Recent moraine formation at advancing temperate mountains glaciers

Implications for the analysis of glacial dynamics and sediment budget calculations

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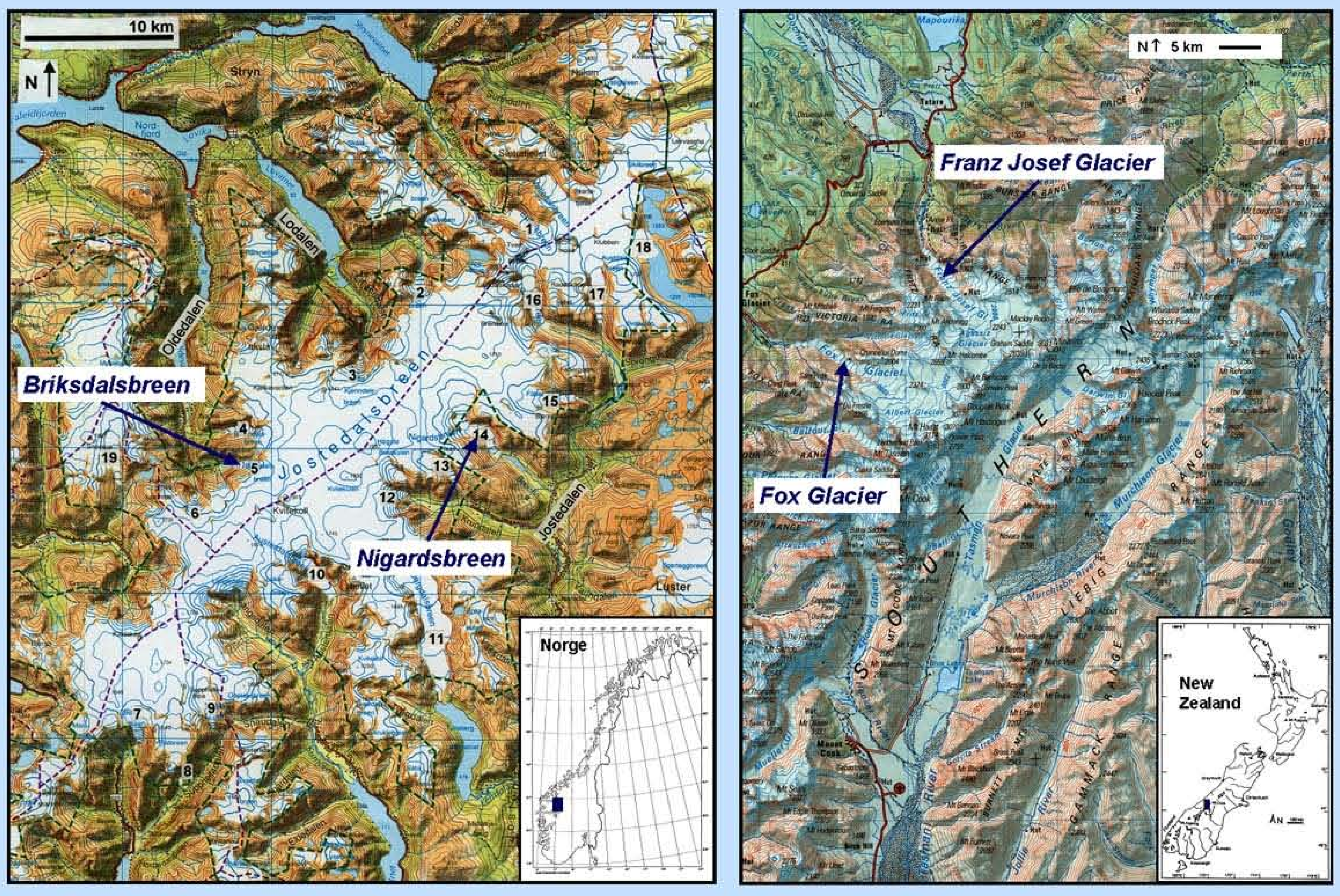
Study areas



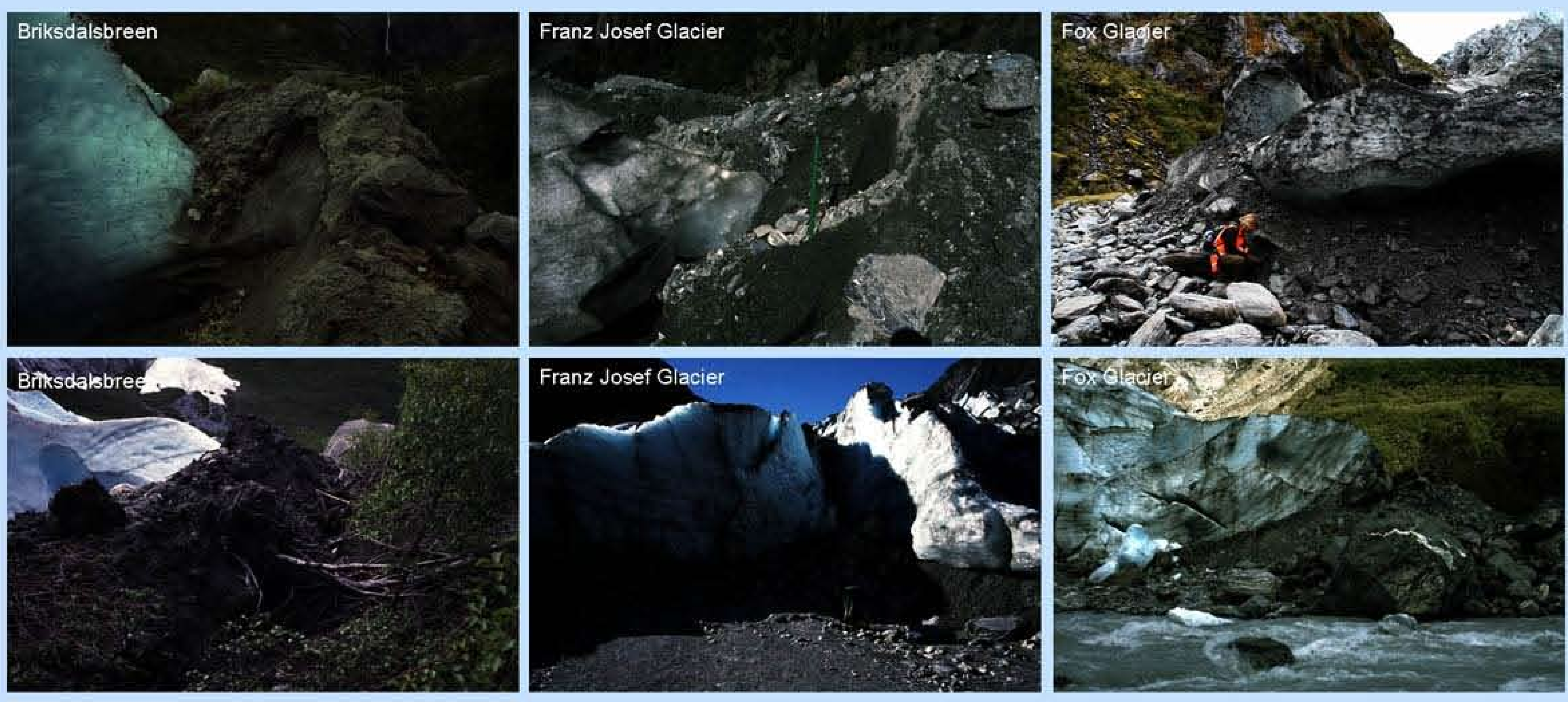
Maps of Jostedalsbreen (left) and central parts of the Southern Alps of New Zealand around the Main Divide at Aoraki/Mt Cook (right). The glaciers mentioned are indicated (*sources: Statens Kartverk, Department of Survey and Land Information NZ*).

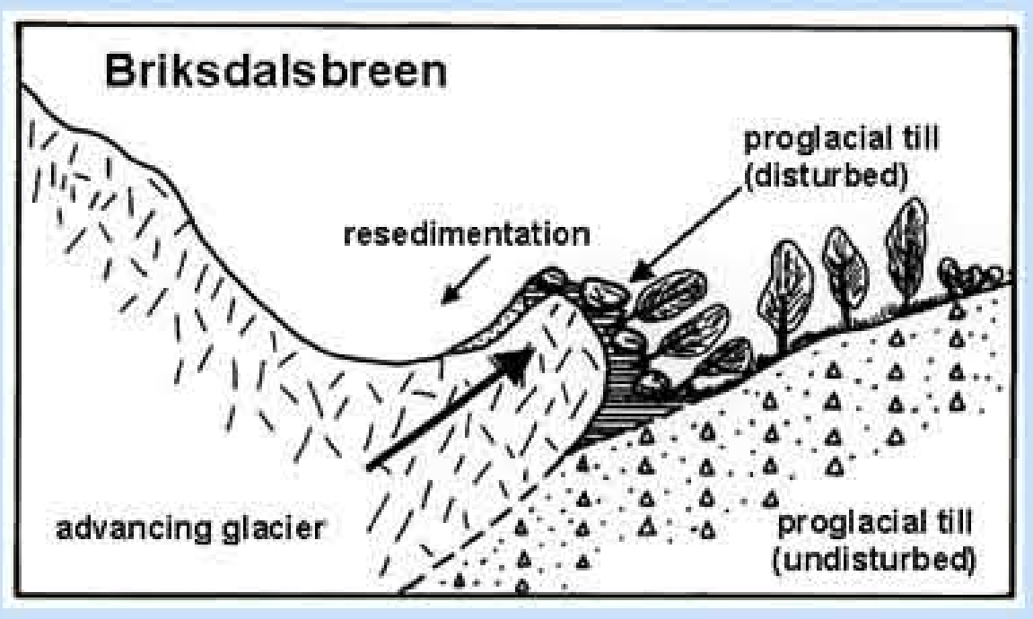
Frontal advance and its reasons

During the 1990s, the short outlets of Jostedalsbreen (as e.g. Briksdalsbreen) experienced a strong frontal advance with annual advance distances of up to 80 m. This advance followed a period since c. 1960 with stationary or slightly advancing frontal positions. The longer outlets participated at this advance after a major retreat period ended in the late 1980s. This widespread frontal advance was a reaction of an overall increase in ice mass during the proceeding decades, and especially since 1988/89. The ice mass gain itself was mainly related to increased winter precipitation.

In New Zealand with its comparable maritime glaciological regime, increased snow accumulation in the accumulation areas was responsible for a parallel advance during the 1990s. This advance was of comparable magnitude to that at Jostedalsbreen (cf. *Chinn et al.* 2005). Since the middle of 2005, a new advance with annual advance distances of up to 90 m takes place in New Zealand after the 1990s-advance had ceased in both study areas around 2000.

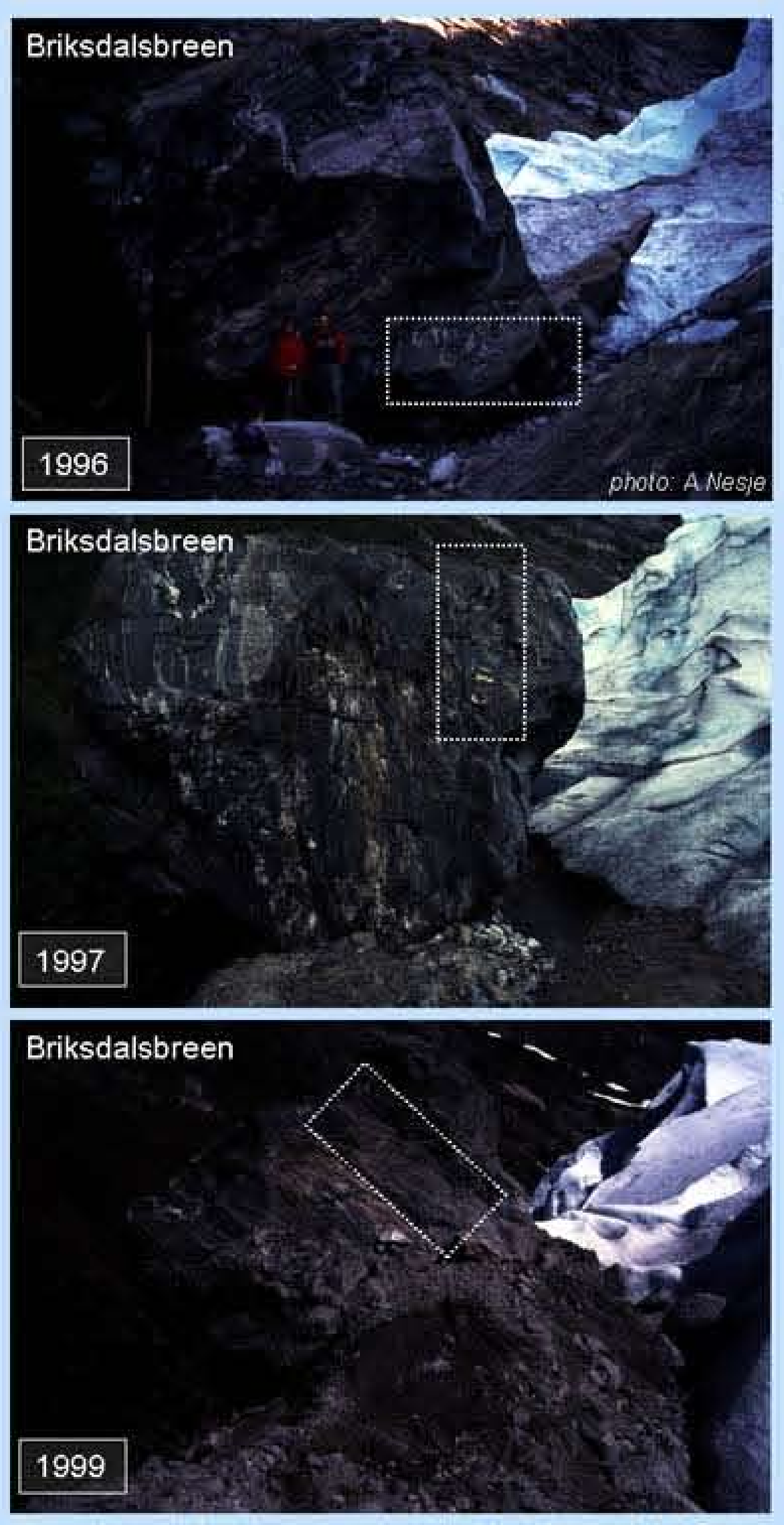
Processes

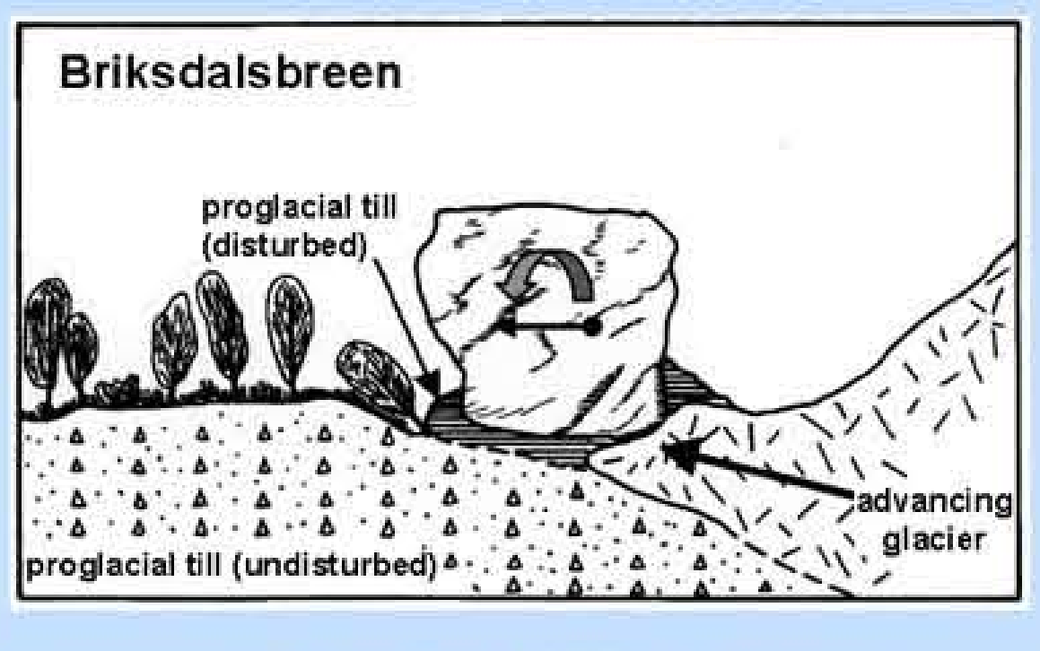




The pressure of the advancing glacier partly directly protruding into the proglacial sediments forced them to be bulldozed up to form end moraines ridges at the glacier fronts. Pre-existing vegetation, remnants of soil and even older Holocene deposits were eventually incorporated. Where the proglacial material showed low shear strength (e.g. fine-grained, water-soaked glaciolimnic material), the resulting end moraine ridge was higher than in other parts of the foreland where sediments had a higher shear resistance (e.g. older glacial till). At no stage, important subglacial debris bands were observed. Therefore, subglacial processes of sedimentation and subglacial deposition are believed to be fairly unimportant.

Marginal subglacial cavities at Briksdalsbreen during the advance showed almost clean glacier ice without any thick subglacial debris bands. In one case, glaciofluvial sediment dated to c. 8,300 cal a BP (fossil wood – *Salix spec.*) was bulldozed up.



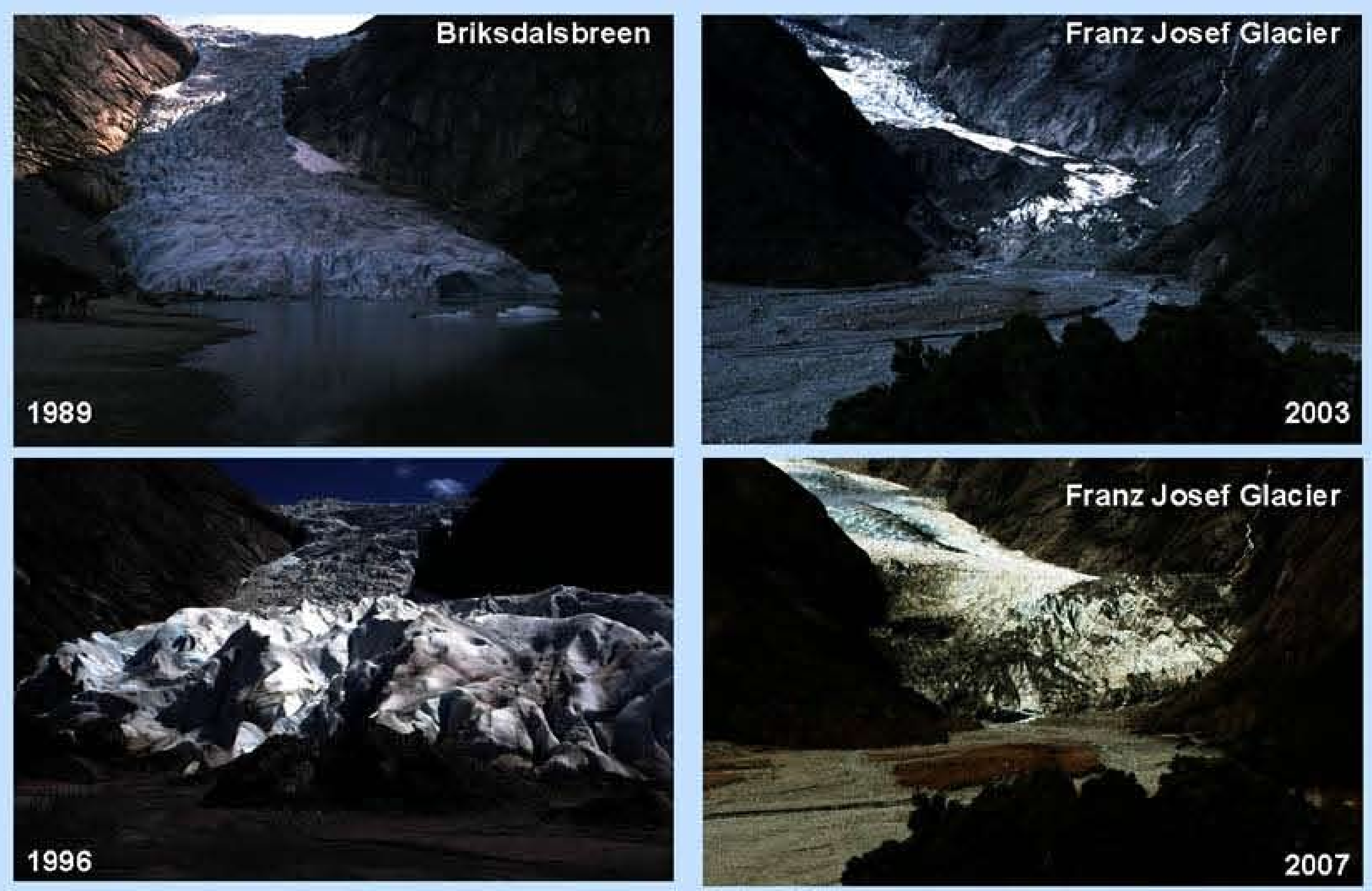


Rotation of a large boulder (> 300 t) at Briksdalsbreen during the 1990s-advance.

Introduction

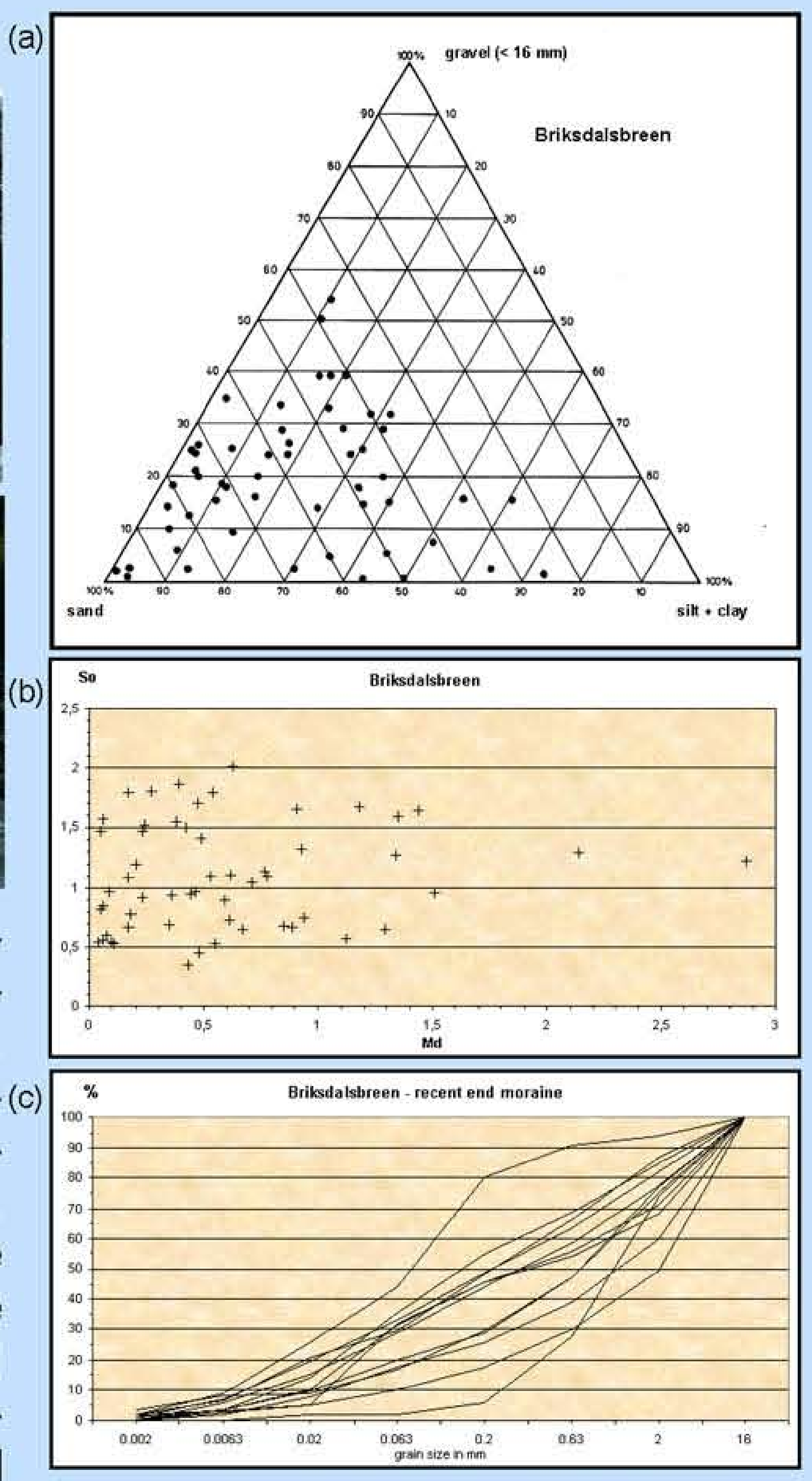
During the 1990s, the formation of frontal moraines was investigated at several advancing temperate mountain glaciers in western Norway. All those glaciers are outlets of the Jostedalsbreen ice cap, the largest glacier in continental Europe. Similar processes were observed during a parallel advance of glaciers in the Southern Alps of New Zealand. Additionally, moraine formation was observed and studied during the most recent advance in New Zealand in 2006 and 2007.

As frontal advances and resulting processes of actual moraine formation were sparse in the past decades of dominating glacier shrinkage and frontal retreat in most mountain regions, the opportunity of carrying out detailed observations and related sedimentological/morphological studies was taken in order to gain more knowledge on the processes involved. Some results from 4 individual glaciers are presented here.



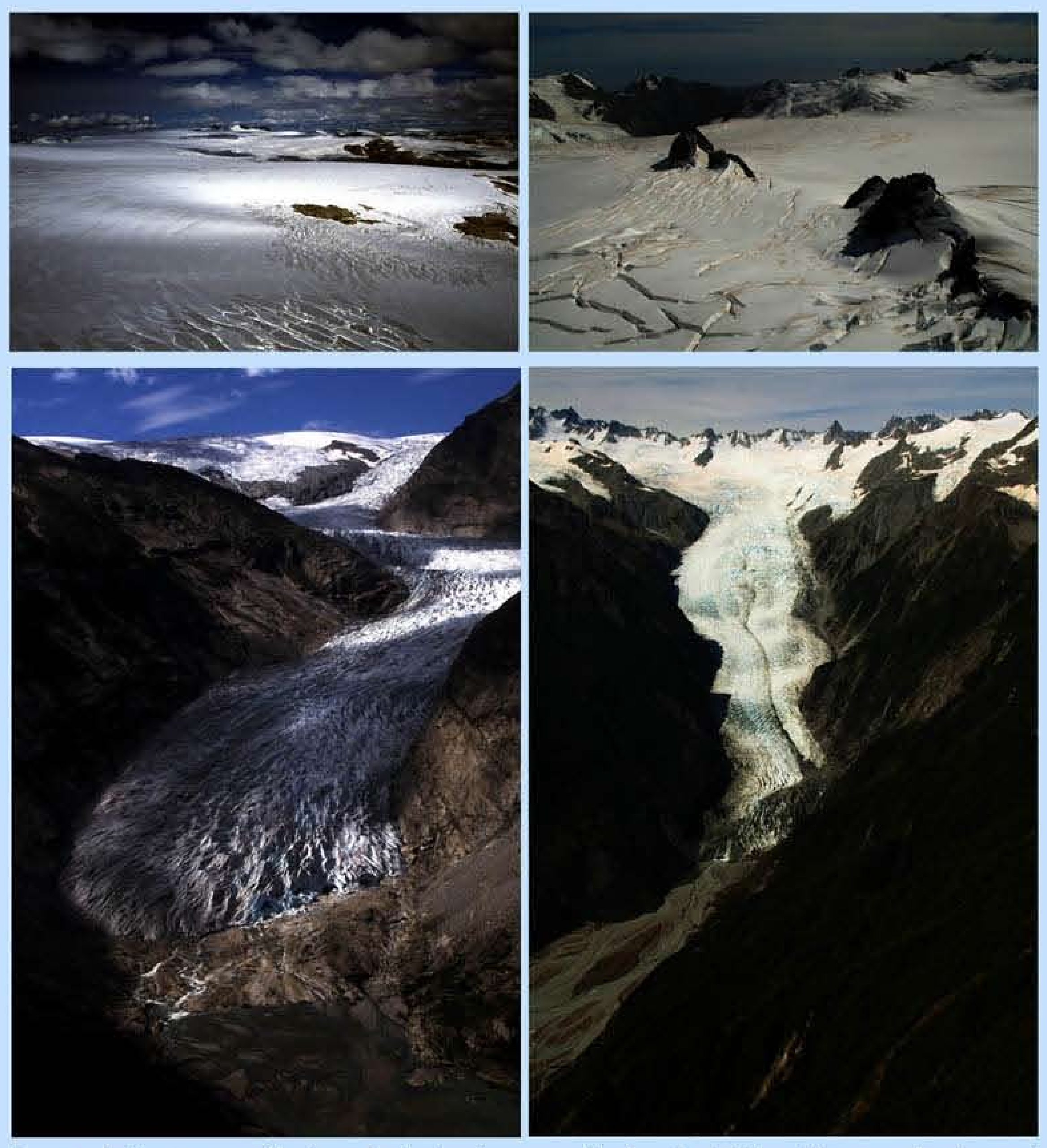
Visual comparison of frontal positions at Briksdalsbreen and Franz Josef Glacier, showing the frontal advances mentioned. Franz Josef Glacier advanced 84 m from 2006 to 2007.

Sedimentology



Percentage of grain size fractions (a), So/Md-diagram (b), and grain size distribution (c) of selected sediment samples taken from the recent end moraines at Briksdalsbreen (So = sorting index after *Selmer-Olsen*, Md = grain size median).

Sedimentological studies at Briksdalsbreen (above) show the heterogeneity of the sediments within the end moraines (glaciofluvial and glaciolimnic sediment, proglacial till). At Nigardsbreen, end moraines are absent due to the lack of pro-glacial sediments potentially bulldozed up to create those end moraines. The entire sub- and englacial debris is finally transported by melt-water. It is mainly (100 % of bed load and c. 70 – 85 % of the suspended sediment) deposited in the proglacial lake and the progressively growing delta (*Østrem et al.* 2005).



Accumulation areas (top) and glacier tongues (bottom) of Nigardsbreen, the largest outlet glacier of Jostedalsbreen (left), and of Franz Josef Glacier, located west of the Main Divide of the the Southern Alps/New Zealand (right).

Environmental settings

Briksdalsbreen	Nigardsbreen	Franz Josef Glacier	Fox Glacier
altitude at glacier front			
350 m a.s.l.	350 m a.s.l.	290 m a.s.l.	280 m a.s.l.
calculated annual air temperature at glacier front			
+ 4.1 °C	+ 3.7 °C	+ 10.2 °C	+ 10.1 °C
permafrost			
absent	absent	absent	absent
character of proglacial glacier bed			
soft gacier bed glaciofluvial/glaciolimnic sediments and till	bedrock	soft glacier bed glaciofluvial sediments	soft glacier bed glaciofluvial sediments
supraglacial debris			
none	none	sparse	sparse
selected advance distances			
1988 – 1997: + 352 m	1991 – 2003: + 262 m	1984 – 1999: + 1,200 m	1984 – 1999: + 800 m

Conclusions

Although a number of different individual processes occur during their formation, those laterofrontal and frontal moraines investigated can be classified as “push moraines” sensu *Benn & Evans* (1998), or alternatively as “bulldozed moraine” following *Winkler & Nesje* 1999. Thrusting/glacio-tectonic processes or the complex moraine built-up in an incremental fashion described from stationary glacier fronts are absent due to the lack of permafrost or harsh winter frost at the glacier tongues studied here.

Processes involved and resulting morphology of the moraines depend upon the properties of the pre-existing, proglacial sediments (e.g. grain size, pore-water content, shear strengths). A causal relationship between the size of end moraines and either magnitude or duration of the related frontal advance does not exist. Moraine sedimentology, therefore, purely reflects the sedimentology of the proglacial sediments.

Deposition of freshly eroded sub-, en-, and supraglacial debris is neglectable in most cases. The debris produced subglacially by glacial erosion is not deposited in form of end moraines, but transported and deposited by glaciofluvial action. In terms of sediment storage, end moraines play no important role for the sediment budget as they mainly consist of pre-deposited, proglacial sediments of different genetic (and temporal) origin. It is, however, a different case with the alpino-type lateral moraines of mountain glaciers (not present at the glaciers studied here). In that case, important amounts of supraglacial debris are deposited to form impressive lateral moraine ridges or complex moraine systems.

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