MORPHOLOGY, DISTRIBUTION AND FORMATION OF RELICT MARGINAL MORAINES IN THE SWEDISH MOUNTAINS

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ABSTRACT. Relict marginal moraines are commonly used landforms in palaeoglaciological reconstructions. In the Swedish mountains, a large number of relict marginal moraines of variable morphology and origin occur. In this study, we have mapped 234 relict marginal moraines distributed all along the Swedish mountains and classified them into four morphological classes: cirque-and-valley moraines, valley-side moraines, complex moraines and cross-valley moraines. Of these, 46 moraines have been reclassified or are here mapped for the first time. A vast majority of the relict moraines are shown to have formed during deglaciation of an ice-sheet, rather than by local mountain glaciers as suggested in earlier studies. The relict marginal moraines generally indicate that deglaciation throughout the mountains was characterised by a retreating ice-sheet, successively damming glacial lakes, and downwasting around mountains. The general lack of moraines indicating valley and cirque glaciers during deglaciation suggests that climatic conditions were unfavourable for local glaciation during the last phase of the Weichselian. This interpretation contrasts with some earlier studies that have reconstructed the formation of local glaciers in the higher parts of the Swedish mountains during deglaciation.

Key words: marginal moraines, moraine formation, deglaciation, Swedish mountains

Introduction

Marginal moraines are glacial landforms formed at the margin of glaciers and ice-sheets, and they demarcate the outline of the parent glacier at the time of moraine formation. Hence, marginal moraines are used widely in palaeoglaciological studies, both in ice-sheet reconstructions (e.g. Denton and Hughes 1981; Ehlers and Gibbard 2004), and in reconstructions of local and regional glacier fluctuations (e.g. Karlén 1973; Porter 1975; Dahl *et al.* 2002).

Marginal moraines vary greatly in both morphology and origin. Some are small till ridges, a few metres long and less than a metre high, whereas others are complexes hundreds of kilometres long consisting mainly of glaciofluvial sediments. A wide range of processes, such as dumping, squeezing, sediment push and ploughing, have been suggested to form marginal moraines (Benn and Evans 1998). In this paper, we focus on morphology and spatial distribution of relict marginal moraines in the Swedish mountains. For a more extensive discussion on formation processes and sedimentary geology of marginal moraines we refer to Benn and Evans (1998). We adopt a broad definition of marginal moraines, defining all ridge-like landforms formed along glacier margins and in near-marginal positions as marginal moraines. The term relict is here used to indicate that a moraine was formed by a former, presently non-existent glacier.

For any relict marginal moraine, a first palaeoglaciological interpretation includes the location of the parent glacier on either side of the moraine ridge. For most relict moraines, this may be firmly determined from topographical setting and plausible locations of former glaciers. However, the Swedish mountains have experienced a diverse glacial history, including alpine glaciation of local cirque and valley glaciers as well as regional through-flow of glacier tongues from an ice-sheet having its main centre of mass east of the mountain range (e.g. Karlén 1973; Kleman 1992; Kleman *et al.* 1997). Thus, for relict moraines, two general palaeoglaciological interpretations can be invoked: (i) formation by local/regional mountain glaciers located on the up-valley side of the moraines; and (ii) formation by ice-sheet lobes flowing into valleys and located on the down-valley side of the moraines. Obviously, because the distribution of relict moraines forms the foundation for resolving the extent of former glaciers in the mountains, correct interpretations are crucial for palaeoglaciological reconstructions. Moreover, the morphology and topographical setting of the moraines provide an insight into the processes forming the moraines and glacier conditions during moraine formation. Thus, investigations of relict moraines can contribute to palaeoglaciological reconstructions of the Swedish mountains.

Study area and previous studies

The Swedish mountains form the eastern part of the northern Scandinavian mountain range in a *c.* 100 km wide belt along the Swedish–Norwegian border. The Swedish mountains are higher in the north (maximum 2111 m a.s.l.) than in the south (maximum 1797 m a.s.l.), but they are still lower than the southwestern Scandinavian mountains, in Norway (maximum 2469 m a.s.l.). The relative relief is generally 400–700 m (Rudberg 1960). Geomorphological investigations of the Swedish mountains have a long history (e.g. Tanner 1914; Holdar 1957; Melander 1980; Ulfstedt 1980; Borgström 1989; Hättestrand 1998) and the general glacial history of the area is relatively well known, concerning both Holocene glacier fluctuations (e.g. Karlén 1973, 1988; Rosqvist *et al.* 2004) and Weichselian ice-sheet history (e.g. Kleman 1992; Kleman *et al.* 1997; Fredin and Hättestrand 2002).

Presently, there are approximately 300 contemporary glaciers in the Swedish mountains, mainly cirque glaciers confined to the highest-elevation areas, Kebnekaise and Sarek Mountains in northern Sweden (Østrem *et al.* 1973). Several Holocene local glacier advances have been inferred from lichenometry and radiocarbon dating of moraines outside contemporary glaciers as well as lacustrine sediment studies (Karlén 1973, 1988; Rosqvist *et al.* 2004). The Weichselian glaciation in the Swedish mountains can be characterised by early west-centred mountain ice-sheets/ice-fields, growing into cold-based, non-erosive **Last Glacial Maximum** (**LGM**) ice coverage with a westward ice-flow over the mountain range, and a rapid late Weichselian deglaciation (Kleman 1992; Kleman *et al.* 1997, 1999; Boulton *et al.* 2001; Fredin and Hättestrand 2002). The general pattern of the last deglaciation of the Swedish mountain area is reasonably well understood. Traces of ice-dammed lakes and ice-flow directional data indicate a pattern of deglaciation with eastward retreat of the western ice-margin up and over the crest of the northern Scandinavian mountain range, simultaneously with a westward migration of the ice dome, located over the Bothnian Bay east of the mountains at the onset of the deglaciation (Ljungner 1949; Lundqvist 1972; Kleman *et al.* 1997; Boulton *et al.* 2001). The ice-marginal retreat was more rapid along (NNE–SSW) than across (WNW–ESE) the mountain range, and the last ice-sheet remnants were located in the Kvikkjokk area (*c.* 67°N) in the northeastern part of the Swedish mountains (Kleman *et al.* 1997; Boulton *et al.* 2001).

Marginal moraines in the Swedish mountains have been interpreted as having formed during Holocene glacier advances, the late Weichselian deglaciation or before the LGM. Holocene local glacier advances have been inferred from lichenometry and radiocarbon dating of moraines outside contemporary glaciers as well as lacustrine sediment studies (Karlén 1973, 1988; Rosqvist *et al.* 2004). Relict moraines have been associated with the last deglaciation or pre-LGM glacial stages. In early studies, relict moraines were exclusively interpreted as frontal moraines formed by local glaciers during or after the deglaciation (Hamberg 1901; Sjögren 1909; Tanner 1914). Holdar (1957) examined moraines in the Torneträsk area, northern Swedish mountains, and opposed moraine formation by local mountain glaciers. Instead, he suggested that the ice-marginal accumulations formed against outlet glaciers of the waning Late-Weichselian Fennoscandian ice-sheet. Bergström (1973) and Soyez (1974) interpreted relict moraines to be formed by alpine glaciation, and concluded that the deglaciation was interrupted or followed by climatic deteriorations causing growth of local glaciers. These interpretations were partly questioned by Melander (1980) and Ulfstedt (1980), but the deglacial local glacier advance hypothesis was still accepted.

Aim

In this paper, we present data on relict marginal moraine morphology and distribution in the Swedish mountains. These data are used to suggest formational conditions for the moraines and palaeoglaciological implications for the final part of the late Weichselian deglaciation. To that end, we have mapped and classified 234 relict marginal moraines and 233 contemporary glacier moraines for comparison (Fig. 1), providing the first comprehensive inventory of marginal moraines in the Swedish mountains.

Methods

Relict marginal moraines were compiled from published map information, mainly geomorphological

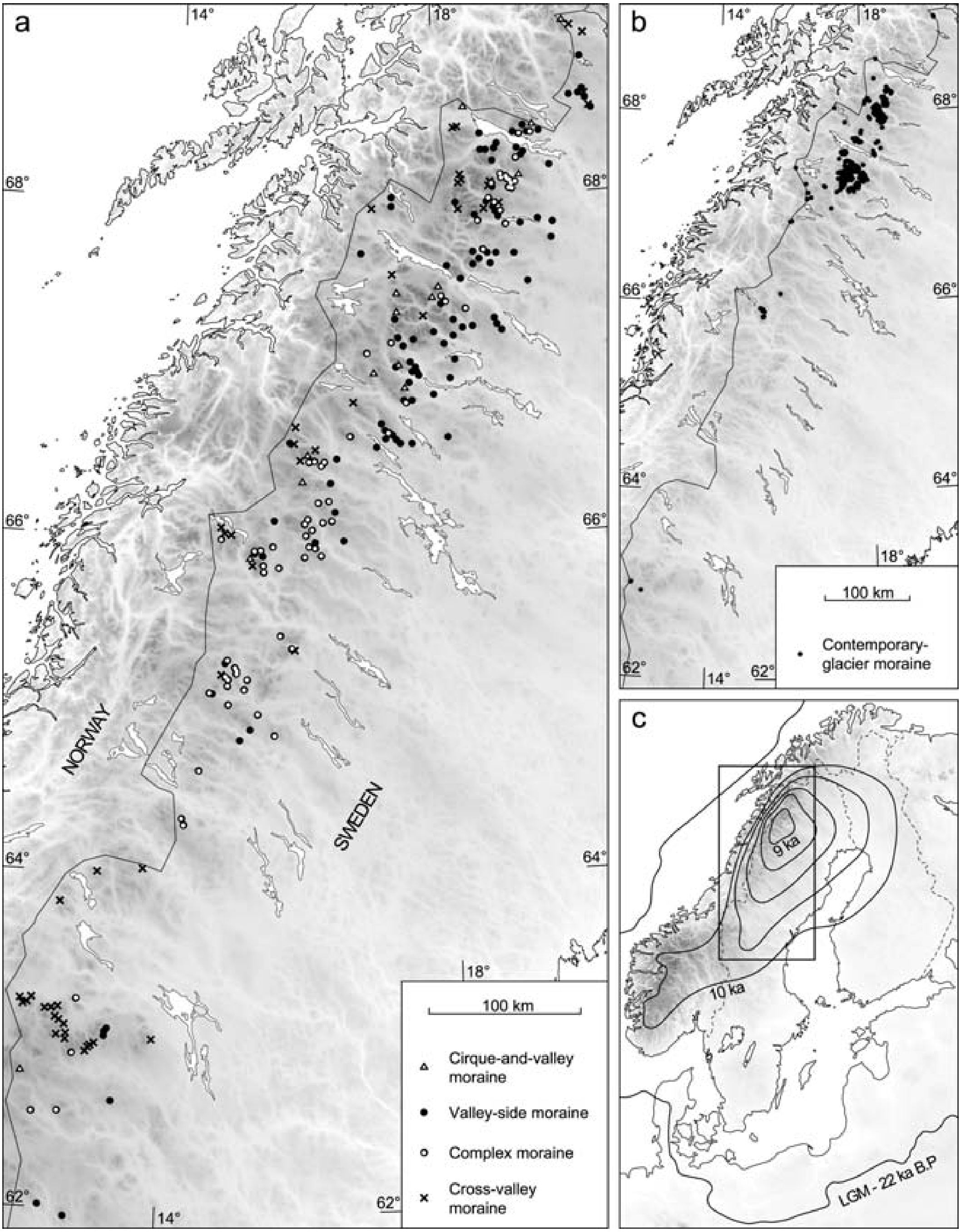

Fig. 1. Mapped moraines. (a) Relict marginal moraines. (b) Contemprary-glacier moraines. (c) Pattern of late Weichselian deglaciation (based on Kleman *et al.* 1997). Elevation model is from GTOPO30

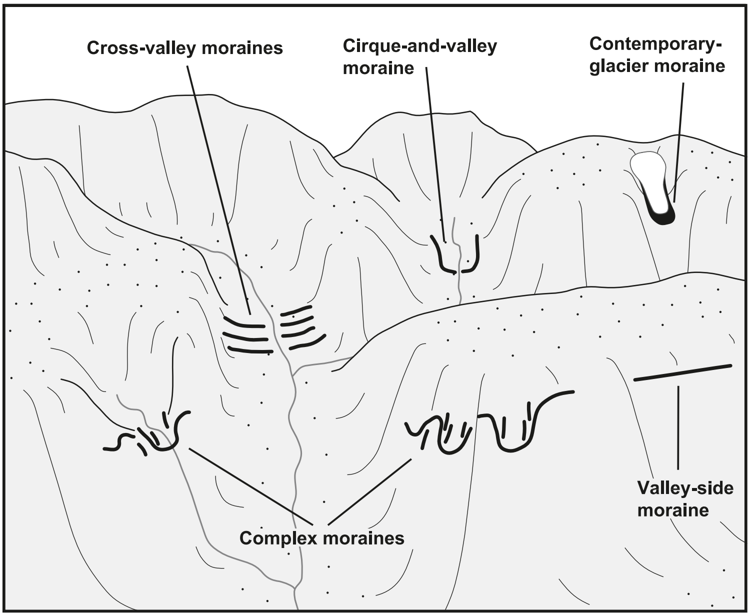

Fig. 2. Schematic illustration of the moraine classes

maps of the Swedish mountains (Melander 1980; Ulfstedt 1980; Borgström 1989; Hättestrand 1998), and from recent interpretation of aerial photographs. The moraines were mapped from colour and black-and-white prints of infrared aerial photographs at a scale of 1:60 000 using a Zeiss Jena Interpretoscope with variable magnification. The relict moraines were classified into four descriptive classes based on morphology and topographical setting. These classes are cirque-and-valley moraines, valley-side moraines, complex moraines, and cross-valley moraines. The moraine classes are defined and described below. Each moraine symbol in Fig. 1 represents one moraine ridge, or several morphologically similar moraine ridges restricted to a small, confined area. The cross-valley moraines, which occur in series of moraine ridges, are all mapped as moraine areas, where each symbol on the map (Fig. 1a) represents one clearly identifiable area of moraine ridges. For a comparison with recent moraine formation, contemporary-glacier moraines (cf. Østrem 1964) were also mapped.

Description and interpretation of marginal moraines

In total, 234 relict marginal moraines and 233 contemporary-glacier moraines for comparison were mapped and classified (Fig. 1). In this section, we present the characteristics, spatial distribution, and interpretation of the moraine classes. The general topographical settings and morphology of the moraine classes are illustrated in Fig. 2. Examples of marginal moraines of each moraine class are shown as vertical aerial photographs in Fig. 3.

Contemporary-glacier moraines

Contemporary-glacier moraines are located along, or some distance outside, contemporary glacier margins. These moraines are here considered non-relict, even though a few may have been formed by former glaciers with an outline similar to contemporary glaciers (cf. Karlén 1973). A total of 233 contemporary-glacier moraines have been identified, located mainly in the highest-altitude areas and reflecting the distribution of contemporary glaciers (Fig. 1b). Most of the contemporary-glacier moraines are arcuate, latero-frontal moraines, formed at the front of cirque/valley glaciers. The length of the moraine ridges ranges from tens of metres up to kilometres. The contemporary glacier moraines can be divided into ice-cored moraines and non-ice-cored moraines (Østrem 1964). The ice-cored moraines are wide and high moraines, often display a furrowed surface, and occur exclusively in direct connection with the parent glacier margin. Generally, the ice-core is buried under 1–3 m of till (Østrem 1964). The moraines inferred to be non-ice-cored, on the other hand, are smaller,

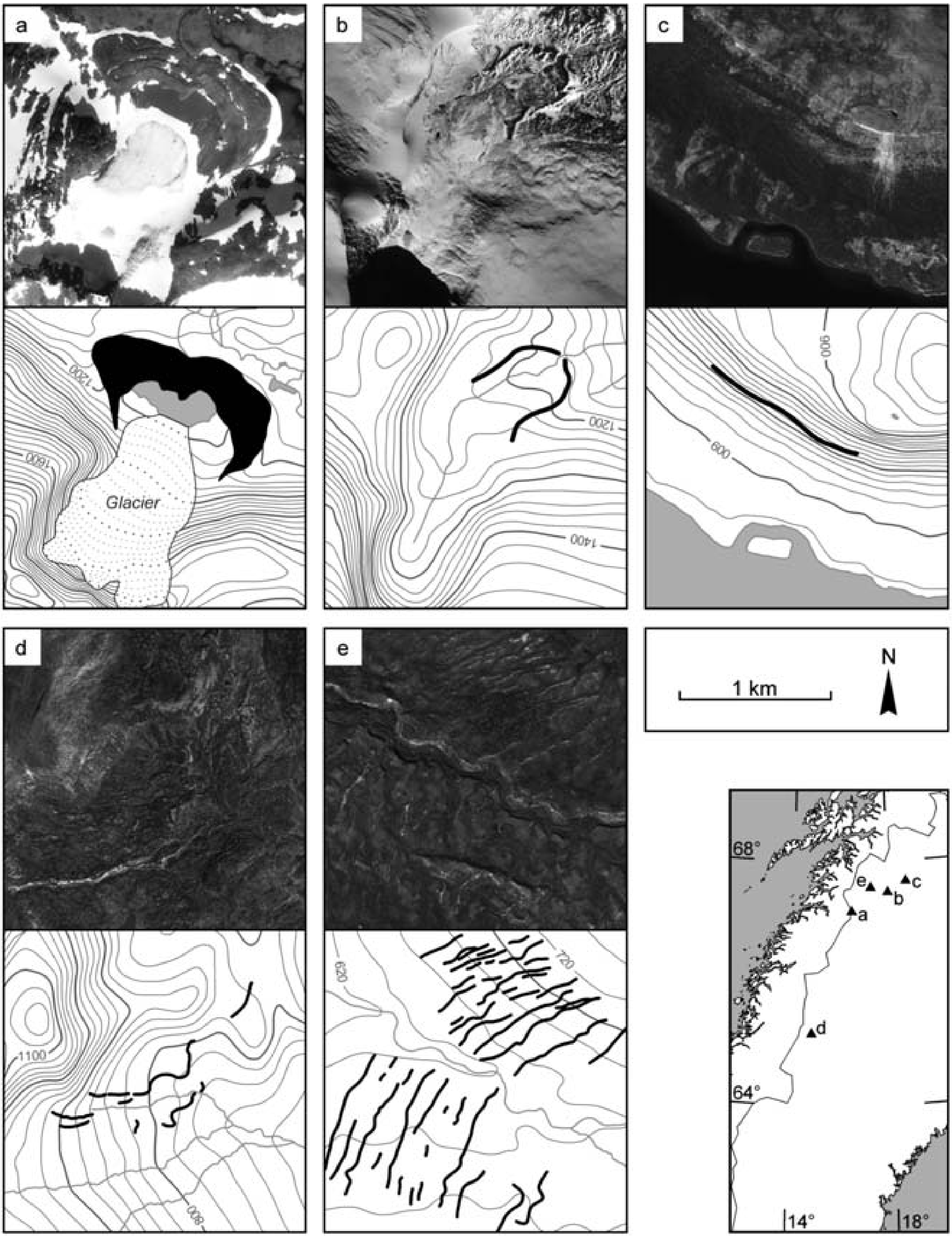

Fig. 3. Vertical aerial photographs and maps (moraine ridges marked black) of the moraine classes: (a) contemporary-glacier moraine (Sulitelma, *c.* 67°10'N); (b) cirque-and-valley moraine (Skanatjåkkå, 67°28'N); (c) valley-side moraine (Tjuoltapakte, 67°40'N); (d) complex moraine (Östra Fjällfjället, 65°09'N); (e) cross-valley moraines (Akka, 67°33'N). Aerial photographs reproduced with permission of National Land Survey of Sweden 2006. From GSD – Ortho photo, permission no 2006/1427

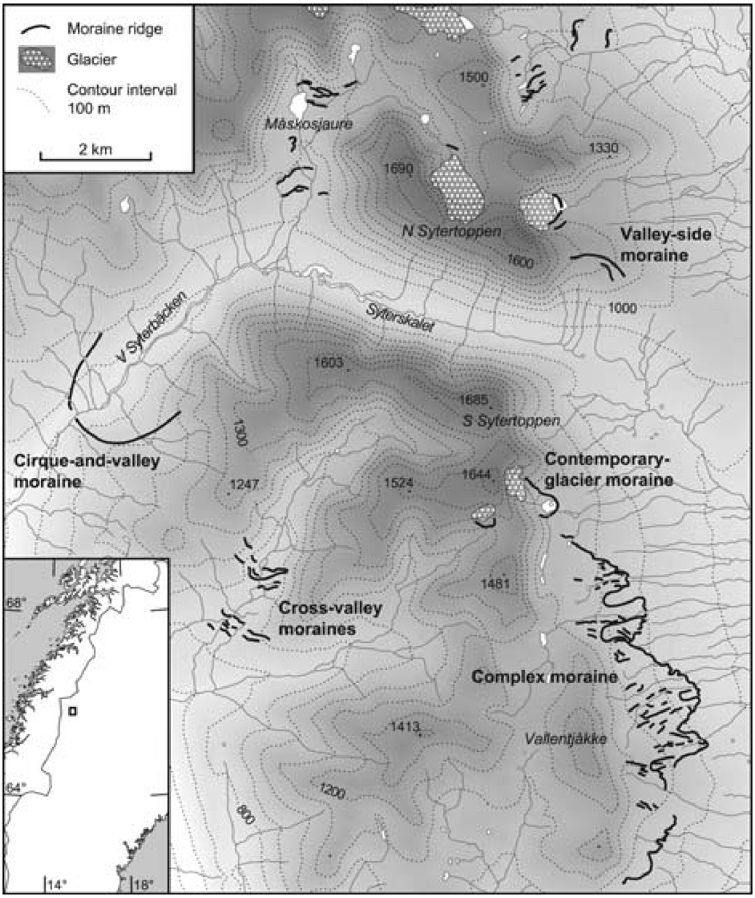

Fig. 4. Norra Storfjället with moraine ridges of all moraine classes. Apart from the contemporary-glacier moraines, all moraines are interpreted as having formed during deglaciation of an ice-sheet. The valley-side moraines east of N Sytertoppen are interpreted as pre-LGM lateral moraines (Fredin and Hättestrand 2002). A late Weichselian ice-sheet centred east of the mountain range formed the complex moraines along the eastern slope of Vallentjåkke. An outlet glacier reached into Syterskalet forming the moraines at the valley mouth of Måskosjaure and the cirque-and-valley moraine at V Syterbäcken. The cross-valley moraines must have formed earlier during the deglaciation when the ice-sheet was downwasting around S Sytertoppen. Elevation model used with permission of National Land Survey of Sweden 2000. From GSD – Height data bank, permission no L2000/646

narrow ridges with a higher length/width ratio, and often occur some distance outside the parent glacier. Ice-cored moraines are concentrated in the high mountain areas, with most of the ice-cored moraines located in the Kebnekaise and Sarek mountains.

Cirque-and-valley moraines

Cirque-and-valley moraines are arcuate ridges mostly situated in ice-free cirques and below cirque-like concavities on valley sides, although a few occur on valley floors. The slightly arcuate to U-shaped outline of the cirque-and-valley moraines indicates a latero-frontal origin. There are 15 cirque-and-valley moraines distributed along the mountain range (Fig. 1b), although they occur mainly in high mountain areas.

Most cirque-and-valley moraines are relatively small narrow ridges some hundred metres long, and the topographical setting and outline of the moraines indicate formation by small (<3 km^2) cirque glaciers (Fig. 3b). Five moraines are located across valley floors or just outside a valley mouth, indicating formation at the front of larger glacier tongues. The parent glaciers were either local/regional valley glaciers substantially larger than any contemporary glacier in the vicinity, or outlet gla-

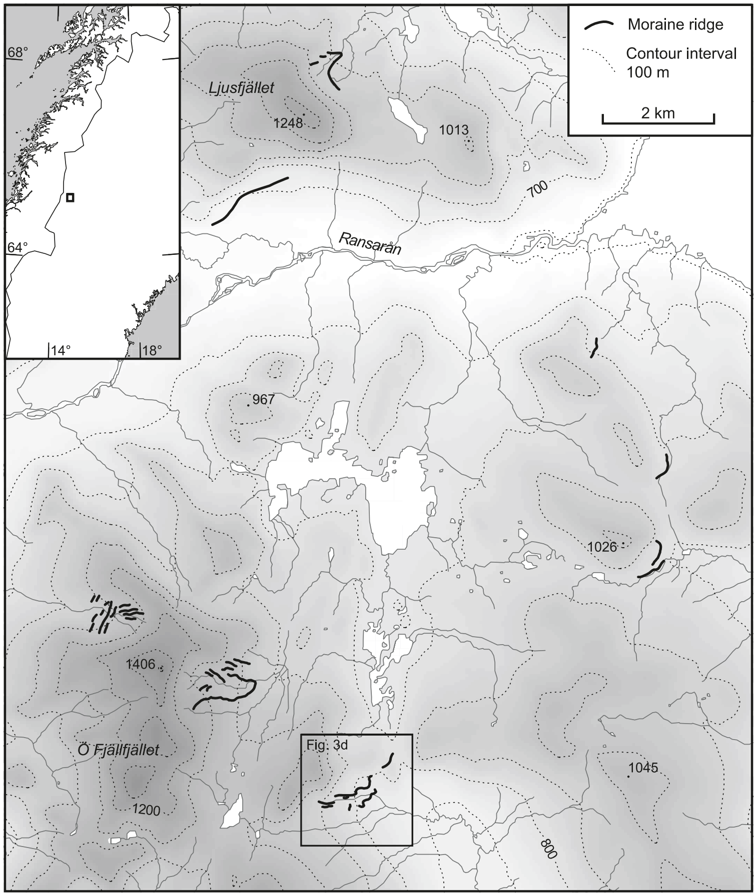

Fig. 5. Relict marginal moraines in Fjällfjällen area. The complex moraines located on east-facing slopes have previously been interpreted as having been formed by local glaciers (Soyez 1974) but are here suggested to originate from a west-facing ice-margin during the last deglaciation. The valley-side moraine south of Ljusfjället was formed by an outlet glacier flowing westward into the Ransarån Valley. The cross-valley moraines northwest of Ö Fjällfjället were formed by the downwasting ice-sheet in an earlier stage of the deglaciation, similar to the cross-valley moraines in Norra Storfjället. (Elevation model used with permission of National Land Survey of Sweden)

ciers from an ice-sheet during deglaciation. Three of these cirque-and-valley moraines are located in valleys having cirques at their heads, and are interpreted as having been formed by local mountain glaciers. The other two moraines, located in through-valleys at Norra Storfjället (65˚52'N; Fig. 4) and Alkavagge (67˚20'N), indicate formation at the terminus of outlet glaciers which presumably emanated from the waning ice-sheet centred east of the mountain range during the last deglaciation (Kleman *et al.* 1997).

The cirque-and-valley moraines mark the frontal position of former glaciers varying in size from small cirque glaciers to large outlet glaciers of the Fennoscandian ice-sheet. They have dimensions similar to the narrow contemporary-glacier moraine ridges inferred to be non-ice-cored moraines, and the cirque-and-valley moraines may be seen as analogues to the non-ice-cored contemporary moraines. It is likely that ice-cored moraines formed by former glaciers are no longer recognised due to disintegration of the moraine ridges during melting of the buried ice-core (cf. Kjær and Krüger 2001).

Apart from the two moraines situated in through-valleys, the cirque-and-valley moraines appear to have formed during local glacier advances. Holocene glacier advances in the Swedish mountains have been inferred from lichenometry,

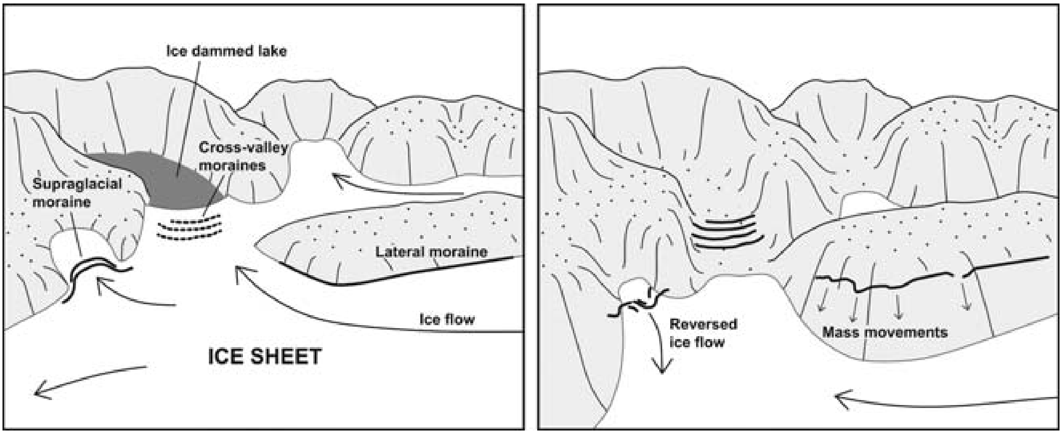

Fig. 6. Schematic figure illustrating the formation of valley-side moraines, complex moraines and cross-valley moraines during deglaciation of an ice sheet

radiocarbon dating of moraines, and lacustrine sediment studies (Karlén 1973, 1988; Rosqvist *et al.* 2004), and we consider most of the moraines to have been formed by Holocene glacier advances. However, two moraines, at Lake Rautasjauri (*c.* 68˚07'N) and at Fietar (66˚53'N), are interpreted as having been formed by local glacier advances predating the last ice-sheet build-up, as indicated by late Weichselian deglacial features overprinting the moraines (Hättestrand 1998).

Valley-side moraines

Valley-side moraines are subhorizontal moraine ridges situated on valley sides or mountain slopes (Fig. 3c). Most of the valley-side moraines are single, relatively straight ridges, but there are examples of valley-side moraines occurring as two or three parallel ridges along the slope. The valley-side moraines vary in size from 100 m to several kilometres long. Generally, the valley-side moraines are interpreted as having formed at the margin of outlet glaciers during deglaciation of an ice-sheet (cf. Kleman 1992; Hättestrand 1998; Fredin and Hättestrand 2002).

A majority of the 98 mapped valley-side moraines are located in the northern part of the area (Fig. 1b). A large group (84 moraines) comprises pre-LGM lateral moraines along the eastern rim of the Swedish mountains (Kleman 1992; Hättestrand 1998; Fredin and Hättestrand 2002). These moraines are linked to a set of meltwater channels of pre-LGM origin (Rodhe 1988), are sometimes overprinted by glacial lineations or cross-cut by meltwater channels, and indicate formation by a west-centred ice-sheet incompatible with the configuration of the late Weichselian ice-sheet centred east of the mountains (Kleman 1992; Hättestrand 1998; Fredin and Hättestrand 2002; Fig. 1c). Erratics from the moraines give cosmogenic exposure ages pre-dating the last deglaciation, and a palaeosol draped by till has been identified on the moraines (Fabel *et al.* 2006). This indicates that the moraines were formed before the late Weichselian deglaciation and the LGM, and have been preserved under cold-based non-erosive ice.

A few valley-side moraines are interpreted as having formed during the last deglaciation along outlet glaciers reaching into the mountains from the late Weichselian ice-sheet centred east of the mountain range. These moraines are morphologically similar to the pre-LGM lateral moraines but are situated west of the pre-LGM moraines and indicate formation by glacier tongues facing and sloping towards the west (e.g. Fig. 5).

Based on morphology and topographical setting, all mapped valley-side moraines are interpreted as having formed during deglaciation of ice-sheets or regional ice-fields rather than by alpine glaciation.

Complex moraines

Complex moraines are ridges with a complex, irregular morphology located along valley sides and mountain slopes (Fig. 3d). The dimensions are similar to the valley-side moraines and the complex moraines may thus extend along mountain slopes for several kilometres. The ridges are often sinuous, bending up and down as if sections of the ridge have been distorted down-slope. They are often broken up and flanked by short ridges orientated down-slope, perpendicular to the general outline of the complex moraine ridge (Fig. 4). A total of 72 complex moraines have been mapped, distributed all along the mountain range, with highest concentrations around 65˚N (Fjällfjällen), 66˚N (Ammarfjällen) and 68˚N (NE of Kebnekaise) (Fig. 1b).

The complex moraines were first described from the middle Swedish mountains by Ulfstedt (1978) who suggested that the ridges are ice-marginal landforms formed by landslides trapped against outlet glaciers left on the valley floor during deglaciation. Hättestrand (1998) noted a similar spatial distribution of complex moraines and the pre-LGM lateral moraines, and suggested that the complex moraines were originally formed as lateral moraines but were subsequently redeposited by mass movements as the supporting outlet glaciers melted (Fig. 6). The complex moraines are often situated below steep mountain faces; at a few sites, complex moraines are located below gaps between valley-side moraines (Fig. 7). The arcuate, sinuous outline of several of the complex moraines (e.g. Fig. 4) indicates a slow down-slope movement (Hättestrand 1998).

One set of complex moraines is located at cirques or cirque-like concavities, and has previously been interpreted as having been formed by former cirque glaciers (e.g. Bergström 1973; Soyez 1974). These moraines resemble the cirque-and-valley moraines with arcuate, down-valley convex ridges, but they exhibit complex ridge patterns that are unlikely to result from formation by a local cirque glacier situated up-valley of the moraine (Figs 3d and 5). Often the moraine ridge bends down/out from the cirque/slope at one or both ends, and at a few locations the moraine ridge continues outside the cirque hollow as a valley-side moraine (for example at Tjidtjakgaise, 66˚36'N). The moraines are similar in dimension and morphology to the complex moraines described by Ulfstedt (1978) and Hättestrand (1998), and are at several locations flanked by short moraine ridges orientated down-slope.

The origin of these complex moraines at cirques is elusive. Formation by mass movements reforming marginal moraines seems unlikely as the moraine ridges at several locations are situated below fairly gentle slopes. Possibly, sections of marginal moraines formed by an ice-sheet (cf. valley-side moraines) may have been pushed down by local cirque glaciers during a subsequent glacier advance, explaining both the U-shaped outline and the complex morphology of the moraines. However, cirques in the vicinity of the complex moraines hold no moraines from local glaciers. We suggest that the complex moraines at cirques formed as ice-marginal supraglacial moraines that were transported into the cirques, similarly to moraines described from Antarctica (Chinn 1994; Hättestrand and Johansen 2005). A faster down-wasting of the glaciers outside the cirques towards the end of deglaciation may have resulted in a reversed ice-flow, out from the cirques, creating the arcuate complex patterns of the moraines, which were subsequently lowered down on the ground during the retreat of the ice margin (Fig. 6).

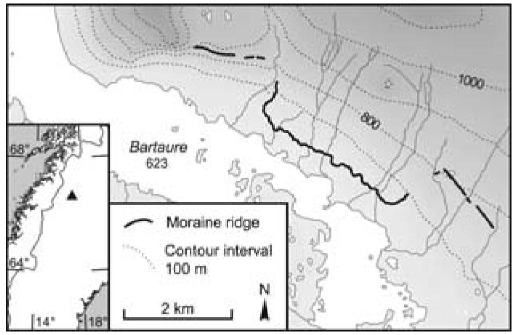

Fig. 7. Complex moraine at Bartaure (66˚37'N) located below a gap between valley-side moraines, indicating their common origin (Elevation model used with permission of National Land Survey of Sweden). The moraines were originally formed as lateral moraines by an outlet glacier flowing eastward from a west-centred pre-LGM ice-sheet (Hättestrand 1998; Fredin and Hättestrand 2002)

Cross-valley moraines

Cross-valley moraines are ridges occurring in regular series across the floor and lower sides of valleys (Fig. 3e). The cross-valley moraines are either relatively straight or display a gently bent curve, commonly convex down-valley. The moraines are sometimes sinuous and broken up. The ridges are narrow with a high length/width ratio and range in size from less than 1 m high and a few tens of metres long up to more than 10 m high and *c.* 1 km-long.

The term cross-valley moraine was first used for series of moraine ridges located across valleys on north-central Baffin Island (Andrews 1963a, b), and is here adopted since it is a descriptive term adequate for the present moraines crossing valleys.

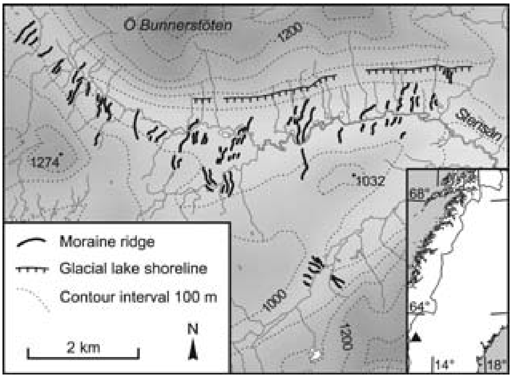

Fig. 8. Cross-valley moraines at Stensån Valley (63°08'N), south of Bunnerfjällen, located below ice-dammed lake shorelines. (Elevation model used with permission of National Land Survey of Sweden)

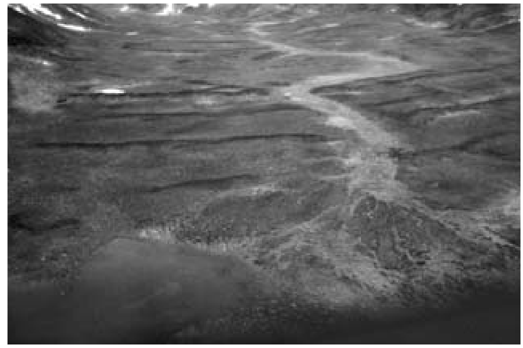

Fig. 9. Cross-valley moraines in Lävasjåkka Valley (68°04'N). *Photo*: Centre for History of Science, Royal Swedish Academy of Sciences (Hoppe 1983)

Similar moraine ridges occurring in series have also been described under other names, such as washboard moraines (Mawdsley 1936; Norman 1938), sublacustrine moraines (Barnett and Holdsworth 1974), and De Geer moraines (Hoppe 1959; Larsen *et al.* 1991; Blake 2000; Lindén and Möller 2005). For all these moraine types there is a correlation between the location of the moraines and the presence of subaqueous environments during deposition, which has led to suggestions of a genetic relation.

Most of the mapped cross-valley moraine series have around ten distinct ridges, but individual fields of more than 50 ridges have been observed (for example in Bunnerfjällen at 63°11'N; cf. Borgström 1979). The moraine ridges are often most pronounced at the sides of the valley floor and commonly continue up on the lower part of the slopes. In the lower, middle part of the valley floors they have often been eroded by streams. There are 49 cross-valley moraine areas distributed all along the mountain range, and the highest concentration occurs in the southern mountains (Fig. 1b).

The morphology of the cross-valley moraines, outlined relatively straight across valley floors and often continuing up on the valley slopes, opposes formation at the terminus of glacier tongues flowing down-valley as such glaciers are more likely to form arcuate end moraines of the cirque-and-valley moraine type. Rather, the moraines are interpreted as having formed at the terminus of glacier tongues flowing up-valley, impounding water bodies during deglaciation (Fig. 5; Borgström 1979). Lundqvist (1972) investigated the traces of former glacial lakes in the Swedish mountains and concluded that ice-dammed lakes occurred all along the mountain range. The distribution of the mapped cross-valley moraines correlates well with the occurrence of former ice-dammed lakes (e.g. Fig. 8). If formed at the ice-margin of a glacial lake, the gently bent convex down-valley curves can be explained as a result of a receding calving bay. Thus, we consider all mapped cross-valley moraines to be subaqueous moraines, formed at an ice-margin damming up a glacial lake during deglaciation, as Borgström (1979) suggested for the Bunnerfjällen cross-valley moraines.

Discussion

Of the 234 mapped relict marginal moraines, 220 moraines are interpreted as having been formed by an ice-sheet/ice-field and 13 moraines are interpreted as having been formed by local glaciers. In addition, there are 233 contemporary-glacier moraines located outside contemporary glaciers.

The 13 cirque-and-valley moraines formed by local glaciers are concentrated to high-altitude areas similar to the contemporary-glacier moraines distribution, and are interpreted as having formed during periods of more glacially favourable climates than presently. Of the moraines formed by an ice-sheet/ice-field, a large number of the valley-side and complex moraines have been shown to pre-date the last deglaciation and to originate from an early Weichselian, or even earlier, west-centred ice-sheet (Kleman 1992; Hättestrand 1998; Fredin and Hättestrand 2002; Fabel *et al.* 2006). The remaining moraines formed by an ice-sheet/ice-field are interpreted as having formed during the last deglaciation. These deglacial moraines are often related to ice-dammed lake traces and generally indicate an eastward ice-marginal retreat towards the lower areas along the eastern part of the mountain range.

The moraines formed by local glaciers are dominated by frontal moraines. Moraines formed by an ice-sheet/ice-field, on the other hand, were mainly deposited at valley sides and mountain slopes (valley-side moraines and complex moraines) at the side of outlet glaciers. A simple explanation of this contrast is the ice-marginal frontal/valley-side ratio. Small, local mountain glaciers have relatively long frontal ice-margins, compared to a downwasting ice-sheet with long ice-margins along valley sides. Apart from the cross-valley moraines, interpreted as being related to ice-dammed lakes, there are only two moraines (at Syterskalet and Alkavagge) interpreted as having formed at the front of outlet glaciers reaching out from an ice-sheet. Fredin and Hättestrand (2002) presented two explanations of the fact that there are a number of lateral pre-LGM moraines but no associated frontal moraines. Either frontal moraines, situated lower in the topography where basal melting ice is more likely to occur, have been eroded, or because even small ice surface elevation changes at the location of the lateral moraines may yield substantial frontal ice-marginal variations, due to changing mass balance conditions, the ice front may not have been stationary enough for frontal moraines to be formed. For moraines formed during the last deglaciation, only the latter explanation is conceivable

The moraines formed during the last deglaciation are all, apart from the two cirque-and-valley moraines formed by outlet glaciers, formed by glaciers located on the down-slope side of the moraines. The deglacial moraines indicate an ice-sheet downwasting around mountains, and in several cases the moraine morphology and location oppose local cirque glacier advances (e.g. Fig. 5). Several of the moraines, particularly those classified as complex and cross-valley moraines, have earlier been interpreted as having been formed by local glaciers situated up-valley of the moraines. Moraines located across valley-mouths are often presumed to have been formed by mountain glaciers situated up-valley of the moraines, even though the moraines display straight outlines incompatible with a frontal origin. For example, the moraines located at the valley-mouth of Måskosjaure at Norra Storfjället have been interpreted as frontal moraines formed by a local mountain glacier (Bergström 1973; Ulfstedt 1980), even though they are arced into the valley rather than out from it (Fig. 4).

The sinuous outline of the complex moraines resembles several U-shaped moraines located side by side (e.g. Fig. 4). If only one such moraine arc is formed below a cirque-like hollow it may easily be mistaken for a frontal moraine formed by a local glacier. This is well illustrated by the complex moraines in Fjällfjällen (*c.* 65°N) located on east-facing slopes and resembling the cirque-and-valley moraines (Fig. 5). In mountains east of Fjällfjällen there are no similar moraines. This led Soyez (1974) to conclude that the area experienced a period of local glacier advance during the deglaciation when the mountains further east were still covered by the ice-sheet. However, we argue that the moraine morphology, with ridges continuing on slopes neighbouring and flanking the cirques, opposes formation by local glaciers. The location of the moraines on east-facing slopes, as well as valley-side moraines with similar orientation, rather supports an interpretation of the moraines having formed at a west-facing ice-margin located down-slope of the moraines.

The often convex down-valley outline of the cross-valley moraines may lead to misinterpretations of the moraines as series of frontal moraines formed by a local glacier situated up-valley of the moraines. One example of particularly arcuate, convex down-valley moraine ridges is the series of moraine ridges located across the Lävasjåkka Valley (68°04'N) in northern Sweden. Tanner (1914) first described the moraines and suggested formation by a local glacier receding up toward the Mårma Mountains west of the moraines. This interpretation has since been accepted, even though Melander (1980) noted striae in conflict with an east-facing glacier and opposed such an origin. The outline of the moraine ridges across the valley is somewhat too straight to be consistent with formation by a glacier situated up-valley of the moraines (Fig. 9), and the characteristic series of moraine ridges, at several locations related to glacial lake traces, implies formation by a glacier tongue situated down-valley of the moraine ridges impounding a water body.

The subaqueously formed cross-valley moraines all mark the position of ice-margins damming glacial lakes (cf. Borgström 1979). This is significant for ice-dammed lake reconstructions as the damming ice-margin otherwise can only be inferred from traces of glacial lakes and the topography. We suggest that all cross-valley moraines in the Swedish mountains, like landforms such as shorelines, outlet channels and lacustrine sediments (Lundqvist 1972), mark the existence of former ice-dammed lakes, when other glaciolacustrine traces are lacking.

In total, we have found 21 deglaciation moraines that we argue have been misinterpreted as local glaciation moraines in earlier studies. Our reinterpretations have little influence in the general way the last deglaciation is reconstructed, because they only add to an already large number of ice-marginal features that reflect the ice-marginal retreat pattern during the last deglaciation. However, some of these moraines have been used as the prime evidence for invoking climate conditions favourable for local glaciation, either during the last deglaciation or during earlier Holocene phases (Bergström 1973; Soyez 1974; Ulfstedt 1980; Melander 1980). A consequence of the reinterpretation of these moraines is that much of the evidence for local glaciation centres in the high mountain areas during the last deglaciation is no longer valid, and hence there is motivation for new deglaciation reconstructions in the area to be made. Since the deglaciation moraines are distributed all along the mountains, no specific ice-marginal still-stand or readvance during the deglaciation can be identified. However, the moraines mark ice-marginal positions and could thus be used for dating the very last part of the late Weichselian deglaciation.

Conclusions

Relict marginal moraines in mountain areas are useful landforms for reconstructing former glacial events. However, to draw correct conclusions from the moraines, their origin must be firmly determined. Moraines formed during deglaciation of ice-sheets by glaciers situated down-valley of the moraines may be morphologically similar to moraines formed during advances of local glaciers situated up-valley of the moraines. Thus, in mountain areas formerly covered by ice-sheets, it is justified to consider that completely different glaciers may have formed marginal moraines of similar morphology.

A large number of relict marginal moraines of variable origin and morphology occur along the Swedish part of the Scandinavian mountain range. A vast majority of the relict moraines were formed by an ice-sheet/ice-field, either during the late Weichselian deglaciation or by a pre-LGM west-centred ice-sheet/ice-field. The moraines formed during the late Weichselian deglaciation indicate a downwasting ice-sheet and oppose rather than support growth of local mountain glaciers during the deglaciation.

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