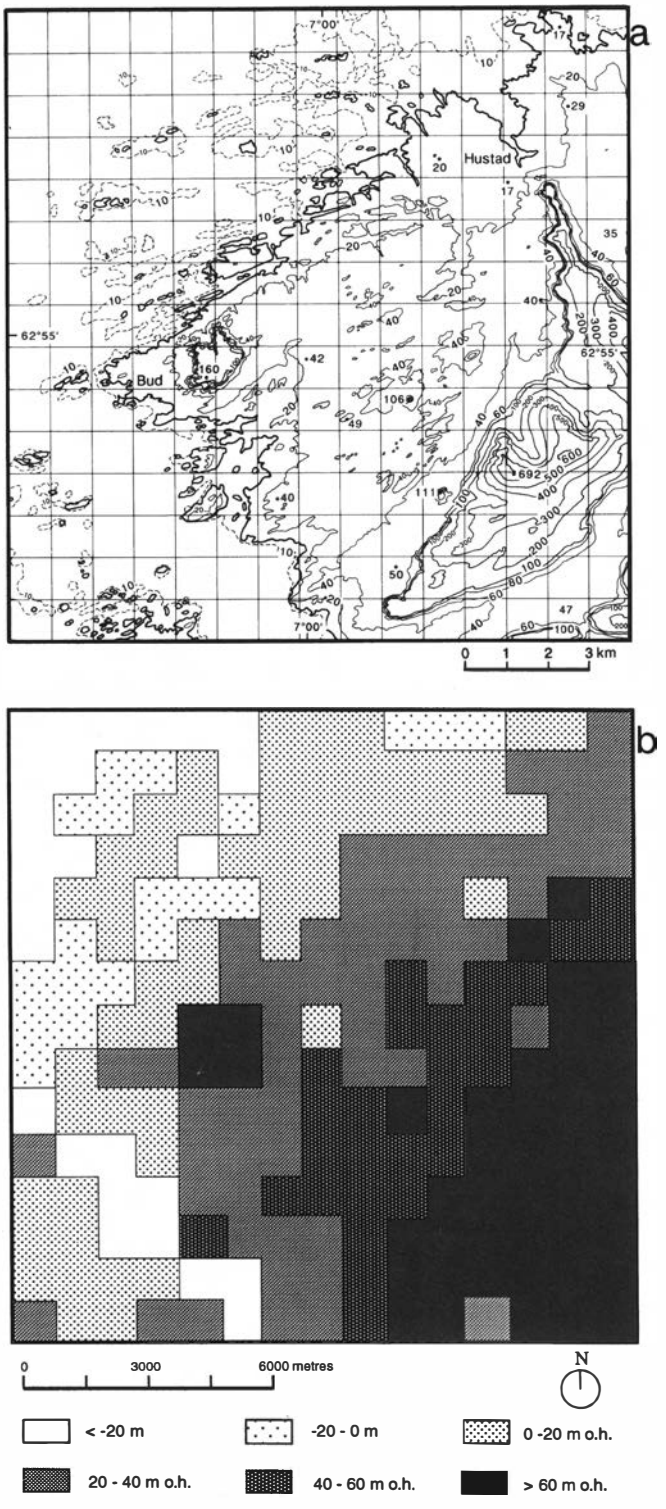


Fig. 2. Example of the method used to simplify the height variations. (a) Part of map sheet Hustad (zone 16), showing strandflat. Contour interval 20 m. (b) Simplified height distribution of the same area, as explained in text.

Area of strandflat

An estimation of the total strandflat area of the various map sheets (or group of map sheets along one latitudinal zone) is given in Fig. 3. Included in this total is the area of the submerged part (0–20 m), which is also shown separately in the figure.

Between Karmøy and Ytterøyene/Florø (zones 1–11), the total strandflat areas vary somewhat in size, with a maximum in the Bulandet/Askvoll area (zone 10) of about 400 km^2. The submarine strandflat is rather insignificant up to the Solund islands northwest of the Sognefjord (zone 9), constituting around 5% of the total area. Farther northwards, the total size of the strandflat decreases, but the relative importance of the submarine part increases to about 70% in the Bremanger (zone 12) area. Around the Stadt peninsula the strandflat is very poorly developed, but further northwards along the coast of Møre, its total area increases to a maximum of about 900 km^2 in the Smøla area (zone 18). The submerged strandflat shows only a limited increase in size. The coast between Stokksund and Bodø has a wide and well-developed strandflat, covering its greatest area between Vikna and Træna (zones 24–31). The area of the submarine part of the strandflat is generally greater than in the areas farther south, and can approach 50% of the total area. The proportion does, however, vary. In Table 2 it is shown in summary how the total strandflat area, as well as the submarine part, increases from south to north.

Height distribution (maturity) and levels of the strandflat

From a distance the strandflat appears even, and with a level that can easily be measured (Fig. 4). On closer inspection, the picture is different. It usually has a very rugged surface with varying heights, and it is difficult to identify a 'general level'. The present analysis of topographic maps with 1 km^2 squares, and with a contour interval of 20 m, gives an approximation of the height conditions, and the possibility of expressing the height distribution in hypsographic curves.

The height condition of the strandflat is important for two reasons: the height distribution expressed by hypsographic curves gives a measure of the 'maturity' of the strandflat, i.e. the degree to which the landscape has been worn down towards a base level (the sea), possibly also revealing the existence of more than one surface. Secondly, an accordance between the level of the strandflat and the Late Weichselian marine limit will indicate a mode of formation, related to glacial isostasy.

Figs 5a, b, c show hypsographic curves of the various map sheets, and Fig. 6 shows the maturity of the strandflat, expressed as a percentage of the most abundant 20 m contour interval.

Along the coast between Skudesneshavn (Karmøy) and Solund (Fig. 5a), the strandflat shows a relatively low maturity, increasing markedly northwards towards Stadt. In the coastal region of southern Møre (Fig. 5b) the strandflat is well developed, in the inner as well as the outer parts, while farther north there is a marked difference between the inner and outer parts. An extreme difference in development can be seen in the Smøla area,

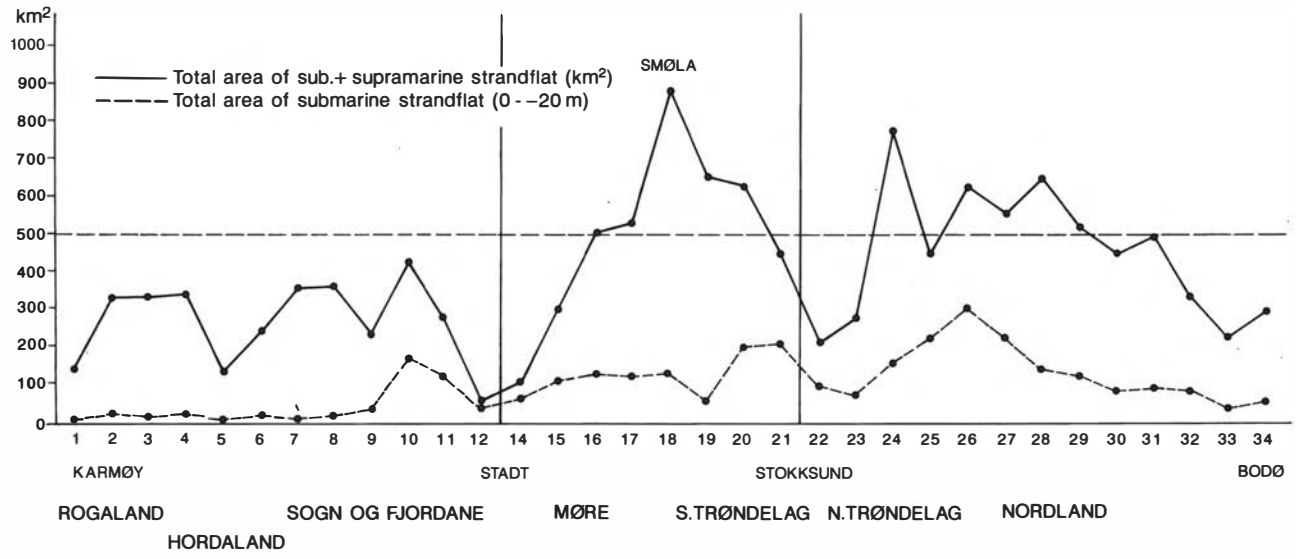


Fig. 3. Total area of strandflat, and of submarine part of strandflat, (in km^2), between Karmøy island and Bodø. Numbers refer to single map sheets, or map-sheet zones. See Table 1.

where the island of Smøla and the strandflat outside (18a) show a very high degree of maturity, while the strandflat inside (18b, map sheet Skardsøya) is far less developed. North of the Smøla–Hitra islands, along the coast towards Bodø (Fig. 5b, c), the strandflat is generally well developed, with a high degree of maturity, in the inner, as well as the outer parts.

The levels of the strandflat can be expressed in various ways: (1) the 'general level', or mode, which is the most commonly occurring level (assigned the middle value of the contour interval), (2) the median, which is the fiftieth percentile on the hypsographic curve, or (3) the upper 'knickpoint', which marks the change of slope, where the strandflat abuts against a steeper backwall (Fig. 7). This level can usually only be measured approximately, and it varies a great deal within a limited area, greatly dependent on lithology and exposure.

The variations in strandflat levels along the coast between Karmøy and Bodø are shown in Figs. 8 and 9. At Karmøy a general level is not very distinct, but is probably between 70 and 90 m a.s.l. Northwards, towards the Sognefjord, the strandflat has a general level of 50 m sinking markedly north of Solund to below sea level in the Florø–Bremanger area. Comparing these strandflat levels with the Late Weichselian (Younger Dryas) marine limits along the same stretch of coast, there is an approximate similarity from Bømlo and northwards. At Karmøy, however, the strandflat level, or levels, are far above the marine limit. The elevation of the upper knickpoints is also presented in Fig. 8. These levels, which are between 60 and 80 m a.s.l., and therefore a good deal higher than the general strandflat level, are fairly constant up to the Fedje–Mongstad area, but drop from there down to a minimum in the Bremanger–Stadt area.

Table 2. Area of strandflat (total and submerged), along the coast from Karmøy island to Bodø.

	Total area (km^2)	Submarine area (km^2)	%
Karmøy–Stadt (1–12)	3.272	462	14.1
Stadt–Stokksund (14–21)	4.101	999	24.4
Stokksund–Bodø (22–34)	6.172	1.699	27.5
Sum	13.545	3.160	23.3

Along the Møre–Trøndelag coast the Late Weichselian isobases intersect the coastline, and the marine limits consequently increase in elevation northwards (Fig. 1B). The general level of the strandflat shows a similar increase in elevation from below sea level in the Fosnavåg area to about 80 m a.s.l. in the Kristiansund–Tustna area. The same increase in the elevation of the upper knickpoints is noted. This parallelism between the strandflat level and marine limits is broken in the Smøla area (zone 18), where the strandflat is low. Further north in the Frøya–Hitra area the elevation of the strandflat is higher, but still much lower than the marine limit.

Along the coast of N. Trøndelag and Helgeland, the discrepancy between the general strandflat level and the Late Weichselian marine limit is very great. The strandflat is low, to a great extent less than 20 m a.s.l., with large areas below sea level, while the marine limit is 80–100 m. a.s.l. The upper knickpoints vary in height, but the highest are close to 100 m. a.s.l.

Sea-formed caves

The maximum and minimum heights of sea-formed caves along the coast between Stadt and Bodø (Holtedahl 1984; Larsen & Holtedahl 1985; Sjøberg 1988) are also presented in Fig. 8. These caves usually occur on the

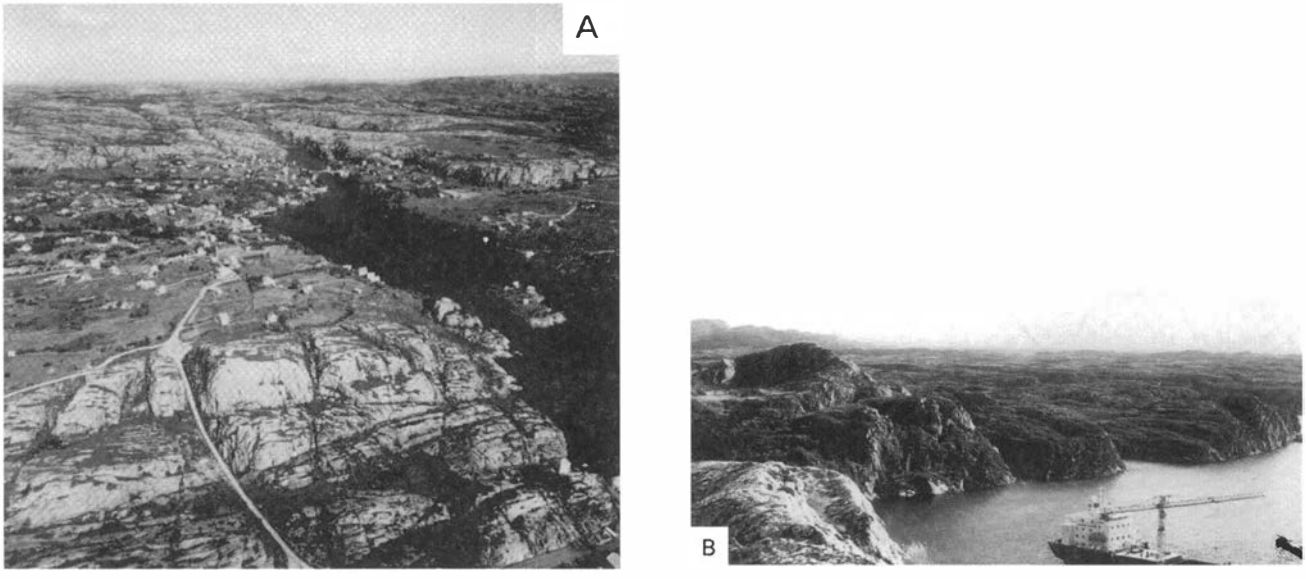


Fig. 4. Strandflat at Televåg, west of Bergen. A: Photo: Fjellanger Wideroe A/S. B: Photo: J. Aarseth.

steep backwall of the strandflat, facing the sea. The roof levels, presumably marking former sea levels, are high above the Weichselian marine limit, as well as the highest knickpoints. Their high position and the dating of sediments inside the caves indicate a pre-Weichselian age, possibly as much as 55,000 years, or more (Larsen et al. 1987).

In the Møre area investigations by Valen (1995) suggest at least four generations of sea caves, and that at least two of these were formed at times of glacioisostatic depression of the crust. The highest sea-formed caves along the coast north of Møre follow, according to Sjøberg (1988), a linearly increasing trend from south to north for about 500 km, from where it decreases. This is explained as being due to postglacial isostatic adjustment, combined with neotectonic uplift. (For cave identification, see Appendix 1.)

The knickpoint levels in the area Stadt–Tustna (zones 14–17, Fig. 8)

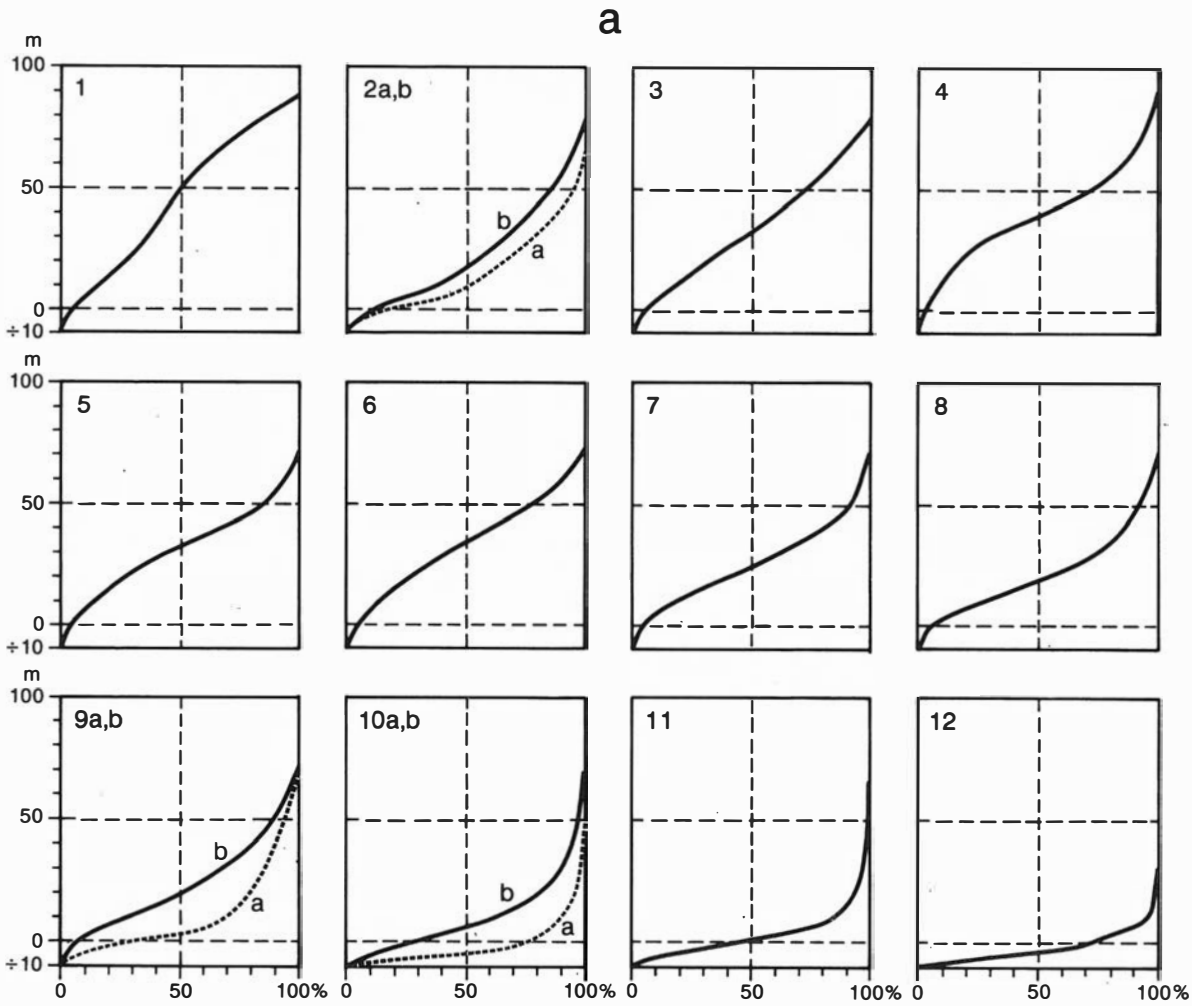
During fieldwork in the coastal area of Møre, the author noted a certain agreement in the height of the upper rocky ledges along parts of the strandflat (H. Holtedahl 1959, 1960a, 1960b). These ledges (knickpoints) represented the actual change of slope towards the backwall. A possible continuation of these levels inland along some fjords was postulated. Owing to the lack of accurate maps, and the inaccuracy of aneroid readings, however, these results are uncertain.

With the availability of maps at the 1:5000 scale and a contour interval of 5 m (Economic Map Series, Statens Kartverk) it was possible to obtain more information on the level of knickpoints. These were plotted on a map covering the area, and further plotted on a projection plane normal to the Late Weichselian (Younger Dryas) isobases (Fig. 10). As was expected, the knickpoint levels show great local variation due to lithology, rock structures and exposure to the sea. Generally, the strandflat level and the knickpoint are lower on the outer, and most exposed, side of islands, than on the inner, rocky part. Often, however, this inner level cannot be accurately measured, owing to Quaternary overburden.

In the southern area (between Stadt and the Breisunddjupet), where the general strandflat level is −10 m, the knickpoints vary a great deal, from close to sea level to 45–50 m a.s.l. A very marked rocky ledge, covered with drift, is seen on the southern side of the island of Nerlandsøy, at a level of about 45 m a.s.l. (Holtedahl 1984, Fig. 3). This knickpoint level, which is well above the Late Weichselian marine limit on the outer coast, is less common inland, but occurs sporadically in the fjord areas.

A more common level of 25–30 m a.s.l. occurs on the outer islands, as well as along the outer parts of Rovdefjord and Storfjord. North of the Breisunddjupet, and south of the Hustad peninsula, (general strandflat level −10 m to +10 m) a knickpoint level of 45–55 m a.s.l. is occasionally observed on the outer coast, which is the dominant level along the Storfjord, as well as the outer Romsdalsfjord. This level is above the Younger Dryas marine limit (Main Line) in the fjord areas, and above the older Late Weichselian marine limits on the outer coast.

In the area Hustad–Tustna further north (general strandflat level: 10–70 m a.s.l.) the knickpoint levels have much less of a vertical spread than farther south, and seem to correspond more or less with the levels of the Late Weichselian marine limits (the 12,400 yrs BP line, Svendsen & Mangerud (1987)).



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2 a: Utsira
b: Haugesund
3: Bømlo
4: Slåtterøy/Fitjar
5: Marsteinen/Austevoll
6: Fjell
7: Herdla
8: Fedje/Mongstad
9 a: Utvær
b: Solund
10 a: Bulandet
b: Askvoll
11: Ytterøyene/Florø
12: Bremanger

Fig. 5. (a–e, here and overleaf) Hypsographic curves showing height distribution on standflat.

Maturity and levels of the strandflat: a discussion

The general level of the strandflat, as well as its upper level (the knickpoint), in the coastal area between Bømlo and Kristiansund–Tustna, has a clear connection with the Late Weichselian marine limit (Fig. 8) (zones 3–17). This leads to the conclusion that the main strandflat-forming processes took place during periods of glacioisostatic crustal depression, and at a time when the inland ice had withdrawn from the coastal area.

When the general strandflat level and the Late Weichselian marine limit to some extent correspond, it means that the strandflat during periods with interglacial conditions was only moderately denuded. Examples of this are found in the Bømlo–Fjell area (zones 3–6). The southern Karmøy strandflat (zone 1), where the general strandflat is higher than the marine limit, shows greater resistance, or less active denudational processes. This is also shown by the hypsographic curve.

The hypsographic curves from the Solund area and northwards towards Stadt (zones 9–12) show an increasing degree of maturity, which means that the present level, besides the glacioisostatic effect, is also a result of increased denudation (Fig. 5a). If the highest knickpoints at the inner base of the strandflat represent the highest, and possibly the oldest part of the strandflat, the difference in height may give a measure of the denudational effect.

The inner part of the strandflat along the coast from Stadt to Kristiansund/Tustna (zones 14–17) has a level which corresponds closely to the Late Weichselian marine limit, while its outer part is lower than this limit. This is also shown by the hypsographic curves (Fig. 5b). The denudation has reached a more mature stage in the outer parts than in the inner. Special conditions are seen

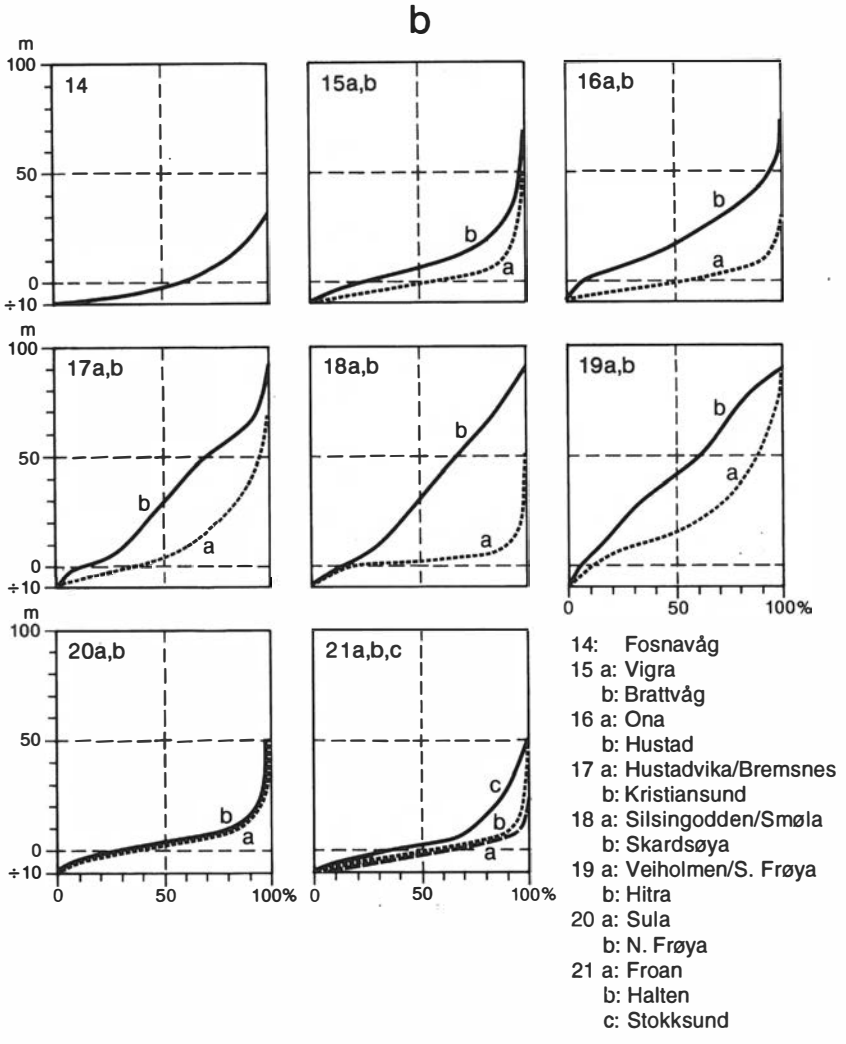

Fig. 5b.

in the area of Smøla (zone 18). Here the discrepancy between the marine limit and the level of both the outer and inner strandflat is very great. As seen from the hypsographic curves, however, the difference in maturity between the outer and inner parts is quite marked. North of Smøla (zone 19), the level of the strandflat, both in its inner and outer parts, is again higher, but lower than the marine limit.

The strandflat north of Hitra (zone 19) is in marked contrast to the strandflat further south. For its inner part the general level is mainly less than 20 m a.s.l., and the outer part to a large extent below sea level. The Late Weichselian marine limits are very high, between 100 m a.s.l. and 50 m a.s.l. At the same time the hypsographic curves show great maturity, in the inner as well as the outer parts. The heights of the highest knickpoints are somewhat uncertain, but do reach the level of the Late Weichselian marine limits. The denudation of the strandflat along the coast of N. Trøndelag and Helgeland is therefore much greater than that in the coastal areas farther south.

An overview of the strandflat as a whole reveals two types of strandflat surfaces; one tilted, approximately parallel to Late Weichselian shoreline features, and one more or less horizontal (Figs. 8, 9, 10). Large peripheral areas, both submerged and emerged, have surfaces which do not show any signs of tilting. From the description above, and the interpretation of the hypsographic curves, these more or less horizontal areas represent a mature stage of denudation, which is more or less incised into an older, glacial-isostatically tilted surface.

Turning back to the Møre strandflat (Fig. 10), the vertical variation in knickpoint levels is greatest in the southern part, especially on the Sunnmøre coast, where the general strandflat level is very low (−10 m), the denudational maturity high, and the Late Weichselian marine limits low. The general picture (as seen from Fig. 10) is a series of strandflat levels, or remnants of levels, which, according to their knickpoint values, indicate approximate horizontality. This must, however, be stated with a certain reservation, as in the outer strandflat areas, the observed knickpoint levels may be far apart, and therefore not proven to be synchronous. Furthermore, the levels cannot be measured with great accuracy.

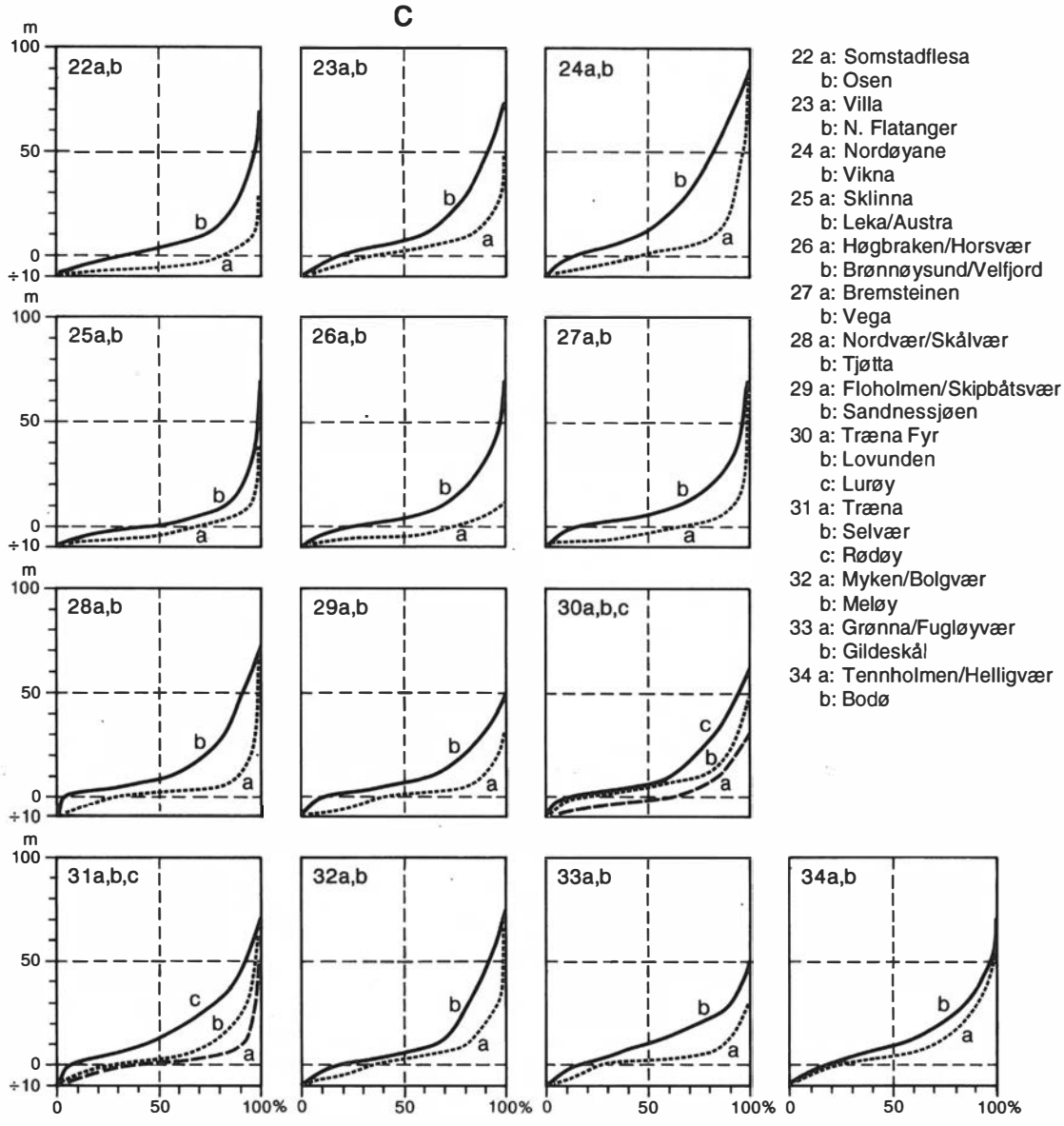

Fig. 5c.

Certain strandflat levels continue into the fjords and there are two possible explanations in this: either they represent strandflat development cutting laterally into an already existing fjord, as suggested by Nansen (loc. cit.), or they may mark the bottom of an old valley generation into which another, and younger, valley generation has been cut, and which constitutes the present submarine part of the fjord.

With regard to the assumed presence of several strandflat levels, or remnants of levels, a similar situation is described from western Scotland (Dawson 1994), except that here the platforms are tilted. The islands of Tiree and Coll in the Inner Hebrides are dominated by staircases of glaciated rock-platform surfaces, which are interpreted as strandflat areas. Eroded remnants of these are thought to be represented further east in the Inner Hebrides. The platforms exhibit differential glacioisostatic uplift, and are believed to have been formed under at least four separate periods of prolonged intervals of Quaternary cold climate. Horizontal levels are not described in this area.

Time of formation

According to the previous discussion, the main development of the Norwegian strandflat must have taken place during glacial and interglacial conditions, probably during the Late Pliocene and Pleistocene. Studies of ODP cores from the Vøring Plateau (Jansen & Sjøholm 1991) indicate that the first significant expansion of the Scandinavian ice sheet presumably started to form about 2.57 million years ago. The period between 2.57 and 1.2 Ma was dominated by generally constant glacial activity, with small amplitudes between glacials and interglacials. After 1.2 Ma the glacial activity increased, and after 0.6

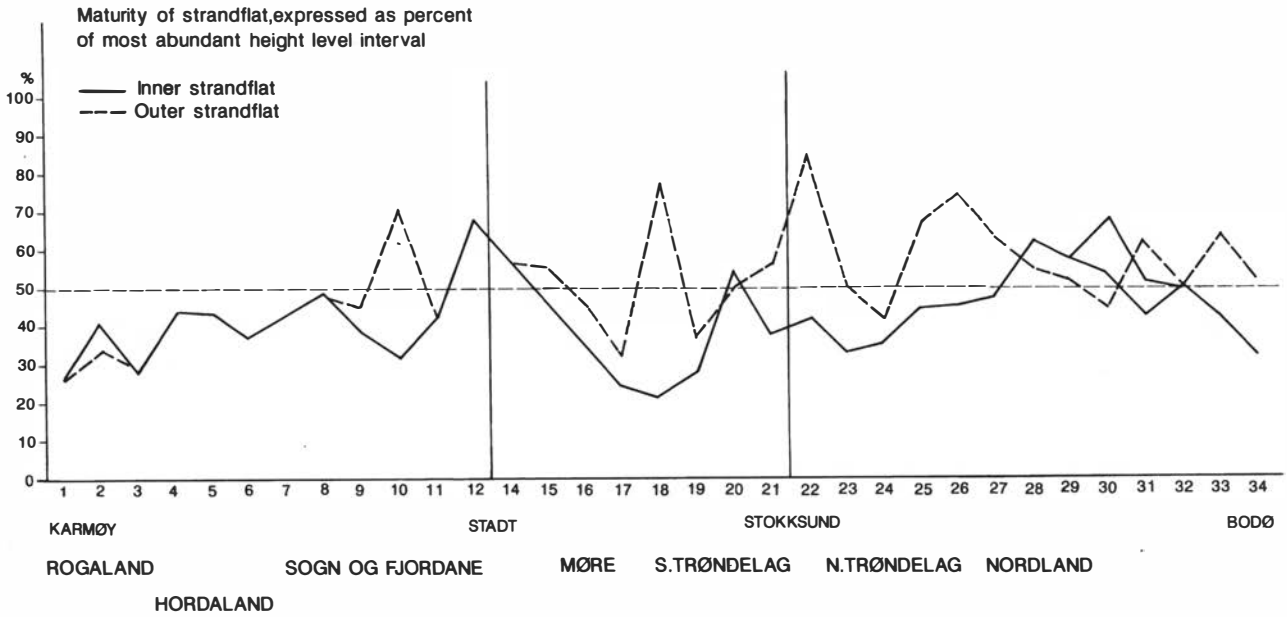

Fig. 6. Maturity of strandflat, expressed as percent of most abundant height interval.

Ma the climatic conditions were characterized by short, warm interglacials between significant glacials. Which of these periods had the most favourable conditions for a strandflat development is still an open question.

As mentioned by Nansen (1904, 1922) and others, including the present writer (H. Holtedahl 1960a, b, 1967, 1975, 1993; Larsen & Holtedahl 1985), it seems likely that the original preglacial coastal landscape was, to a great extent, broken up into fjords and sounds prior to the strandflat formation. A number of trough-like depressions in the submarine strandflat are most likely caused by glacial erosion, and are difficult to explain without the existence of surrounding high land (Fig. 14). The fact that the strandflat is more or less well developed on all sides of the islands also indicates that the islands were formed before the strandflat. The continuation of the strandflat into fjords points to the same conclusion. A very active stage of glacial erosion must therefore have occurred at an early stage of the strandflat development.

Porter (1989) pointed out that the most active period for development of the strandflat was neither during glacial maxima, nor during interglacials, but mainly at times of 'near-average Quaternary glacial conditions'. This was based on the marine isotope record. In W. Norway, the western margin of the reconstructed average ice sheet was thought to be located in a position similar to the ice margin of late-glacial time, between about 12,000 years ago and the Younger Dryas maximum at about 10,500–10,200 yrs BP.

The main gradient of the strandflat, as it is roughly measured in the Møre area, based on knickpoint values (Fig. 10), seems to fall close to the gradients of the 12,400 yrs BP line and somewhat above the 10,300 yrs BP line (Younger Dryas or Main Line, Svendsen & Mangerud (1987)). During this time, i.e. Older and Younger Dryas chronozone, climatic conditions were especially favourable for physical weathering, especially frost shattering of rock material (Reite 1980; Rasmussen 1981; Larsen et al. 1988; Dawson 1980, 1994; Blikra & Longva 1995). A climatic situation somewhat similar to the Late Weichselian may therefore have been favourable for the development of the strandflat further back in time.

The partial horizontality of the strandflat, typical for the peripheral areas in the south, but also for the inner parts in the north, requires denudation during a stable situation of the Earth's crust. The most likely time for this is an interglacial, or interstadial. This does not necessarily come in conflict with the conclusion above. What it does show, however, is that coastal denudation can also be active during these milder phases, a phenomenon which can readily be demonstrated along many parts of the present coast today. Nansen (1922) had some difficulty in explaining the horizontality of his various strandflat levels: 'We are thus led to the conclusion that the strandflat has been developed chiefly during interglacial periods with cold climates, and especially during the very cold time preceding each glacial period, and during its first part, before the outer coast was covered by the inland ice, and as long as the level of the shoreline still remained stable.'

The reason for the difference in development of the strandflat north and south of Hitra (Figs. 9, 10) is not clear. One factor may be lithology, but the variation in rock types is not so significant as to explain the difference. The major part of the coastline under consideration consists of crystalline rocks of Caledonian or Precambrian age, where the resistance to erosion and other strandflat-forming processes is more dependent on the structural pattern than on lithology.

Fig. 7. Strandflat with 'knickpoint' at the island of Kinn, Sogn og Fjordane (zone 11). Photo: I. Aarseth.

Another, and possibly more important factor is a difference in climate. Again, referring to the Younger Dryas stadial, conditions in northern Norway were especially favourable for the cutting of shorelines in bare rocks (Rasmussen 1981). These special conditions could be explained by the position of the summer sea-ice limit, which, according to Jansen et al. (1983) was situated somewhere along the coast of northern Norway during this time.

The time aspect, as well as oceanic exposure, may also be considered. In this connection it may be mentioned the increase in strandflat maturity which occurs going northwards from Karmøy to Stadt (Fig. 6). Most of this coast faces the Norwegian Channel and the enclosed North Sea, but with the northern parts more exposed to the open Norwegian Sea. The existence of a Skagerrak glacier filling the Norwegian Channel during long periods (E. L. King, H. P. Sejrup, pers. comm.) may also be of importance in explaining this difference in strandflat development.

The coastal landscape prior to strandflat formation, and origin and uplift of the paleic surface

In any discussion of age and processes related to the formation of the strandflat, the question of the pre-strandflat landscape becomes pertinent. Obviously, a coastal base-levelled plain, produced by subaerial denudation, would need less alteration to gain the features of a strandflat, than a coast with lofty mountains.

To approach the problem of reconstructing the coastal landscape in pre-strandflat times, a contour map marking a smooth surface touching the most westerly summits was constructed (Fig. 11). The surface is extended into the sea, towards the boundary between the crystalline basement and overlying, mainly Mesozoic sedimentary rocks, thus defining a maximum height and extent. (The reconstruction was based on aeronautical charts – ICAO–1,500,000, Statens Kartverk.) This surface represents the most western part of an uplifted planation surface (paleic surface Gjessing 1967; Base Tertiary surface Doré 1992; Mesozoic peneplain Riis 1996), which is especially well preserved in central parts of southern Norway. As can be seen from the map, as well as from profiles drawn mainly normal to the coast (Fig. 12a–c), there is great variation in the gradient of the sloping plane.

In the Karmøy region (Fig. 12a, zones 1 and 2) the slope has a low gradient, and the vertical distance between the surface of the strandflat and the hypothetical paleic surface cannot be very great. This assumption may be supported by the occurrence of a downfaulted sedimentary basin of Late Palaeozoic/Early Mesozoic (?) age, within the strandflat area (Bøe et al. 1992). Northwards, towards the Sognefjord, the slope is moderate, with the exception of the areas at the outer part of the Hardangerfjord (zone 4) where lofty mountains occur (H. Holtedahl 1975). The strandflat farther north, towards Stadt and along the Møre coast (Fig. 12a, b), is fringed by fairly high mountains (zones 9–17).

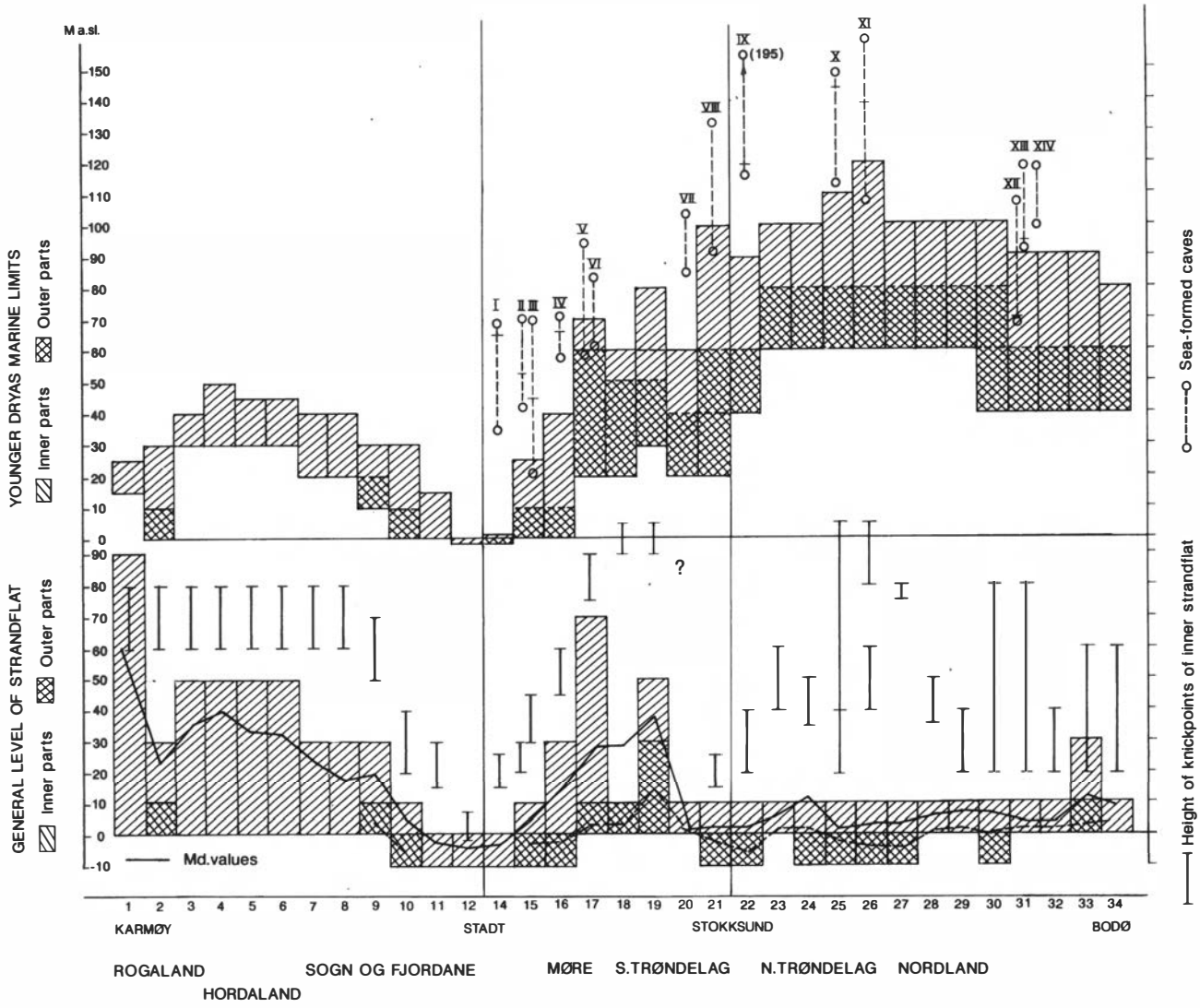

Fig. 8. Variation in general, median, and knickpoint levels of strandflat along the coast between Karmøy island and Bodø, compared with levels of Younger Dryas marine limits and some sea-formed caves.

Very different conditions exist along the Trøndelag coast, where the very extensive and mature strandflat areas of Smøla, Frøya and Sula (zones 18–20) have a surface assumed to be not far below the reconstructed paleic surface. The occurrence of downfaulted Mesozoic rocks connected with the Møre–Trøndelag Fault Zone in the Edøyfjord south of Smøla, and in the Beitstadfjord area in the inner part of the Trondheimsfjord (Bøe & Bjerkli 1989), perhaps suggests a boundary between basement rocks and overlying Mesozoic sediments, which was situated not far above the present surface. The same may be the case in the N. Frøya–Sula–Frohavet area.

The slope of the reconstructed paleic surface from Villa–Flatanger to south of Vega (zones 23–26) has a low gradient and a mature and well-developed strandflat. Further north, islands occur on the peripheral outer strandflat, rising from sea level to altitudes of 700–800 m, e.g. Vega (zone 27): 852 m a.s.l., Dønna (zone 28): 838 m a.s.l., Lovund (zone 30): 621 m a.s.l., Træna (zone 31): 330 m a.s.l., Landegode (zone 34): 803 m a.sl., (Fig. 13). If the paleic surface reconstruction incorporates these very peripheral islands lying a short distance from the Mesozoic boundary, it requires a very high gradient. This is not unfeasible, however, considering the angle of the Mesozoic sediments, and the existence of local faults (Sigmond 1992).

The formation of the planation surface (paleic surface) must represent a very long period of base-levelling. According to Doré (1992), the evidence for repeated landmass rejuvenation in the Tertiary suggests little scope for the extended period of stability which is required to form such a widespread surface. It is proposed that the surface more probably developed during the great rifting events of the Jurassic, after which there was a long period when relief was progressively reduced. These events were followed by the major transgression of the Late Cretaceous, with flooding of the continental margin, and deposition of sediments indicating that any remaining areas of relief were subdued.

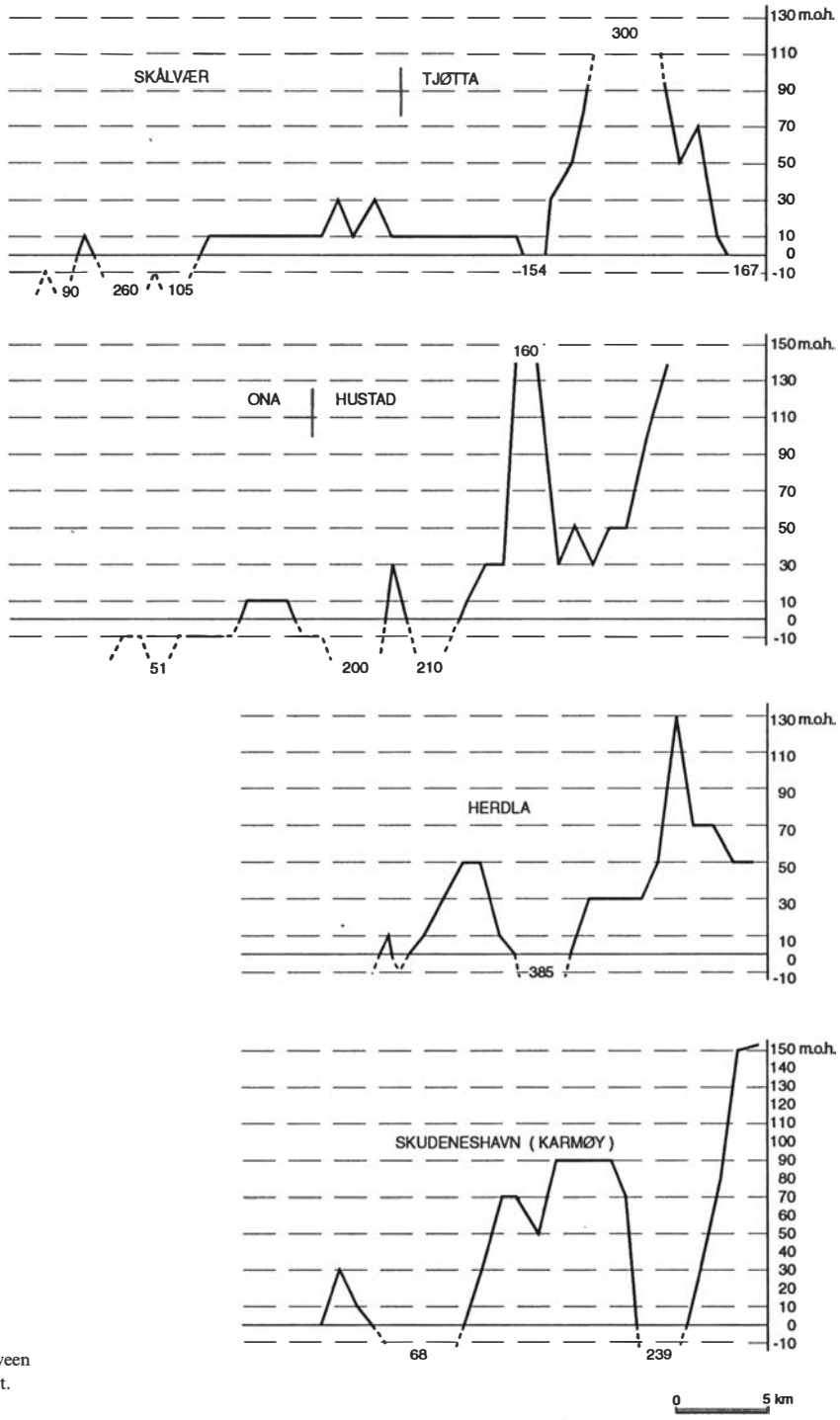

Fig. 9. Simplified sections of strandflat along the coast between Karmøy and Bodø, showing general level and development.

The extent to which Mesozoic sediments covered the present peripheral land areas is unknown, but the presence of downfaulted Mesozoic occurrences, on the strandflat, as well as further inland, strongly suggests a previous continuation of these younger deposits inland.

The 'paleic stage' is traditionally characterized by gentle, well-rounded mature landforms, produced mainly by weathering and mass movements in a semi-arid climate. From the mountain massives, with a certain relief in the central parts of the landblock, the landforms diminished in relief and sloped gently away towards the peripheral parts. The coastal areas are expected to have had a smooth surface with gentle forms.

The Norwegian strandflat is generally believed to be younger than the cessation of the Tertiary uplift of Scandinavia. The actual timing of this uplift has caused much discussion. Strøm (1948) assumed the existence of old surfaces, as the result of two cycles of erosion, and two phases of uplift, tentatively in the Miocene and Pliocene. A late Cenozoic oblique uplift is mentioned by other authors (O. Holtedahl 1953; Gjessing 1967; Peulvast 1985). According to Peulvast (1985), a flexure hinge

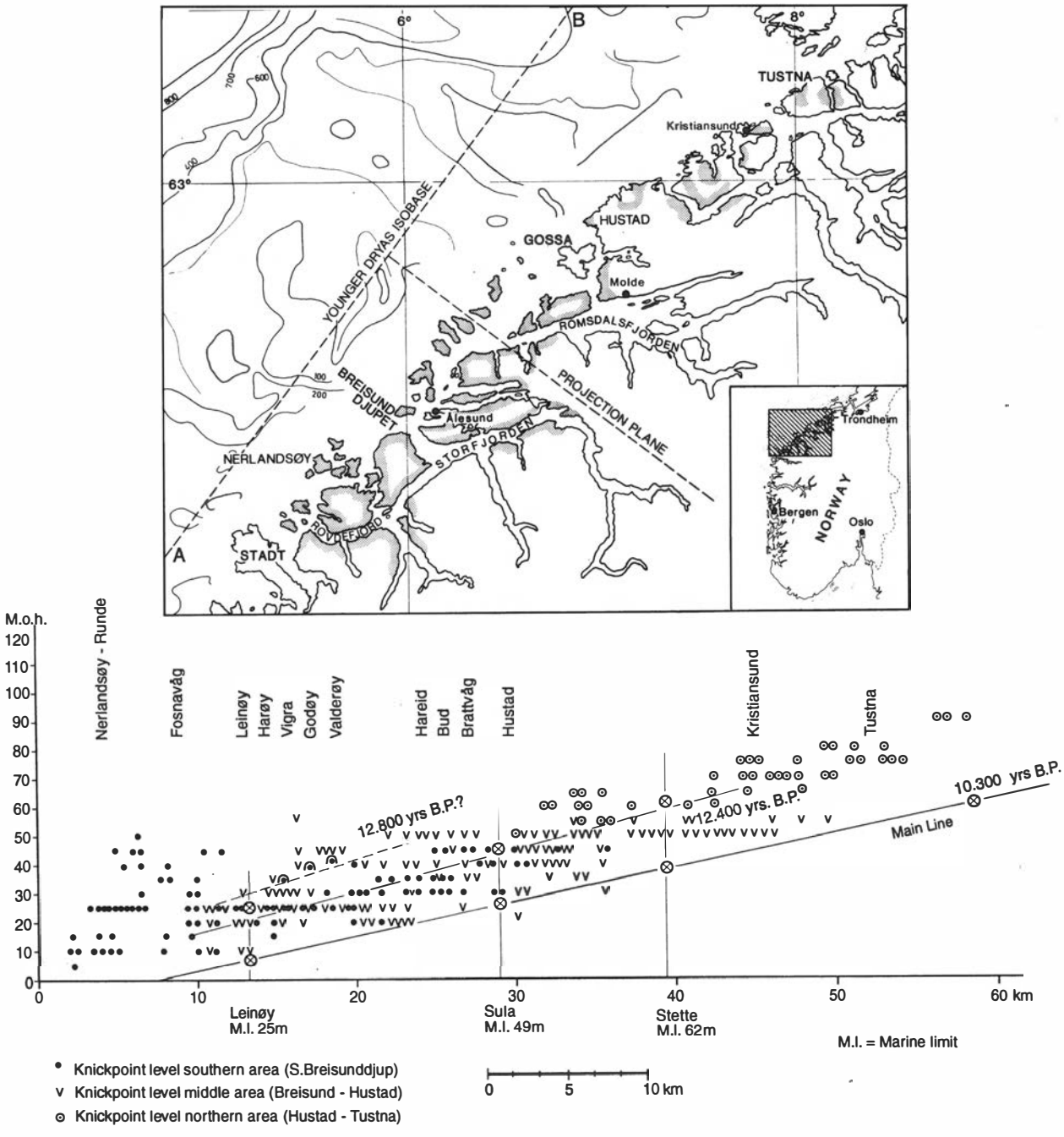

Fig. 10. Approximate levels of inner strandflat (knickpoint), projected on plane normal to Younger Dryas isobase in the Møre area. Symbols representing Stadt–Breisunddjupet, Breisunddjupet–Hustad, Hustad–Tustna. Shoreline diagram after Svendsen & Mangerud (1987). Based on aneroid readings and 1:5000 scale maps with contour interval 5 m. Shading shows analysed areas.

line, related to the oblique uplift, is located off the outer edge of the strandflat.

Torske (1972) suggested a pre-Eocene age for the uplift, whereas Stuevold et al. (1992) believed the uplift started in the Late Oligocene. A strongly episodic nature of Tertiary sedimentation adjacent to the landmass was stressed by Doré (loc. cit.), indicating periods of accelerated rejuvenation. Rundberg (1989) identified important rejuvenation phases occurring in the Palaeocene, Late Eocene–Early Oligocene and Pliocene times.

A Late Pliocene uplift phase, depositing large prograding wedges on the whole of the Mid-Norwegian shelf, was suggested by Riis (1992), Riis & Fjeldskaar (1992) and Riis et al. (1990), assuming the uplift to be mainly due to isostatic re-equilibration after glacial erosion.

Similar sediment wedge build-ups off Mid-Norway were studied by Poole & Vorren (1993), who associated the wedges with an uplift of the mainland during the early Late Pliocene (Mid-Pliocene, ca. 4 My?) and during the Late Pliocene, the latter uplift associated with a glacial phase, indicating large continental ice sheets reaching coastal areas. According to Poole & Vorren

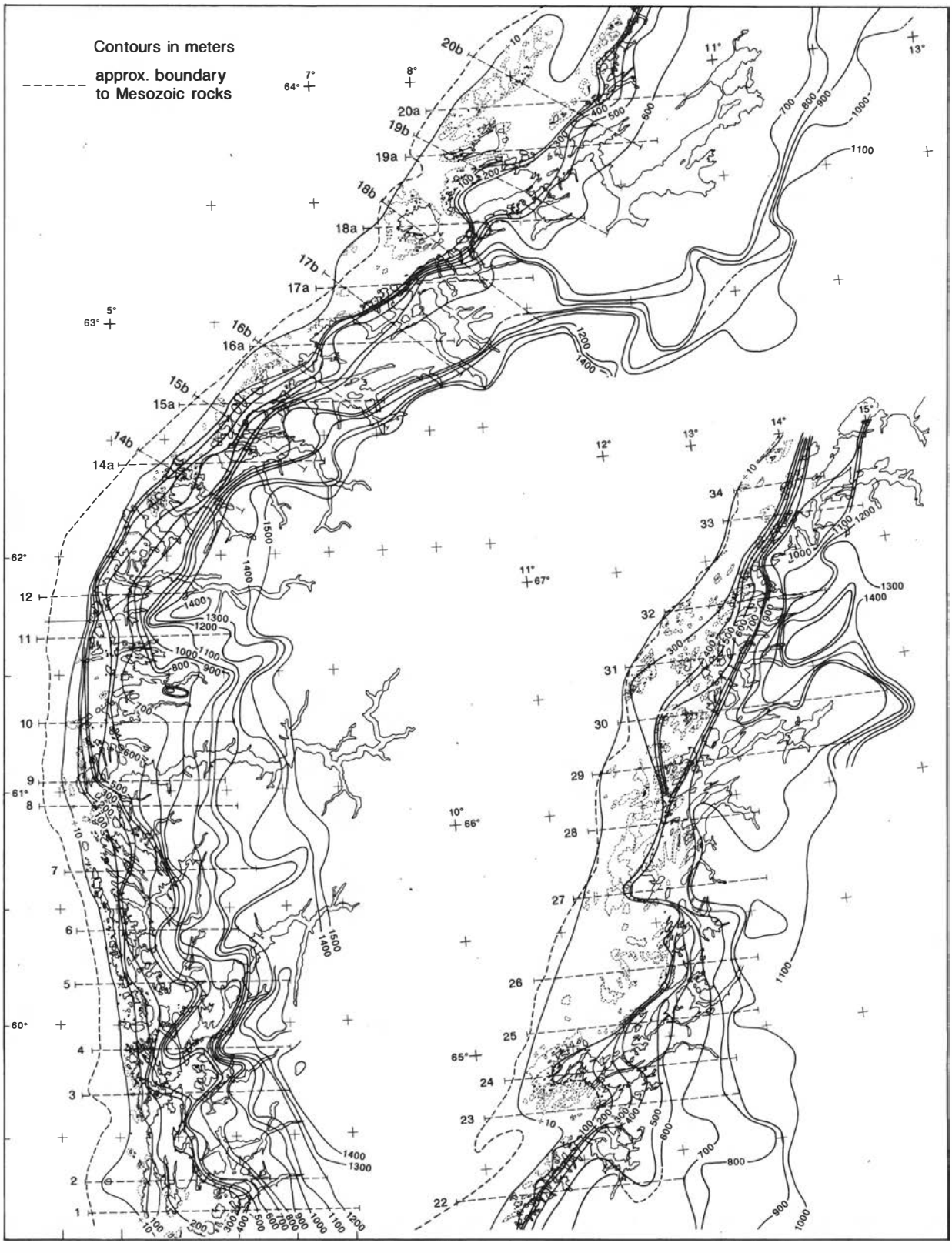

Fig. 11. Contour map showing reconstructed pre-strandflat (paleic) surface. Contour interval 100 m.

(1993), it is highly probable that the strandflat started to form during the Late Pliocene, caused by large-scale frost shattering.

Considering that the strandflat formation to a large extent is associated with a glacial climate, and with a development going back to the Late Pliocene, this agrees well with studies of ODP cores from the Vøring Plateau in the eastern Norwegian Sea (Jansen & Sjøholm 1991).

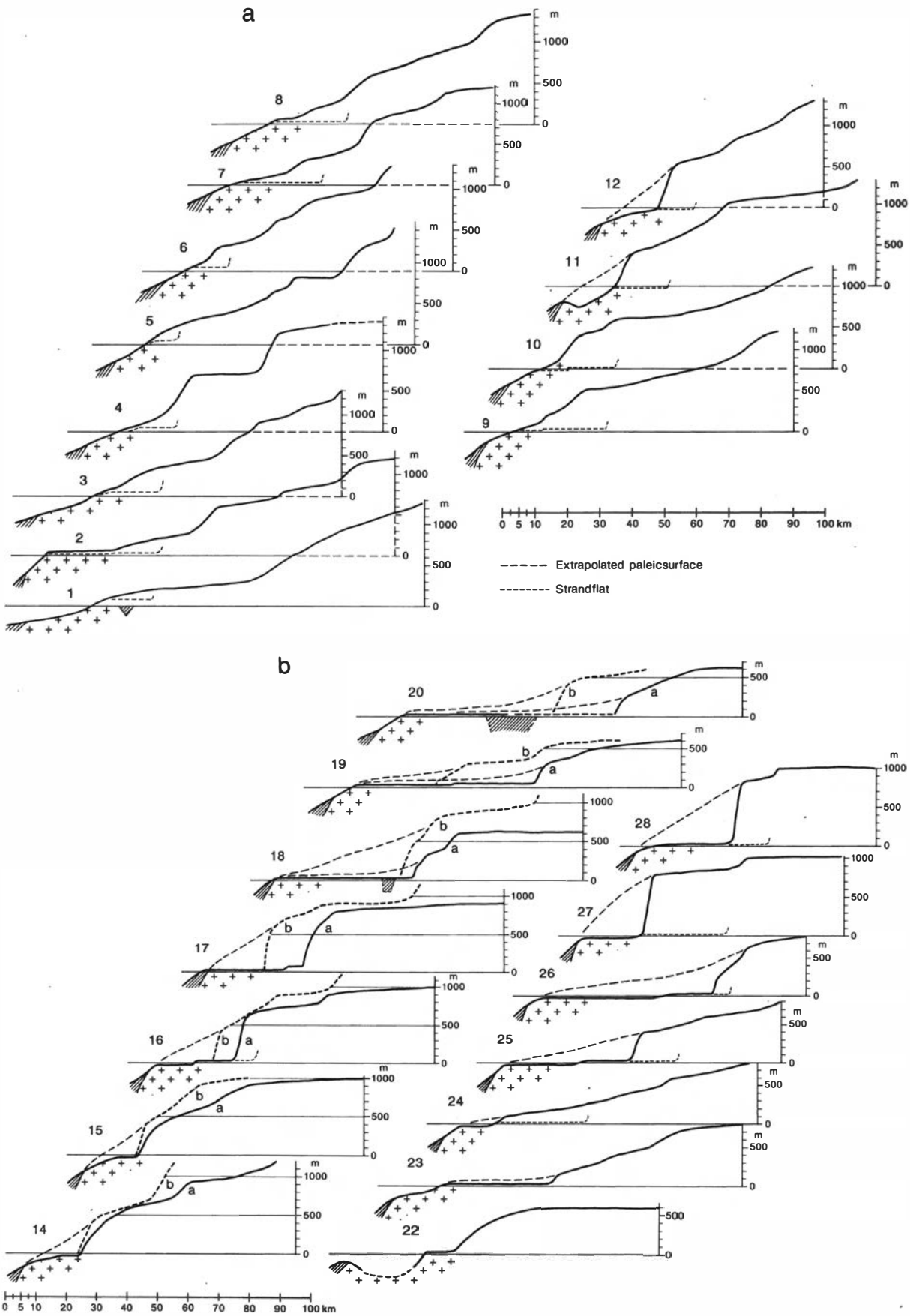

Fig. 12 (a–c). Profiles of reconstructed paleic surface. (a) Karmøy-Stadt, (b) Stadt–Nordvær, (c) Nordvær–Bodø. Location see Fig. 11. The surface is extended towards the boundary between the crystalline basement and overlying, mainly Mesozoic, sedimentary rocks.

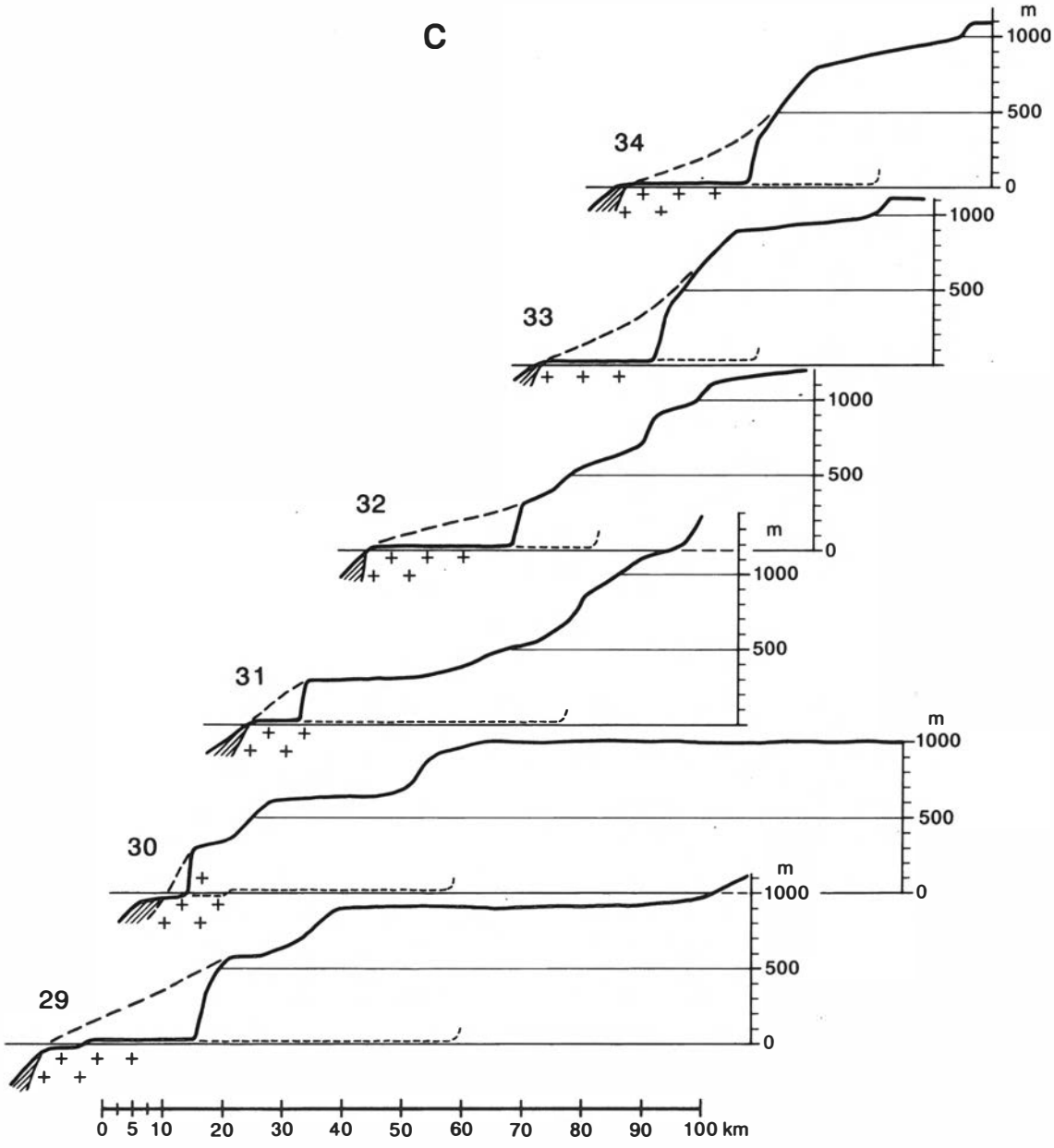

Fig. 12c.

Through studies of influx of ice-rafted material, an intensification of glaciation at about 2.75 Ma was shown to have taken place.

The development of the landscape of the western Scandinavian landblock during uplift phases of the Tertiary, has yet to be worked out. Besides the influence of rejuvenation stages, the development was also dependent on climatic factors. A gradual change from dry, or semi-dry conditions to a more humid and temperate climate facilitated the development of young landforms by fluvial erosion and transport agents, before the glacial processes became the most dominant factors. The old paleic landforms are, however, thought to be well preserved in many parts of Norway (Gjessing 1967), and suggestions of the existence of mature preglacial valleys, belonging to the paleic landscape, have also been put forward by many authors (Ahlmann 1919; Gjessing 1967; H. Holtedahl 1975). This is based on morphological criteria only, as dating of these features has not been possible. Nesje et al. (1992) and Nesje & Whillans (1994) mapped the paleic surface in the Sognefjord area and concluded, on the basis of volume estimations, that a paleic drainage basin had been developed prior to the Quaternary glaciations.

The significance of exhumation of a pre-Jurassic denudation surface: a discussion

As shown above, the reconstructed paleic surface had, in certain areas along the coast, a very moderate slope,

Fig. 13. Strandflat with projecting mountains (norw.: 'nyker') in the island group Træna (profile 31). Photo: Fjellanger Wideroe A/S.

approaching the present strandflat level. Down-faulted blocks with Mesozoic, partly marine sediments, were present in some of these areas, suggesting a coastline to the east of the present one, and a cover of sediments, which later were removed by denudation. The strandflat in these areas, as exemplified by the great width in the Smøla island region, can be explained, either by a relatively small modification of the paleic surface or, more likely, by exhumation and some further erosion of a pre-Jurassic crystalline basement surface.

Morphological features of the strandflat are thought to have been modified in the time subsequent to exhumation, by glacial or other processes. Precambrian or Caledonian crystalline bedrock is usually strongly fractured, and the topography is very irregular, with depressions and steep-sided valleys following the structural pattern. The surface is partially smoothed by glacial scouring, but the main features are structurally controlled. An example is shown in Fig. 4A from the island Sotra, west of Bergen. Recently, a thin zone of down-faulted Late Jurassic sediments was discovered under a fjord in this area (Fossen 1995). It is believed that preglacial, possibly pre-Jurassic, deep weathering, especially along fracture zones, or other weakness zones, with subsequent denudation, can explain some of these special morphological features. It is questionable whether features on the submarine strandflat can be explained in the same way (Fig. 14). The importance of a preglacial regolith in explaining present landscape forms was suggested by Asklund (1928) for southern Sweden and the Norwegian strandflat, and has later been discussed in relation to landscape forms in Fennoscandia generally (Fogelberg 1985).

In conclusion, it follows that certain strandflat areas, especially on the coast of Karmøy and Trøndelag, possibly also other areas where down-faulted Mesozoic sediments occur, can be partly explained as a result of exhumation and some further erosion of a pre-Jurassic denudation surface. The explanation cannot, however, be accepted in the coastal areas where fairly high mountains exist on the peripheral parts of the strandflat. The reconstructed paleic surface here is, as shown above, fairly steep. As the strandflat is well developed in these areas, great volumes have been removed by the strandflat-forming agencies.

Conclusion

The strandflat was most likely formed in Late Pliocene/Pleistocene times, i.e. during the last 2.57 Ma. The preglacial (paleic) coastal landscape varied greatly. Some areas flattened out towards sea level, with a gentle slope-

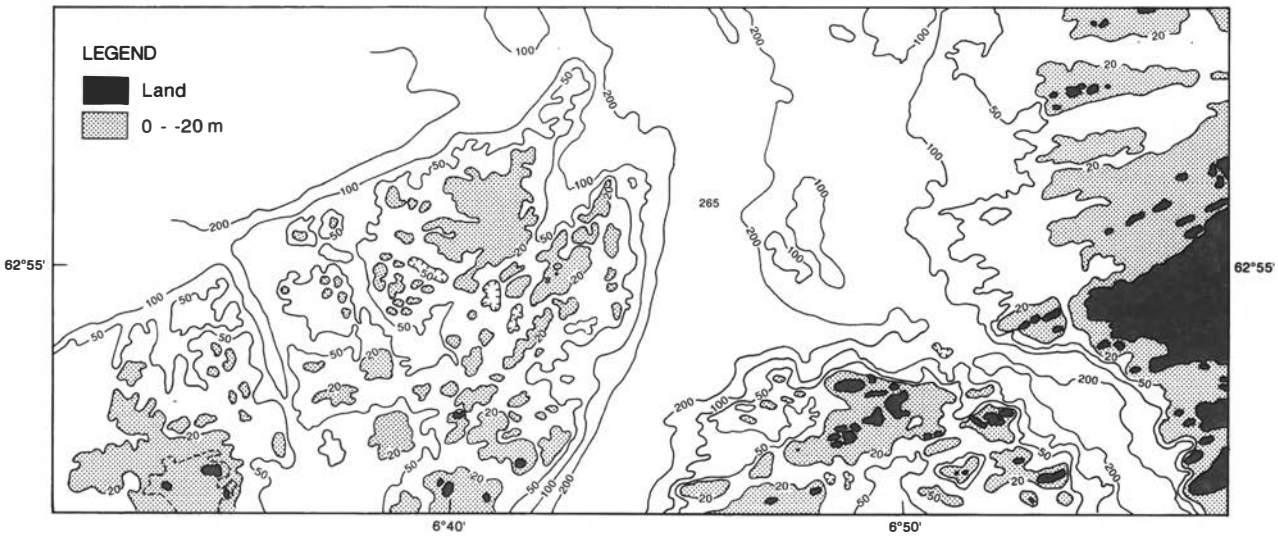

Fig. 14. Submarine strandflat west of Hustad peninsula (zone 16), showing irregular topography, intersected by submarine glacial (?) valleys.

gradient inland. Others had a steeper slope towards the ocean. A fluvial system had developed. In certain areas (Karmøy, Trøndelag) where the paleic surface was close to the present surface, the strandflat may represent an exhumed pre-Jurassic surface.

At an early stage, the coast was intersected by sounds and fjords, largely by the erosive action of glaciers. Further glacial erosion, mainly by local glaciers, was important in reducing the former land area to a low-lying plain, approaching sea level. Subaerial weathering, especially frost weathering, was particularly active during glacial stages, but may also have been important during interglacal or interstadial stages, when the coastal areas were not covered by the inland ice.

Marine abrasion was, no doubt, also an active factor, especially in conjunction with weathering processes in the shore region. This is shown by the usually lower level of the strandflat on the exposed side of islands, than on the lee side. The frequently sharp boundary between the strandflat and cliff behind is also a strong argument for marine abrasion.

The great variation in sea level during the Late Pliocene/Pleistocene, attributable to glacial-isostatic and eustatic movement, greatly facilitated the formation of the strand-flat, and was also a contributory factor to its irregularity. The fact that the general level of the strandflat, especially on the W-coast and the NW-coast, shows a relationship to the Late Weichselian marine limit, suggests that the planation process occurred to a large extent during times when the crust was unstable and isostatically depressed, i.e. during glacial–deglacial stages. A climatic situation similar to that of the Late Weichselian may have been conducive to the development of the strandflat.

Large strandflat areas, emerged and submerged, are planed down to approximate horizontality. They are especially well developed along the N. Norwegian coast, but do also occur south of Hitra island in peripheral parts. The horizontality suggests formation during stability of the crust, i.e. during interglacials or interstadials. The much more mature and developed strandflat along the Nordland coast may be attributable to a climatic difference rather than to lithological factors.

The strandflat is polycyclic, and remnants of higher levels are present close to the backwall in many areas, and also at some distance inside the fjords. A possible connection between these features may exist.

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Appendix I

Sea-formed caves (Fig. 8).

I. Dolsteinhulen, Sandsøy
II. Rønstadhelleren, Lepsøy
III. Sjonghelleren, Valderøy
IV. Gulberget, Hustad, V.Trollhola, Averøy
V. Bremsneshola, Averøy
VI. Duehelleren. Bjungn
VII. Harbakkshulen, Stokksund
VIII. Halvikshulen, Osen
IX. Lispingdalskyrkja, Nordgutvik (Austra)
X. Torghatten, Brønnøysund
XI. Hestmanøy, Hestmona
XII. Tonneshola, Melfjord