The Norwegian strandflat: A reconsideration of its age and origin

EILIV LARSEN & HANS HOLTEDAHL

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Based mainly on stratigraphical data and information on sea-level and cirque glacier erosion rates, the age and processes for the formation of the Norwegian strandflat are discussed. It is concluded that the main processes are frost-shattering in combination with sea-ice transportation and planation during glacial stages in the last 2.5 Ma.

E. Larsen, Geological Survey of Norway, P.O. Box 3006, N-7001 Trondheim, Norway.
H. Holtedahl, Department of Geology, Section B, University of Bergen, Allegt. 41, N-5000 Bergen, Norway.

Since Reusch (1894) introduced the term 'strandflat' and discussed its origin, a number of scientists have proposed different geneses and ages for its formation. With quantitative data at hand, it is now possible to exclude some of the earlier hypotheses.

It is difficult to define precisely 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 abuts onto a steep slope. In many cases the supramarine strandflat can be seen as a brim of low lying land around islands (Fig. 2).

Along the Norwegian coast, the strandflat is developed from Stavanger to Magerøya (Fig. 1). In this region, its width varies from 50–60 km in Helgeland and the northern part of Møre to a more or less total absence in the Stad area (Fig. 1) (Holtedahl 1959). The strandflat is not confined to the Norwegian coast, but is developed along Arctic and Antarctic coasts in many parts of the world. Nansen (1904) arrived at the conclusion that typical strandflat areas are only found in formerly glaciated regions. This however, has been disputed by Fairbridge (1977), who claimed that shore platforms in formerly unglaciated areas of western France and along the west coast of U.S.A. should be considered strandflats.

A wide range of processes has been suggested for the formation of the strandflat. These include marine abrasion (Reusch 1894), subaerial denudation (Ahlmann 1919, Evers 1962), glacial erosion (O. Holtedahl 1929), frost-shattering and sea-ice erosion (Nansen 1904, 1922), or some kind of combination of different processes (Holtedahl 1959, Klemsdal 1982). Büdel (1978) argued that the strandflat was formed under a tropical climate as an etch-plain with inselbergs.

Clearly, the different processes imply very different ages for the formation of the strandflat, and suggestions have therefore varied from pre-Quaternary to glacial or interglacial stages in the Quaternary. Holtedahl (1959) reviewed the different theories with respect to formation and age.

Age of the strandflat

In the Møre area a number of marine caves are situated above the Late Weichselian marine limit (Holtedahl 1984). The caves are developed in zones of structural weakness on the steep slopes that form the inner limitation of the strandflat. The age of the caves is thus a minimum age for the formation of the strandflat. Recent stratigraphical investigations in the cave Skjonghelleren (Fig. 1) have shown that it contains some 15–20 metres of unconsolidated sediments (Larsen et al. 1984). An excavation in the inner part of the cave down to about 6 metres below the sediment surface shows bouldery beds in alternation with fine-grained laminated sediments (Fig. 3). The laminated beds were deposited subglacially in a waterfilled cave while the bouldery beds were formed during ice-free periods (Larsen et al. 1984). Two ^{14}C dates on fossil bones and three

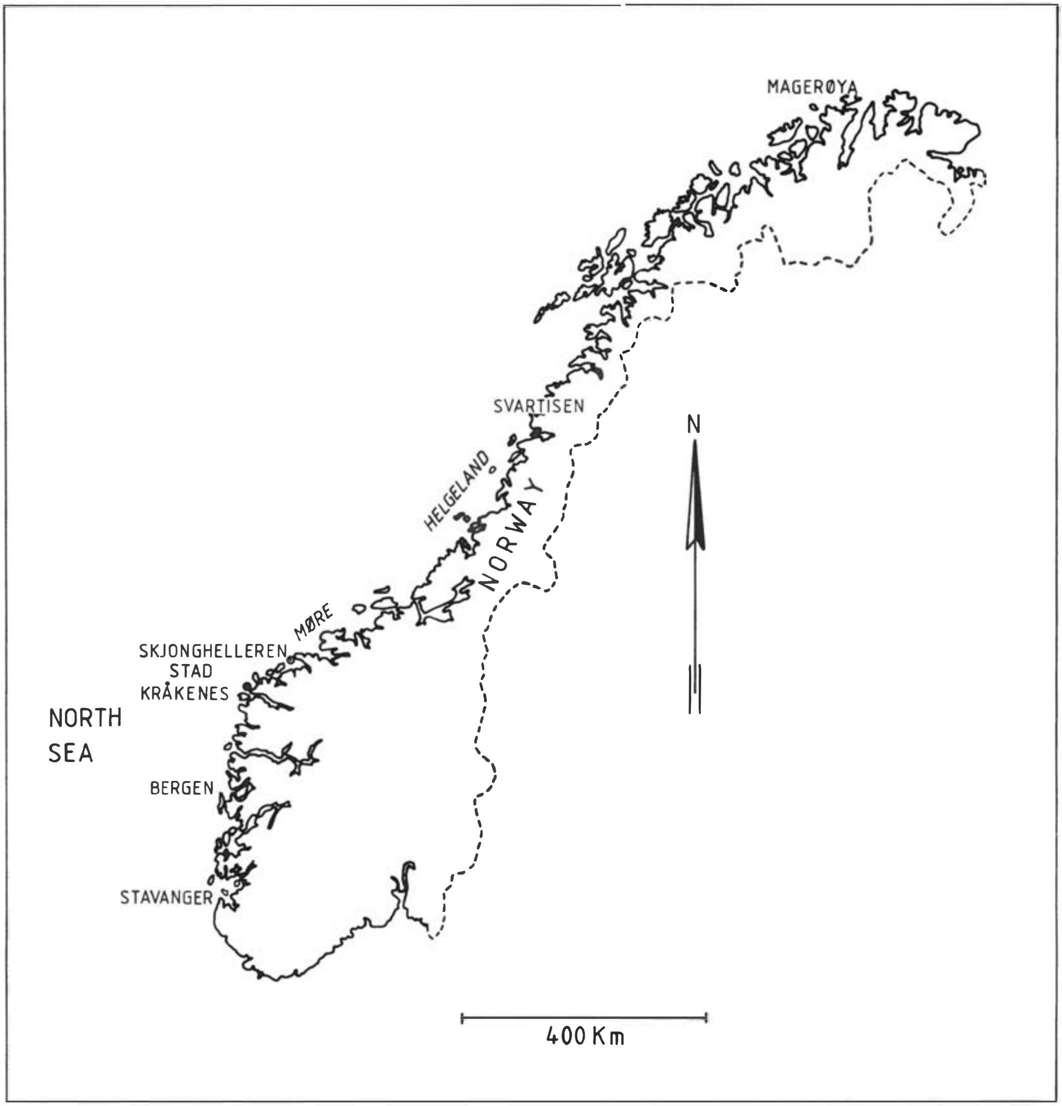


Fig. 1. Map of Norway with geographical names mentioned in the text. The strandflat is developed from the Stavanger area to Magerøya.

U/Th dates on speleothems from the upper interstadial bed all gave ages around 30,000 yrs. B.P. (Larsen et al. 1984, in press) (Fig. 3). This age is thus a minimum age for the formation of the cave. Considering the shallow depth of the dated bed, the nature of the excavated sediments below that bed (Fig. 3), and the total sediment thickness, it is evident that the cave is far older than the age obtained. It has been suggested by Larsen et al. (in press) that the base of the sediment sequence is Early Weichselian, and that the cave was formed during the initial phases of the last glacial stage. If correct, this implies that considerable strandflat development might have taken place in this area in Early Weichselian time and that practically no strandflat development has taken place since then. This seems to be true in spite of the assumption that western Norway was ice-covered only for some 30 % of the last glacial cycle (Miller et al. 1983). Dated sediments located on the strandflat, other than cave sediments, also provide minimum ages for the

Fig. 2. The island of Valderøya with the low brim belonging to the strandflat. The cave Skjonghelleren is situated on the steep mountain slope that abuts on the strandflat. Photo looking south.

formation of the strandflat. No pre-Eemian sediments are known to exist at the Norwegian strandflat, but at Brøggerhalvøya, Spitsbergen, a thick stratigraphical sequence is situated on the strandflat. The oldest sediments have an absolute age between 0.3 and 1 Ma inferred from amino acid ratios in molluscs (Miller 1982). This implies that the strandflat in that area is older than the cited time span.

The Norwegian strandflat must be younger than the cessation of the Tertiary uplift of Scandinavia (e.g. Holtedahl 1959), which provides a maximum age for its formation. Faults in the border zone between the North Sea sedimentary rocks and the crystalline rocks to the east may have been active in Pliocene time or even later (Egeberg 1977). No faults have been detected on sparker records of the Late Pliocene sediments from the northern North Sea (Rokoengen & Rønningsland 1983). This implies that Late Pliocene tectonic movements either took place solely within the basement area or that they had ceased by Late Pliocene time. It is, however, reasonable to assume that a subsidence of the North Sea occurred in connection with the Tertiary uplift (Rokoengen & Rønningsland 1983). This indicates that at least most of the Tertiary uplift had come to an end by Late Pliocene time. From this it follows that the strandflat is younger than the Middle Pliocene. One piece of seemingly conflicting evidence is found in the results from the Fjøsanger section near Bergen (Mangerud et al. 1981) (Fig. 1). Based on stratigraphical reasoning, these authors have determined a net uplift between 10 and 40 metres since the Eemian. Mangerud et al. (1981) concluded that this uplift is mainly a result of longterm tectonic movements, possibly with some additional effect of isostatic compensation for glacial erosion. Holtedahl (1984) is also of the opinion that neotectonic movements have been active and responsible for the high positions of sea-formed caves along the coast of Møre. If back-cutting of cliff walls has kept up with the rate of uplift, there might be no

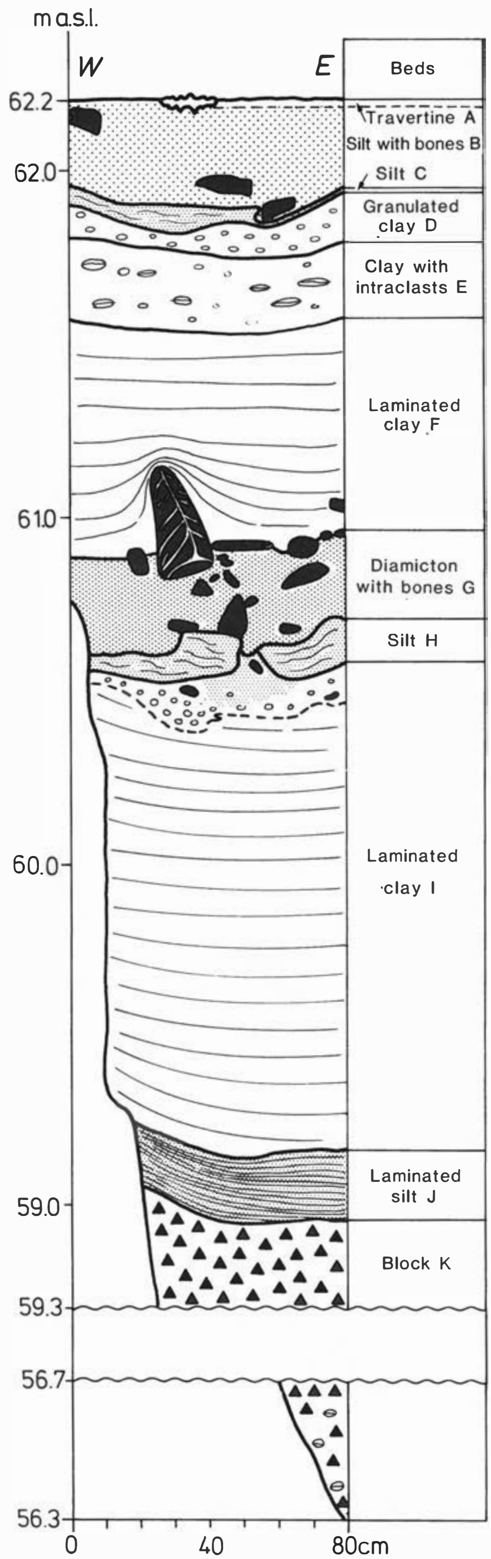


Fig. 3. The sediment sequence in excavation 2 in Skjonghelleren. Two ^{14}C dates on fossil bones and three U/Th dates on speleothems from diamicton with bones G, all gave ages around 30,000 yrs. before present. A nearby coring in the cave shows another laminated sequence underlain by a bouldery bed below block K. Bedrock was reached at 15 m. After Larsen et al. (1984, in press).

conflict. Another point worth making is that the conclusions regarding tectonic movements (Mangerud et al. 1981, Holtedahl 1984) are not quite so straightforward. The uplift deduced from Fjøsanger, for instance, might well have been episodic. There is also the possibility that the Fjøsangerian Interglacial is older than the Eemian (J. Mangerud, pers. comm. 1984), in which case the uplift rate will be greatly reduced. Holtedahl's (1984) conclusion on tectonic movements is based on the assumption that all the high-lying caves were formed at the same time. This assumption cannot be tested at present.

Processes

The different theories for the formation of the strandflat have been listed above. Based on observations in Antarctica, O. Holtedahl (1929) strongly favoured the idea of cirque glaciers cutting backwards into mountain slopes. This was later supported by Dahl (1947). From measurements of the volume of sediments deposited from a Younger Dryas cirque glacier at Kråkenes (Fig. 1), Larsen & Mangerud (1981) found that the erosion rate of that glacier (0.5–0.6 $mm \cdot a^{-1}$) was in accordance with the estimated rates from modern and other former glaciers. Using this erosion rate, an estimate of 65 to 80 Ma is obtained for a cirque glacier to erode 40 km backwards. The erosion rate of Larsen & Mangerud (1981) is a mean for the whole glacier bed, and the backward erosion is thought to have been somewhat greater. Even if the coast were to a large extent dissected into fjords before the Quaternary (e.g. Rokoengen & Rønningsland 1984), so that cirque erosion could have started from many sides, the erosion rate is so low that cirque glacier erosion can be excluded as the main process for strandflat formation. This is certainly also true for the French and the U.S. west coast strandflats (Fairbridge 1977). Along the south shore of the St. Lawrence an extensive strandflat has developed, but there is no relief for cirque glacier formation; thus in this area this factor can be excluded (Fairbridge 1977). There is, however, no doubt that cirque glacier and ice-sheet erosion have to a large extent modified the strandflat, but we conclude that the feature itself is non-glacial.

In the very first paper on the strandflat, Reusch (1894) interpreted the feature to be a result of wave abrasion. Extensive strandflats were later described from areas sheltered from wave erosion (e.g. Holtedahl 1959, Fairbridge 1977, Hansom 1983). Hansom (1983) also shows that the modern strandflat of South Shetland Islands, Antarctica, is best developed in the more sheltered locations due to a longer persistence of winter sea-ice. From this, it is inferred that wave abrasion was also of secondary importance in strandflat development. Along the coast of Møre the strandflat seem to be higher at positions sheltered from wave abrasion (Fig. 4). We interpret this as a result of waves being an important secondary process, especially on the exposed sites.

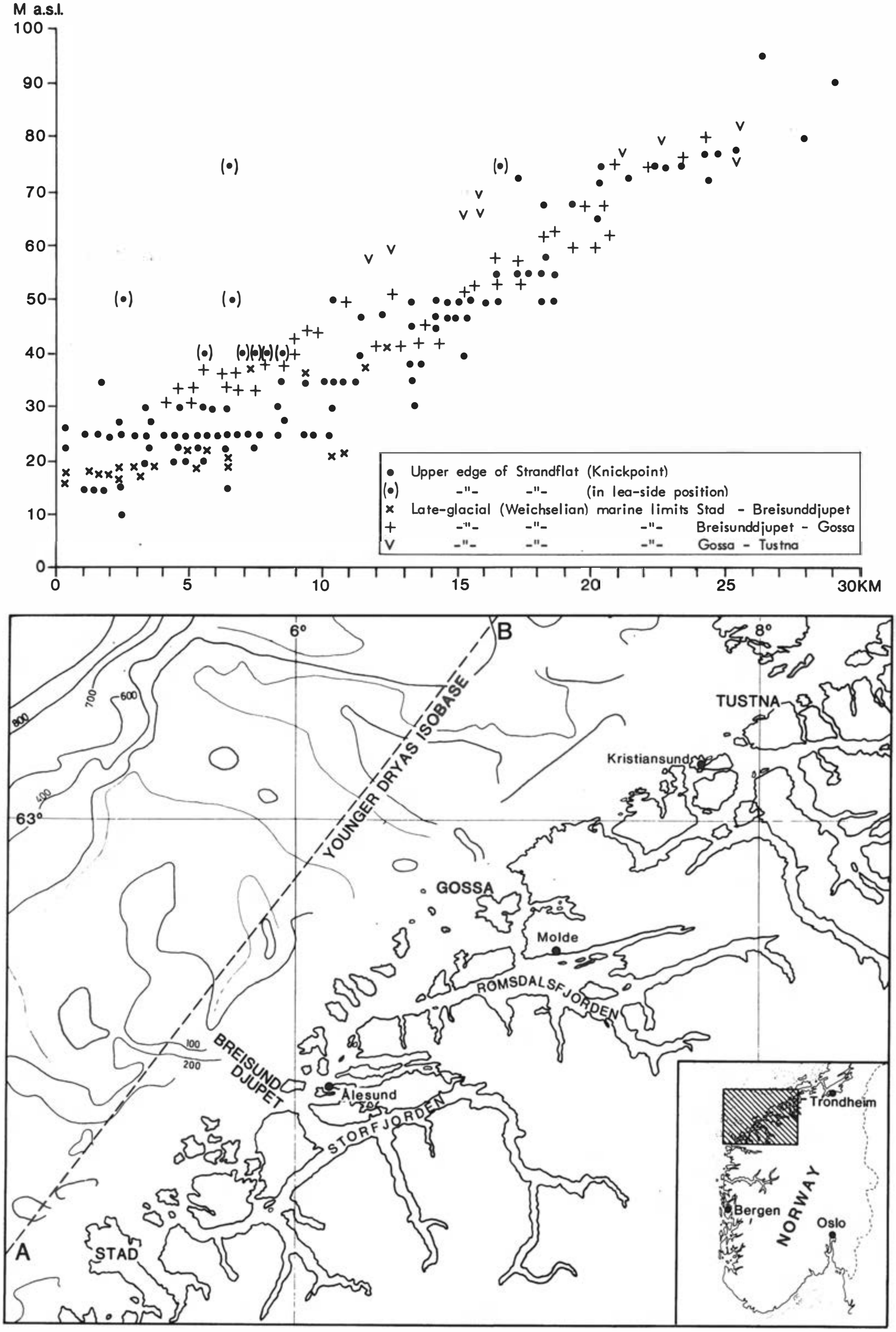
Ahlmann (1919) and Evers (1962) claimed that the strandflat was mainly formed as a subaerial denudation level. Holtedahl (1959) felt that this is to a large extent disproven by the existence of islands with high mountains located within the strandflat far from the coastal mountain range. Later, Büdel (1978) has pointed out that inselbergs are typical for tropical and sub-tropical rock platforms.

Based on observations along arctic coasts, Nansen (1904, 1922) concluded that the strandflat was a result of frost-shattering along the sea cliffs and removal of the material and planation by sea-ice and wave abrasion. Nansen (1922) also noted that the strandflat was developed in areas sheltered from any considerable wave action, and he thus tended to give sea-ice, in combination with frost-shattering, prime importance. Floating ice forms an 'ice-foot' along the shore (Bentham 1937). In this way it may incorporate boulders and other loose material on the shore which is then removed by the ice as this moves along or away from the shore due to currents. In places where tidal activity is strong, blocks frozen into the ice may be lifted from the bedrock during rising sea-level (Fairbridge 1977). Estimates of rates of modern cliff retreat in polar areas vary greatly, from 0.6–0.8 $cm \cdot a^{-1}$ in the South Shetland Islands, Antarctica (Hansom 1983) to 2.5–5.0 $cm \cdot a^{-1}$ in Spitsbergen (Jahn 1961). The Younger Dryas shore-line in the Svartisen area, North Norway, is frequently cut into bedrock (Rasmussen 1981). Rasmussen infers the same processes as discussed here, and calculates a mean cliff retreat of ca. 4 $cm \cdot a^{-1}$. Dawson (1980) has estimated a cliff retreat for the assumed Loch Lomond Stadial rock platform in parts of western Scotland to be about 7 $cm \cdot a^{-1}$. Applying the figure 4 $cm \cdot a^{-1}$ from Rasmussen (1981), it would take some 1 Ma to cut a 40 km wide strandflat.

Discussion and conclusion

It is clear that the inferred maximum age of the Norwegian strandflat (younger than Middle Pliocene) places constraints on the climate during its formation. This, of course, sets limitations as to which processes are the most probable for its development, i.e. the age itself suggests that the strandflat was formed either by cirque glaciation, wave abrasion or sea-ice erosion and frost-shattering.

In the Møre area, where we have concentrated our investigations, there is at least a connection between glacio-isostatic depression of the crust, as recorded from Late Weichselian marine limits, and the elevation of the strandflat (Fig. 4). This strongly suggests that the strandflat was formed during glacial rather than interglacial stages. According to Shackleton et al. (1984), the first major ice-rafting in the North Atlantic occurred at about 2.4 Ma, preceded by a minor pulse of ice-rafting at 2.5 Ma. We thus conclude that the standflat is younger than ca. 2.5 Ma. The time allowed for the formation of the standflat is, however, considerably shorter than 2.5 Ma, since interglacials and periods of total icecover during glacial stages are of less importance. It was concluded previously that cirque glacier erosion and wave abrasion are unlikely to be the main processes which led to the formation of the strandflat. We thus conclude that sea-ice erosion and frost-shattering, as in Nansen's (1904, 1922) model, are most probably the major processes for its formation. Since 2.5 Ma ago, the sea-level has crossed the present sea-level several times. From Rasmussen's (1981) data it was suggested that it would take some 1 Ma to cut a 40 kilometre wide strandflat. We feel that there is sufficient time within the last 2.5 Ma because the strandflat in many places is narrower, and because the formation took place during an increasing dissection of the landscape largely due to glacial erosion. Based on isotope studies on a


M a.s.l.
100
90
80
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60
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40
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5
10
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25
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● Upper edge of Strandflat (Knickpoint)
(●) -"- -"- (in lea-side position)
× Late-glacial (Weichselian) marine limits Stad - Breisunddjupet
+ -"- -"- -"- Breisunddjupet - Gossa
V -"- -"- -"- Gossa - Tustna
6°
8°
B
TUSTNA
Kristiansund
YOUNGER DRYAS ISOBASE
63°
GOSSA
Molde
ROMSDALSFJORDEN
BREISUNDDJUPET
Ålesund
STORFJORDEN
A
STAD
800
700
600
400
100
200
Trondheim
Bergen
Oslo
NORWAY

deep-sea core west of Ireland, Jansen & Sejrup (1984) concluded that global ice volumes were smaller between 0.9 and 2 Ma with a correspondingly higher eustatic sea-level than before and after this time interval. This indicates that the Norwegian coast might have been ice-free during substantial parts of the glacial stages within this time interval, and that the sea-level could have been suitable for strandflat formation. The cited period may thus have been very important for the formation of the strandflat.

From the stratigraphical investigations at Skjonghelleren we inferred that practically no widening of the strandflat has taken place in that area since the Early Weichselian. This is not necessarily true for the entire Norwegian coast between Stavanger and Magerøya. Following our line of reasoning, Rasmussen's (1981) shore-line in the Svartisen area may be considered as part of the strandflat, but since it is the youngest part it is possible to recognize it as an individual shore-line. It therefore seems that the Norwegian strandflat has developed gradually during interstadials and during openings and terminations of glaciations over the last 2.5 Ma, but not everywhere along the coast at the same time. According to Jansen et al. (1983), the summer sea-ice limit during Younger Dryas might have been located somewhere along the coast of northern Norway. This could explain the extensive shore-level formation (and in our terms strandflat formation) during this time interval in northern Norway as compared with southern Norway.

At certain places in Spitsbergen and Antarctica, strandflat formation is taking place today. The French strandflat, if formed by the same processes as the Norwegian, might be associated with maximum glaciations during glacial stages. The point is that even though the strandflats in different areas may largely be of the same age, they might have been formed at different times within the same time interval.

Klemsdal (1982) correctly pointed out that the literature on the standflat reflects a change from emphasizing just one or two processes to a combination of several processes. We tend to favour sea-ice erosion and frost-shattering as the main processes, but, of course, we realize that marine abrasion and glacial erosion have modified the surface.

Fig. 4. Late Weichselian marine limits and inner edge of the strandflat from Stad to Tustna projected on a plane normal to Younger Dryas isobases.

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