The Mesoproterozoic sub-Heddal unconformity, Sauland, Telemark, south Norway.

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In the Sauland area, the Vindeggen group, which corresponds to the northern part of the traditional Seljord group, is overlain unconformably by the Lifjell group (southern part of the traditional Seljord group), whereas the Heddal group unconformably overlies both of these groups. The sub-Heddal unconformity transects progressively older rocks when moving from south to north. In the south, the 1145 Ma old Skogsåa porphyry of the Heddal group lies either directly on the Lifjell orthoquartzite or is separated from it by a thin layer of epiclastic muscovite schist. At Heksfjellet, the unconformity transects the basal Heksfjellet conglomerates of the Lifjell group. Here the Heddal group starts with a c. 1 m thick cobbly mica schist, which passes upwards via an acid volcanic detritus zone into the Skogsåa porphyry. Farther to the north, in the Moltelia area, the unconformity joins and even intersects the sub-Lifjell unconformity. The muscovite schist and the Skogsåa porphyry lie on the rugged, karst-like, palaeoweathered surface developed on the uppermost Vindeggen orthoquartzite, indicating that the Lifjell Group was eroded before deposition of the Heddal group. Consequently, the Vindeggen-Lifjell/Heddal contact is a distinct stratigraphic unconformity. Recent age determinations place the age of the unconformity to be between 1150 Ma and 1145 Ma.

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Introduction

The Mesoproterozoic, c. 1500 – 1100 Ma old supracrustal rocks in the northern part of the Telemark sector of the Gothian-Sveconorwegian domain of SW Scandinavia are known as the Telemark supracrustals (Sigmond et al. 1997) (Figs. 1 and 2). In the classical works by Dons (1959,1960a, b, 1962, 1972), they were subdivided into three groups separated by angular unconformities: (1) the volcanic Rjukan group (lowermost), (2) the quartzite-dominated Seljord group, and (3) the mixed volcanic-sedimentary Bandak group. Later on, Dahlgren et al. (1990b) added the fourth unit to this scheme, (4) the Heddal group, which was said to overlie the Seljord group in the east, although its exact relationship with this and the Bandak group in the west was not known. On the basis of recent field and isotope geological work in the Bandak-Sauland area, Laajoki et al. (2000, 2002) proposed a new classification and nomenclature. The Seljord group is subdivided into the Vindeggen (lower) and Lifjell groups (upper), and the Bandak group into the Oftefjell group (lower), the Høydalsmo group (middle) and the Eidsborg formation (topmost). This scheme and nomenclature will be used in this paper (Fig. 3).

Although unconformities have played an important role in the lithostratigraphic classification of the Telemark supracrustals, none have been described in any detail. Therefore, special attention was paid to them in recent field studies in the southern part of the Telemark supracrustals, and they were named and briefly described in a recent paper (Laajoki et al. 2002). The author has studied some parts of the contact zone between Vindeggen and Lifjell groups and the Heddal group in Sauland, identifying several outcrops where the contact and basal lithologies of the Heddal group are exposed (Laajoki 2001). The present paper describes these observations and concludes that the Vindeggen-Lifjell/Heddal contact is a major unconformity within the Telemark supracrustals, and is referred to informally as the sub-Heddal unconformity. Consequently, the proposal for the establishment of the Heddal group made by Dahlgren et al. (1990b) is justified.

Geological setting and lithostratigraphy of the study area

The Telemark supracrustals of the N-S trending Rjukan Proterozoic rift (Sigmond et al. 1997) occupy the northeastern part of the Telemark-Bamble terrane of the Mesoproterozoic Sveconorwegian orogen in southern Norway (Figs. 1 & 2). Geochronological data presented by Dahlgren et al. (1990b), Dahlgren and Heaman (1991), Sigmond (1998), Bingen et al (2001a, b, in prep.) and Laajoki et al. (2002) place their ages somew-

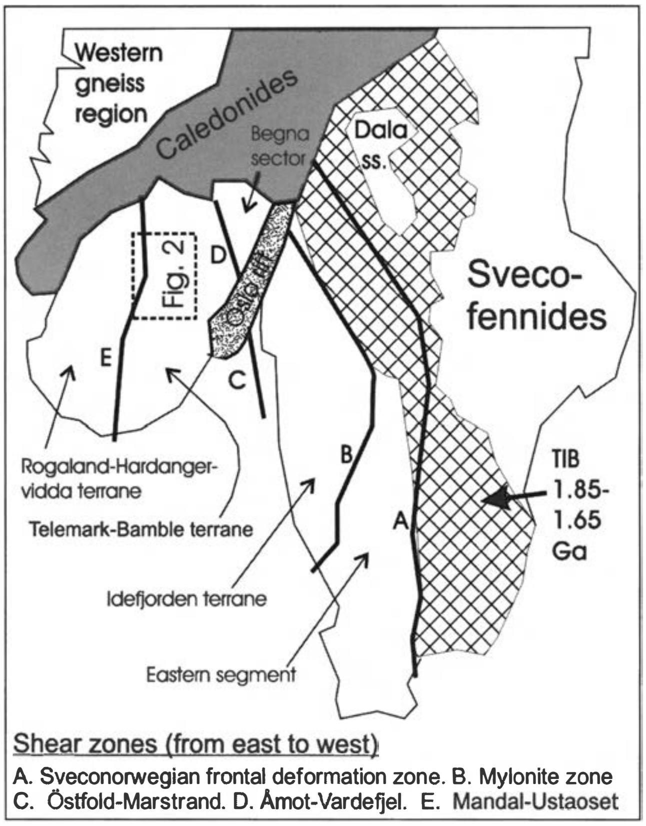

Fig. 1. Sketch map of the Sveconorwegian province (modified from Bingen et al. 2001a). The area covered by Fig. 2 is framed. TIB = Transscandinavian Igneous Belt.

here between 1500 and 1100 Ma. The geological setting and revised lithostratigraphy of the belt are treated in the accompanying paper (Laajoki et al. 2002). The study area is located in the southern part of the Rjukan rift (Fig. 2), which can be subdivided into four main lithological entities: (1) The Central core zone, which comprises the Gøyst complex of unknown age (Sigmond et al. 1997), the c. 1500 Ma old (Dahlgren et al 1990b; Sigmond 1998) Rjukan group unconformably overlain by the quartzite-dominated Vindeggen group. The northern part of the Rjukan group is intruded by numerous 1500 – 1100 Ma old plutons of the Uvdal belt (Sigmond 1998). (2) The Western part, where the Vindeggen group is overlain unconformably by the Oftefjell group, which includes the 1155 ± 3 Ma old Ljosdalsvatnet porphyry (Laajoki et al. 2002) and is unconformably overlain by the Høydalsmo group. The latter includes the 1150 ± 4 Ma old Dalaå porphyry (Laajoki et al. 2002) and is overlain by the Eidsborg formation (Fig. 3). In the north, the relatively young (<1054 ± 22 Ma, Bingen et al., subm.) Kalhovd formation occupies the area between the Rjukan group and the Mandal-Ustaoset fault zone. (3) The Southern part, where the Vindeggen group and the 1155 Ma old Brunkeberg formation are unconformably overlain by the orthoquartzitic Lifjell group (Fig. 3). Its contact with the Vråvatn complex of granitoids and gneisses of unknown ages is tectonic (Fig. 2). (4) The Eastern part is dominated by the volcanic-sedimentary Heddal group, which in the study area lies unconformably both on the Vindeggen and Lifjell groups and contains the 1145 ± 4 Ma old (Laajoki et al. 2002) Skogsåa porphyry in its basal part. In the northeast, on the map sheets of Hamar (Nordgulen 1999) and Odda (Sigmond 1998), there appear several older formations, which seem to be missing in the Sauland area. They include the 1169 ± 9 Ma old dacite of the Myrset formation of the Nore group and the c. 1160 Ma old volcanite of the Sørkjevatn formation (Bingen et al. 2001b; subm.). Nordgulen (1999) correlates the northern part of the Blefjell quartzite with the 1700 – 1500 Ma old (Bingen et al 2001a) quartzitic Hallingdal complex, but as this is uncertain the Blefjell quartzite is marked as a unit of its own in Fig. 2.

The Rjukan, Vindeggen, Lifjell and Heddal groups are all intruded by metagabbroic sills and dykes. These are most abundant in the lower part of the Vindeggen group in the north. The Hesjåbutind gabbro, which intrudes the Rjukan group in the Tuddal area, has a U-Pb zircon and baddeleyite age of 1145 +3/-2 Ma (Dahlgren et al. 1990a).

Age of sedimentation of the Telemark supracrustals

The ages of the Rjukan volcanics (Dahlgren et al. 1990a; Sigmond 1998) and the Ljosdalsvatnet porphyry (Laajoki et al. 2002) constrain the deposition of the Vindeggen group to somewhere between 1500 - 1155 Ma (Fig. 3). Correspondingly, the ages of the Brunkeberg formation and the Skogsåa porphyry of the Heddal group limit the sedimentation of the Lifjell group to a rather narrow time span of about 10 Ma, from 1155 Ma to 1145 Ma (Fig. 3, Laajoki et al. 2002).
The deposition of the Oftefjell group started between 1500 Ma (the maximum depositional age of the Vindeggen group) and 1155 Ma (the age of the Ljosdalsvatnet porphyry) and ended before 1150 Ma (the age of the Dalaå porphyry). The ages of the Ljosdalsvatnet and Dalaå porphyries delimit the beginning of the deposition of the Høydalsmo group between 1155 Ma and 1150 Ma (Fig. 3).

The acid volcanism of the Heddal group started at 1145 Ma (Laajoki et al. 2002). This is probably close to the lower age limit of the entire group, because of the 1155 – 1145 Ma age of the underlying Lifjell quartzite (Fig. 3). The depositional age of the metasediments of the Heddal group on the Hamar map sheet is said to be less than 1112 ± 20 Ma (Bingen et al. in prep.), which is significantly younger than the age of the Skogsåa porphyry of the Heddal group. The sandstone of the Kalhovd forma-

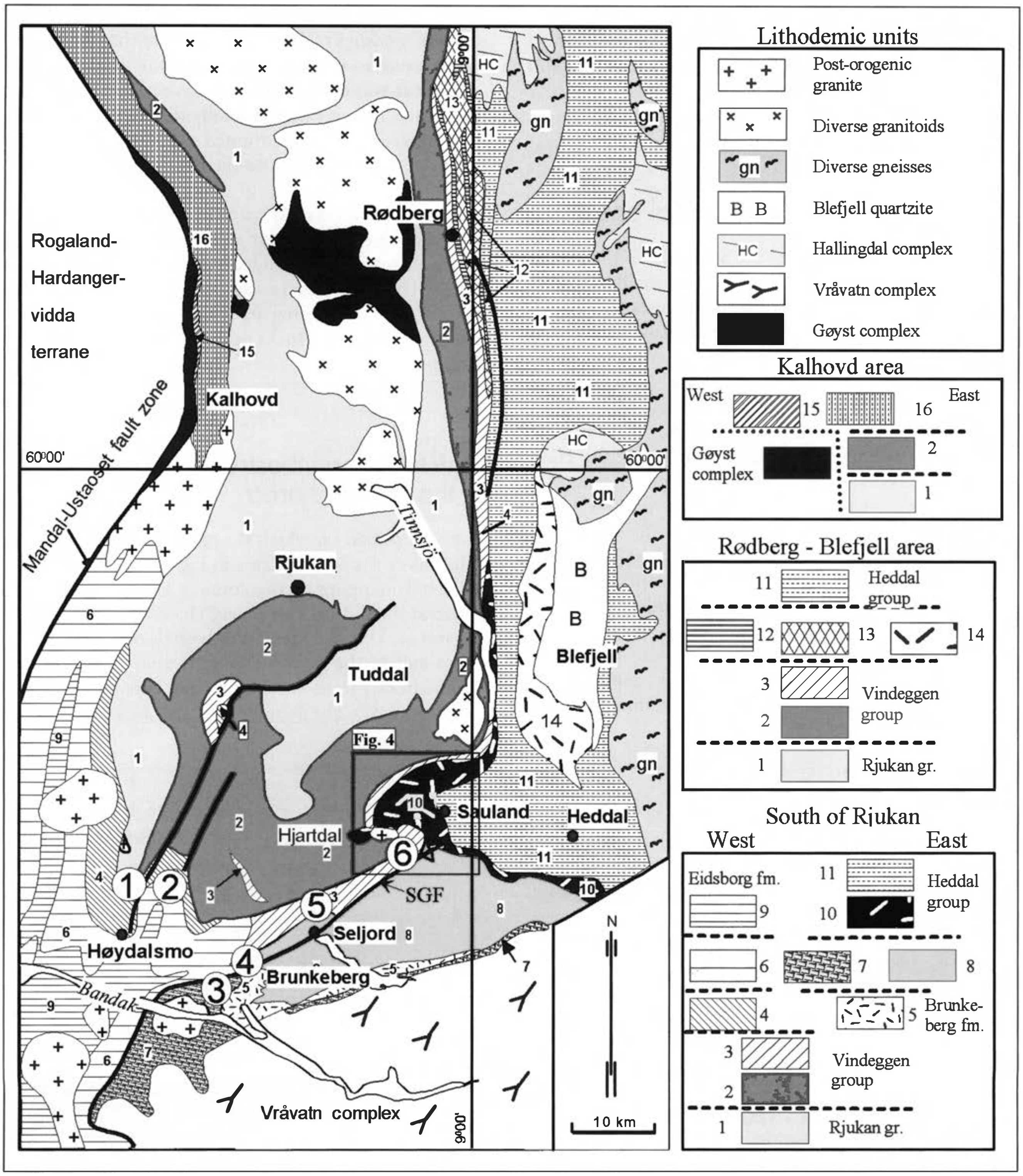

Fig. 2. Simplified geological map of the Rjukan rift basin in central Telemark (compiled and modified from Sigmond et al. 1997; Sigmond 1998; Nordgulen 1999). The lithostratigraphic nomenclature proposed by Bingen et al. (subm.) and Laajoki et al. (2002) is applied. Circled numbers 1 – 6 refer to the columns in Fig. 3. The Sauland area (Fig. 4) is framed. Numbering of the lithostratigraphic units starts from the main study area south of the town of Rjukan and continues via the Rødberg-Blefjell area in the east to the Kalhovd area in the northwest: (1) Rjukan group. (2) Vindeggen group, Upper Brattefjell formation excluded (3) Upper Brattefjell formation. (4) Oftefjell group. (5) Brunkeberg formation. (6) Høydalsmo group. (7) Transtaulhøgdi supracrustals. (8) Lifjell group. (9) Eidsborg formation. (10) and (11) Skogsåa porphyry and metasediments of the Heddal group, respectively. (12) and (13) felsic and mafic volcanics of the Nore group, respectively. (14) Sørkjevatn formation. (15) and (16) felsic volcanics and metasedimentary Kalhovd formation of the Kalhovd area, respectively.

tion was deposited after 1054 ± 22 Ma (op. cit.), which is almost 100 Ma after extrusion of the Dalaå porphyry of the Høydalsmo group (1150 ± 4 Ma, Laajoki et al. 2002), but closer to the deposition age of the Eidsborg formation (<1118 ± 38 Ma, de Haas et al. 1999).

Previous studies of the Heddal group

Only sporadic observations are available on the Heddal rocks, and their lower contact has not been described at all. The parts of the Telemark supracrustals located in the Sauland area (Fig. 4) have previously been examined by Törnebohm (1889), who mentioned that a quartzite-clast conglomerate occurs at Heksfjellet. Werenskiold (1910) mapped the Heddal rocks as granulites and porphyroids, but thought that they are overlain by the Lifjell quartzite, into which the Heksfjellet conglomerate was included. Dons (1960a, p. 8) mapped these rocks as "granulites", "leptites" etc. but he was unsure of their stratigraphic position. The conglomerate at the eastern end of Heksfjellet was included in the Seljord group. On the map published by Dons & Jorde (1978) the Heddal rocks are included in the stratigraphically undifferentiated group.

Dahlgren et al. (1990b) proposed the name Heddal group for the siliceous, volcaniclastic sediments, rhyolitic ignimbrites, tuffs and minor marbles that occur in the surroundings of Heddal. They state that the Heddal group overlies the Seljord group, but it is uncertain whether it was deposited as a continuation of the Seljord group or represents a totally different event. Later on, Dahlgren (1993) mentioned that the Heddal group had been deposited prior to the Bandak group.

Vast areas on the Hamar map sheet are marked as Heddal group metasandstones with minor conglomerates of depositional ages younger than 1120 Ma (Nordgulen 1999). They are not in contact with the Vindeggen group in the west, being separated from it by a narrow belt of metavolcanic rocks of the Nore group (Bingen et al. in prep.).

Structure and lithostratigraphy of the Sauland area

The simplified geological map and stratigraphic columns of the Sauland area in Figs. 4 and 5 area based on detail mapping of the contact zone of the Heddal group at the hills of Himingen, Heksfjellet, and Rennevassnutan, and the Heksfjellet conglomerate at Heksfjellet and in the poorly exposed valley of Slåkådalen. The bedrock can be subdivided into three major structural areas: (1) The Rennevassnutan area lies north of

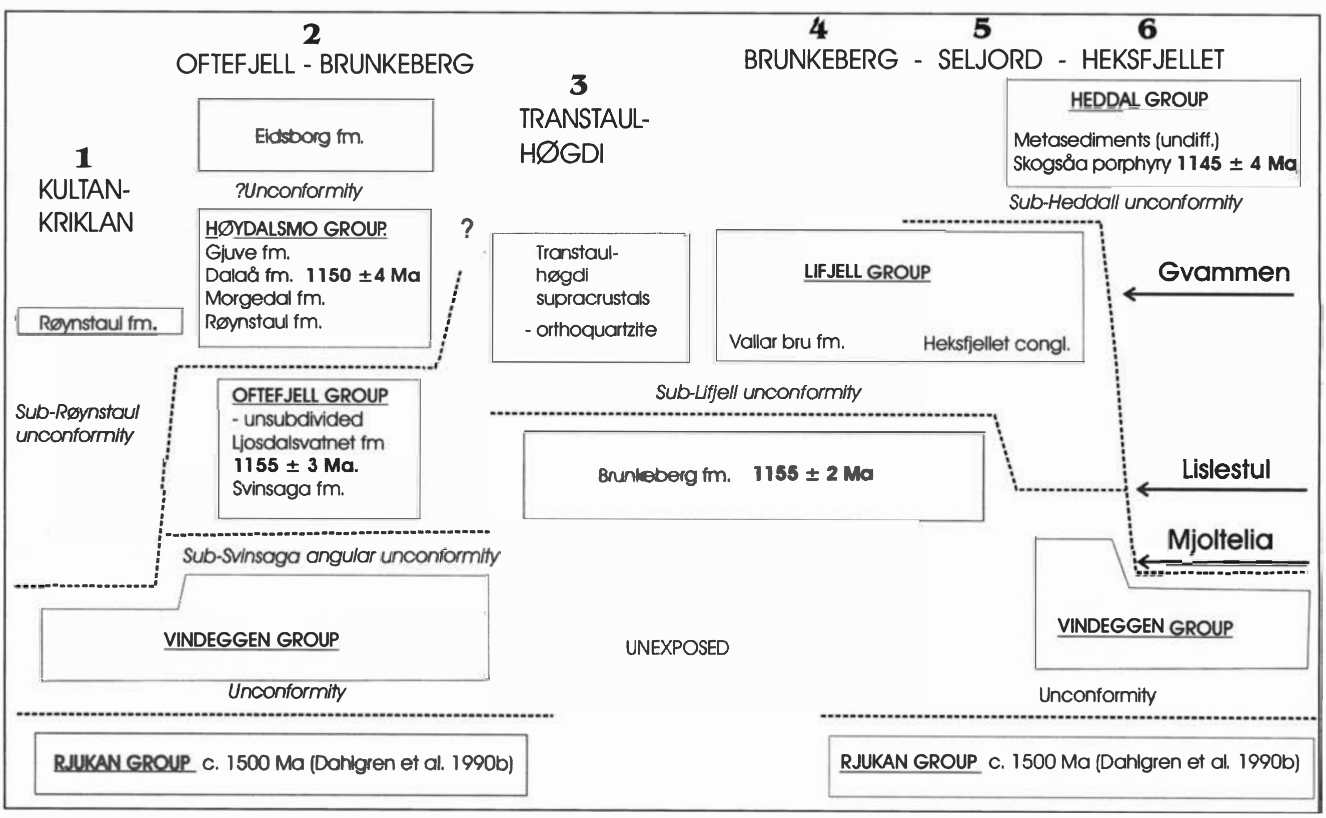

Fig. 3. Lithostratigraphy of the Bandak – Sauland area (modified from Laajoki et al. 2002). Positions of the Gvammen, Lislestul, and Mjoltelia outcrops relative to the sub-Heddal unconformity are given under the Heksfjellet column.

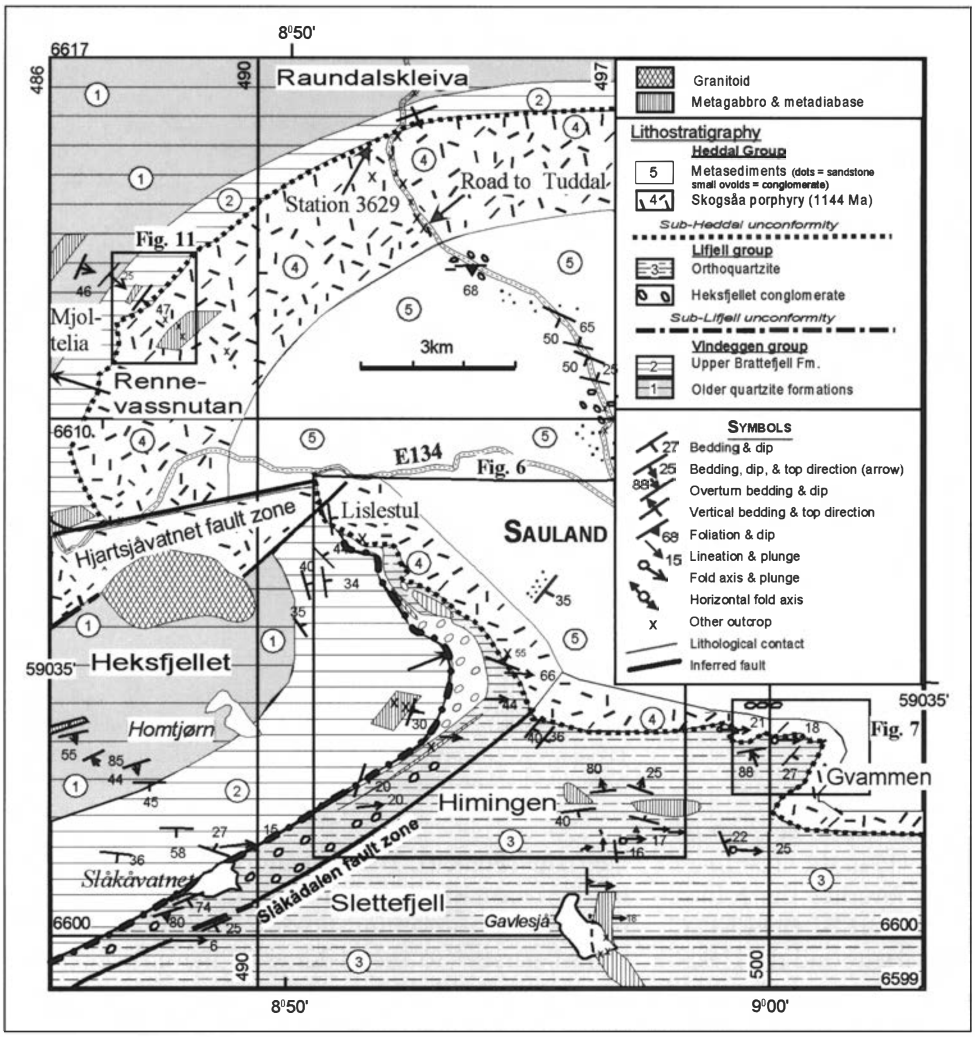

Fig. 4. Simplified geological map of the Sauland area based on the recent mapping by the author and the map by Dons & Jorde (1978). The areas of Figs. 6, 7, and 11 are framed. Grid lines refer to UTM-coordinates.

the Hjartsåvatnet fault zone and represents part of an open syncline which plunges gently ESE. (2) The Heksfjellet area represents part of an anticline plunging gently ESE. It is likely that these two folded units originally formed a syncline-anticline pair, which was later separated by the unexposed Hjartsjåvatnet fault zone. (3) The Slettefjell-Himingen area, which is structurally more complex, represents the northern, partly overturned, part of a large synclinorium folded along axes that are subhorizontal or plunge gently east. The contact between the synclinorium and the Heksfjellet area is marked by the Slåkådalen fault, which is not exposed, but its existence can be demonstrated in the eastern end of the Mjella river gorge (Fig. 6). To the west, a thin metadiabase dyke occupies the fault zone. The fault zone quite likely continues to the western end of Grunningsdalen, where the Vindeggen group in the north is in tectonic contact with the Brunkeberg formation and the Lifjell group in the south (Fig. 2). Strong deformation associated with this fault zone is demonstrated by the intense stretching of the quartzite clasts of the Heksfjellet conglomerate on both sides of Slåkådalen (see lineation observations in Fig. 6).

The original stratigraphic order of the rocks is best preserved in the Rennevassnutan area where the quartzite formations face to and dip regularly 30 – 50° to the southeast. The c. 5 km thick Vindeggen group lies autochthonously upon the Rjukan group (outside Fig. 4). Its uppermost part consists of monotonous, parallel-laminated – rippled orthoquartzite mapped as the Upper Brattefjell formation. This is overlain unconformably by the Heddal group. This part was mapped in the Mjoltelia area, where the *in situ* breccias are exposed at the sub-Heddal unconformity (Skårsetvatnet road column in Fig. 5).

At Heksfjellet, the Upper Brattefjell orthoquartzite of the Vindeggen group is overlain unconformably by the Lifjell group, which starts with an *in situ* breccia and the Heksfjellet cobble-boulder conglomerate (Figs. 5 & 6). The clasts in the conglomerate are mostly quartzites from the underlying Vindeggen group, but acid volcanite clasts are also common in higher parts of the conglomerate. One of the latter gives a U-Pb zircon age about 1500 Ma (Laajoki et al. 2002), indicating that the volcanic clasts were probably derived from the Rjukan group. The Heksfjellet conglomerate is overlain by a typical parallel-laminated – rippled orthoquartzite of the Lifjell group lithologically identical to that of the Upper Brattefjell formation. The Lifjell group is overlain unconformably by the Heddal group. This contact can be mapped on the eastern flank of Heksfjellet and is nicely exposed on the Lislestul outcrop to be described in detail.

Both the Vindeggen group and the lower part of the Lifjell group are missing in the Slettefjell area, which is underlain by the Lifjell quartzite folded openly along axes plunging gently east. The axial planes are mostly vertical, but are overturned to the north in the north. The Lifjell quartzite is in direct contact with the Heddal group (Himingen column in Fig. 5).

As it will become apparent in the next sections, the nature of the sub-Heddal unconformity differs significantly between these three areas.

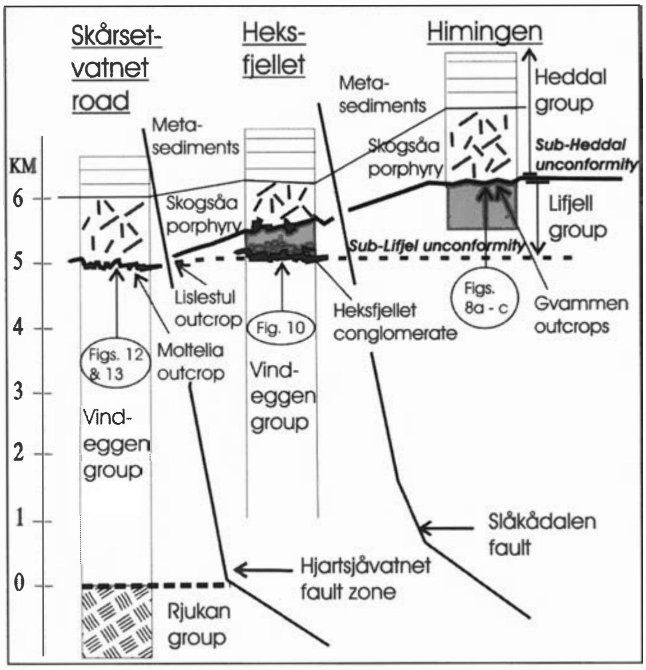

Fig. 5. Simplified stratigraphic columns across the sub-Heddal unconformity in the localities studied. The stratigraphic locations of the outcrops photographed are indicated. Thicknesses are estimates from this study and the map by Dons & Jorde (1978).

Sub-Heddal unconformity in the Sauland area

The sub-Heddal unconformity is known to be exposed at the following localities (Fig. 4): (1) in the Gvammen area, east of Himingen, where it overlies the folded Lifjell quartzite, (2) at the eastern part of Heksfjellet, where it erodes both the Lifjell quartzite and the Heksfjellet conglomerate, (3) in the Mjoltelia area, where the Lifjell group is absent, but where a peculiar palaeoweathering surface is visible on top of the Upper Brattefjell orthoquartzite of the Vindeggen group, and (4) in the Raundalskleiva area, where the Heddal group lies directly on the Upper Brattefjell orthoquartzite. These localities demonstrate that the sub-Heddal unconformity erodes progressively deeper levels of its substratum when it is traced from south to north. The localities will be described in this order. UTM coordinates of the key outcrops are given in respective figures.

Gvammen area

The sub-Heddal unconformity follows seemingly conformably the folded, parallel-laminated Lifjell orthoquartzite in the surroundings of the small Gvammen summer cottage locality (Figs. 4 & 7). (The locality should not be confused with the bigger Gvammen settlement along the Highway 134). At the hinge zone, the bedding in the Lifjell orthoquartzite and the unconformity dip 32° – 23° to 115° – 150°, whereas on the northern flank of the fold the rocks dip steeply or are slightly overturned to the north.

At station 2136, which belongs to the hinge zone, the Skogsåa porphyry lies directly on the Lifjell orthoquartzite (Fig. 8a). The unconformity is slightly affected by recent erosion, but fresh samples cut across it show that the unconformity is sharp and seems to be almost parallel to the bedding in the quartzite. It is, however, subordinately uneven and erosional. No larger quartzite fragments were detected above the unconformity, and porphyry veinlets are absent in the quartzite. The rocks are epidotized in a narrow zone on both sides of the unconformity.

It can be seen under the microscope that the unconformity is obscured by abundant epidote. The Skogsåa porphyry is highly epidotized and its plagioclase has been replaced almost completely by sericite. No distinctive porphyric texture is visible, but the rock contains biotite and muscovite porphyroblasts. Polycrystalline quartz aggregates, which are common, may represent vesicle fill. Some of the quartz grains are embayed indicating their volcanic origin. The Skogsåa porphyry does not seem to have affected the Lifjell quartzite to any great extent, indicating that the latter had been well indurated before the eruption of the porphyry.

At the northern flank of the fold, at station 2127, the unconformity has been folded into a vertical position. A few cm-wide fractures, which continue from the contact about 10 cm into the quartzite, indicate that the unconformity has been exposed to subaerial weathering (Fig. 8b). The fractures are filled by a porphyroblastic biotite-muscovite schist, which represents epiclastic material. This indicates that the Lifjell quartzite was indurated and fractured before deposition of the

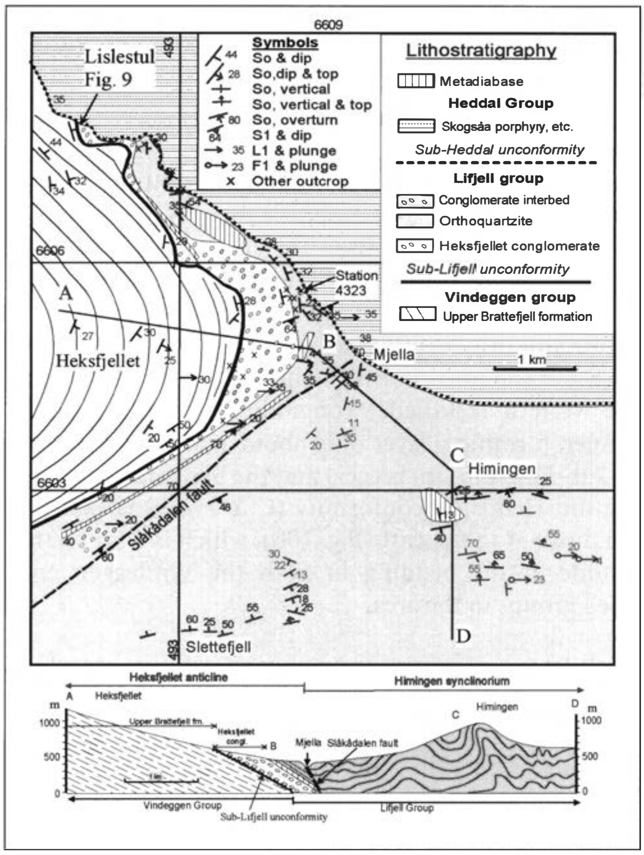

Fig. 6. Detailed map of the eastern part of Heksfjellet and the Heksfjellet-Mjella-Himingen cross-section. Note that the parts A-B and C-D of the cross section are drawn almost parallel to and across the fold axis, respectively. Bedding and younging observations show the significant change in structure across the Slåkådalen fault (dip unknown). Location of the Lislestul outcrop in Fig. 9 is indicated.

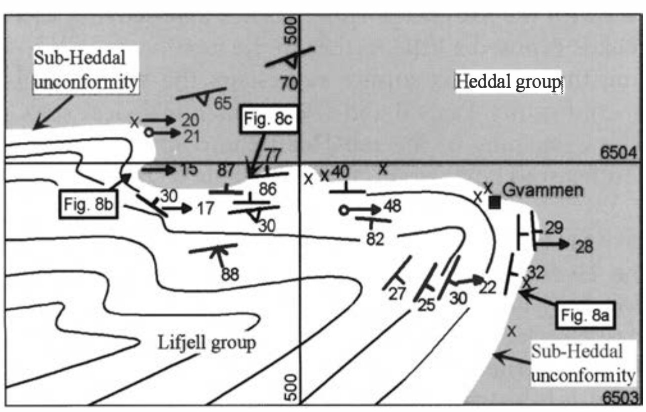

Fig. 7. Detailed map of the Gvammen area. Locations of photographs in Fig. 8 are shown.

precursor material of the muscovite schist. The rock immediately above the unconformity is a similar muscovite schist, which passes gradually into the Skogsåa porphyry.

Some 300 m west of the previous outcrop, at station 2122, the unconformity has been overturned and is intensely sheared. It contains solitary, pencil-like, stretched orthoquartzite clasts in the muscovite schist matrix (Fig. 8c). The Heddal contact rock at the nearby station 2120 is a foliated muscovite-quartz schist composed mainly of muscovite and granoblastic quartz with less abundant biotite and large porphyroblasts of microcline enclosing several mica and quartz grains. One granoblastic orthoquartzitic clast and one embayed quartz grain, probably of volcanic origin, were found in the thin section. Accessory minerals include well-rounded zircon and apatite. These, and the petrographic features described above, point to a metamorphosed epiclastic sedimentary rock, which derived its material from both the underlying Lifjell (?and Vindeggen) quartzite and an unknown (?Rjukan and ?Heddal) volcanic source. Away from the contact the quartzite clasts disappear and the rock grades into a foliated Skogsåa porphyry.

East of Gvammen to Reskjem (Dons 1960a, p. 15) the sub-Heddal unconformity has not been mapped systematically, but sporadic structural observations indicate that it is of the same type as described above; the Skogsåa porphyry lies upon the Lifjell orthoquartzite.

Eastern part of Heksfjellet

The Upper Brattefjell orthoquartzite of the Vindeggen group occupies the hinge zone of an open anticline, which plunges gently to the east (Fig. 6). It is overlain seemingly conformably by the Heksfjellet conglomerate of the Lifjell group. This older erosional surface, the sub-Lifjell unconformity, is marked by an *in situ* breccia of which one example will be given later. The Heksfjellet conglomerate is overlain by parallel-laminated Lifjell orthoquartzite, which is separated from the rocks of the Himingen area by the Slåkådalen fault. Except for the Lislestul outcrop, the sub-Heddal unconformity is not exposed northwest of the northeastern end of the Slåkådalen. However, detailed mapping revealed that the unconformity surface is rather uneven and that it erodes stratigraphically higher parts of the Lifjell group in the southeast than in the northwest (Fig. 6). At station 4323 (Fig. 6), a narrow body of the Skogsåa porphyry continues some 50 m down into the Lifjell quartzite. As the contacts are not exposed, it is not possible to decide whether this is due to sub-Heddal erosion or later faulting.

Lislestul outcrop

The Lislestul outcrop (station 3911), where both the sub-Lifjell and sub-Heddal unconformities are visible, and where the latter erodes the Heksfjellet conglomerate, is located 300 metres southwest of the abandoned Lislestul cottage (Fig. 6). The sub-Lifjell substratum consists of parallel-laminated Upper Brattefjell orthoquartzite, which becomes structureless closer to the

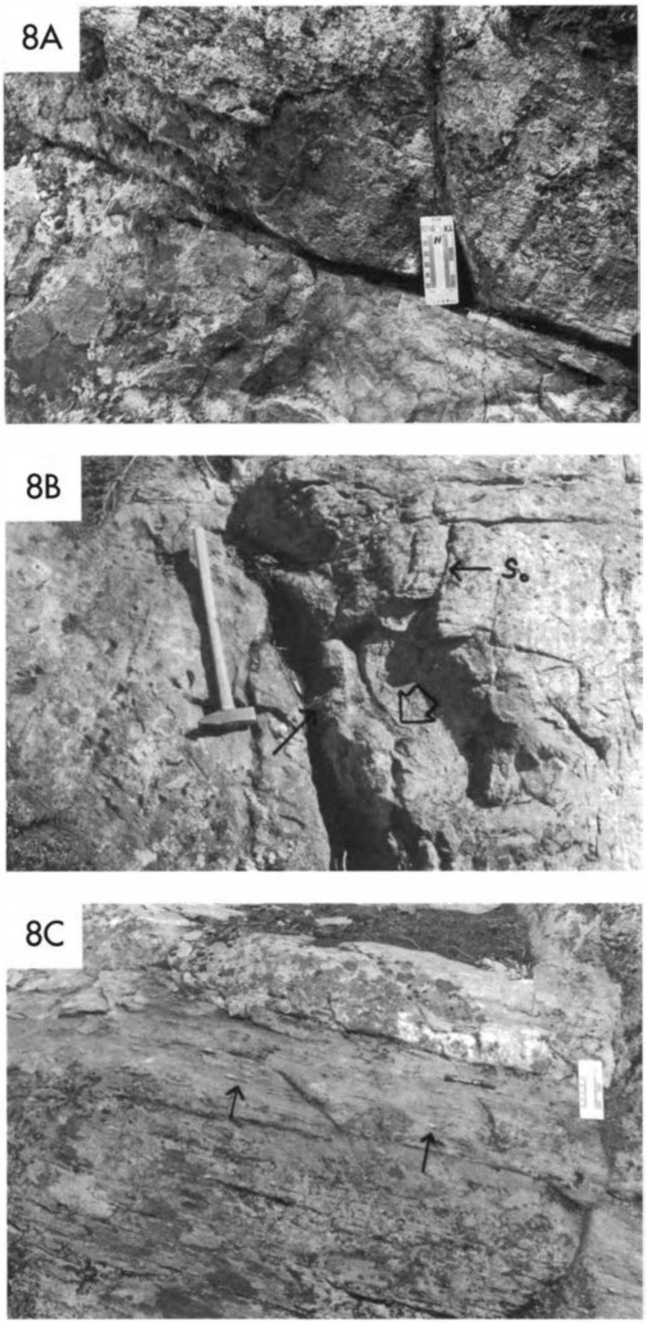

Fig. 8. The sub-Heddal unconformity in the Gvammen area (for locations see Fig. 7).
(A) The sub-Heddal unconformity (under the scale) between the Lifjell orthoquartzite (below) and a Heddal porphyry. Seen from SW. Station 2136KL-N, UTM 500926/6603551. Photo 3706.
(B) Slightly folded, almost vertically dipping unconformity (in the shadow) between the Lifjell orthoquartzite (right = south) and basal Heddal group epiclastic zone (under the 60 cm long hammer). Epiclastic detritus has been squeezed into the fractures in the orthoquartzite (open arrow). The stretched quartz veins (thin arrow) plunge 20° to 88°. The bedding in the quartzite ($H5_0$) defines broad, open S folds. Seen from the west. Station 2127KL-N, UTM 499674/6603897. Photo T13-10.
(C) Vertical view of the slightly overturned unconformity between the Lifjell orthoquartzite (the part above the scale) and basal Heddal group epiclastic zone with small, stretched, quartzite rods (arrows) plunging 15° to 90°. Marker 14 cm. Seen from the south. Station 2122KL-N, UTM 499299/6603985. Photo T13-8.

sub-Lifjell *in situ* breccia (Fig. 9). The latter is only some 10 – 30 cm thick and consists of a basal fracture zone overlain by *in situ* orthoquartzite clasts with scanty muscovite schist matrix (Fig. 10a). This zone passes rapidly into the polymictic Heksfjellet cobble (-boulder) conglomerate. The clasts are mainly quartzite, but acid vulcanite clasts are also common. The conglomerate occurs as two bodies. The contact of the eastern triangular body (c. 20 x 10 m) with the overlying Skogsåa porphyry in the east is not exposed (marked by A in Fig. 9), but the upper surface of the conglomerate suggests that the unconformity dips some 45° to the east. The western Heksfjellet conglomerate body is much thinner, forming a layer only about 1 m thick between the sub-Lifjell *in situ* breccia and the Skogsåa porphyry. The sub-Heddal unconformity (C in Fig. 9) is exposed and dips 55° to the east (Fig. 10b), which is close to the attitude of the bedding in both the Vindeggen and Lifjell groups in the area.

The E-W trending part of the unconformity, marked by letter B in Fig. 9, differs from the parts A and C in that it is vertical and sharp (Fig. 10c) and trends almost at right angles to them. This structure does not continue into the underlying quartzite, and shows only little, if any, displacement of the Heksfjellet conglomerate. Furthermore, it does not significantly deform its surroundings and therefore its origin was probably connected with the pre-syn-Heddal erosion of the Heksfjellet conglomerate. Another E-W trending surface (D in Fig. 9) cuts all rock units under part C of the sub-Heddal unconformity (the Heksfjellet conglomerate, the *in situ* breccia, the Upper Brattefjell orthoquartzite). The contact with the Skogsåa porphyry is not exposed, but this rock is exposed a little farther to the northwest, indicating that also this surface represents the sub-Heddal unconformity. Parts B and D demonstrate a clear stepwise deepening of the sub-Heddal unconformity from southeast to northwest (cf. the Mjoltelia section).

Like the Gvammen outcrops, the basal epiclastic part of the Heddal group passes gradually into the Skogsåa porphyry, and it is not possible to decide where the epiclastic rock ends and the volcanic rock starts. This part, which overlies the western Heksfjellet conglomerate body, is informally called the Lislestul member (Fig. 9). It begins with a c. 1 m thick cobbly rock, where solitary, well-rounded quartzite cobbles, derived most likely from the underlying Heksfjellet conglomerate, occur in a micaceous matrix with microcline-porphyroblasts (Fig. 10d). No conglomeratic clasts were detected, indicating that during erosion the Heksfjellet conglomerate was only slightly indurated, such that clasts could be easily loosened from their host rock. The amount of clast material decreases upwards while the matrix contains gradually more and more volcanic detritus. Mineral clasts of K-feldspar phenocrysts are big enough to be seen by the naked eye.

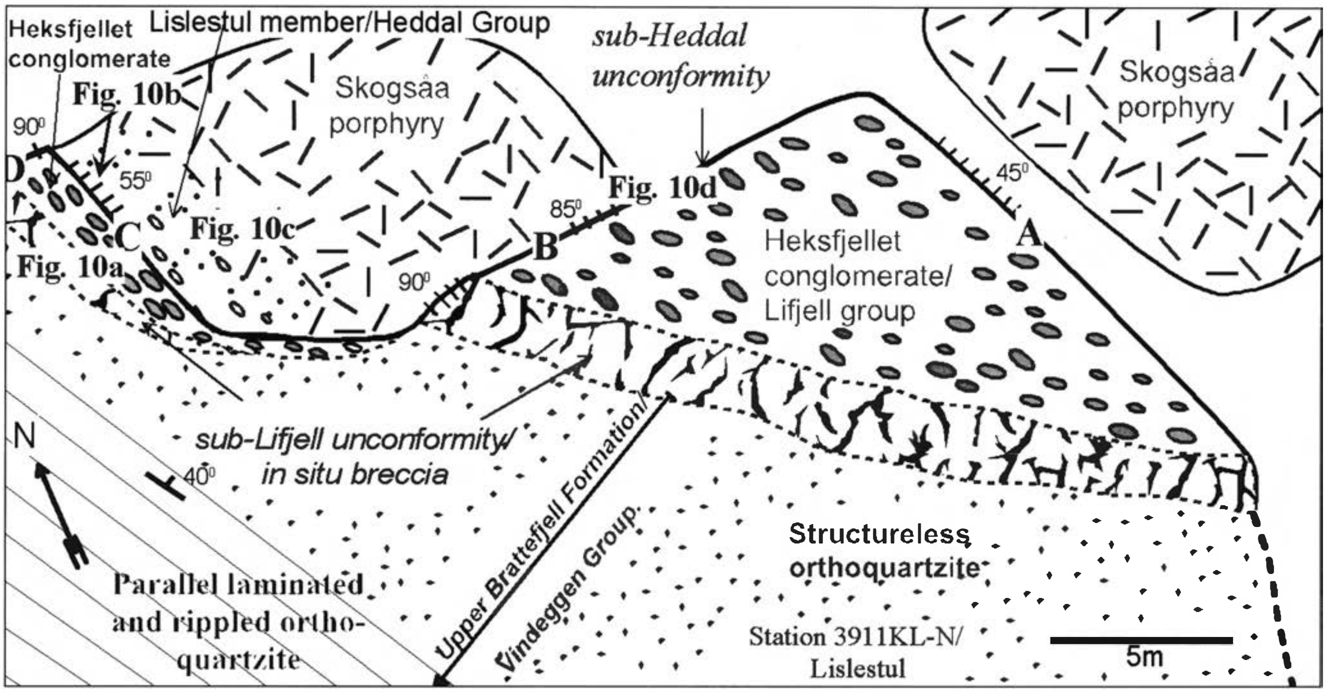

Fig. 9. Lislestul outcrop (station 3911). Sketch of the outcrop showing the sub-Heddal and sub-Lifjell unconformities developed on the Heksfjellet conglomerate and the Upper Brattefjell Formation, respectively. Letters A - D refer to the parts of the sub-Heddal unconformity discussed in the text. Sites of photographs in Fig. 10 are indicated. Note that the contact of the epiclastic Lislestul member with true Skogsåa porphyry is gradual.

Mjoltelia area

The sub-Heddal unconformity was mapped in detail on both sides of the road to Skårsetvatnet (Fig. 11). The unconformity is developed upon the Upper Brattefjell orthoquartzite, which dips 40 – 65° to the southeast. Detailed mapping of the unconformity shows that, from southwest to northeast, it falls progressively to deeper levels of its substratum (Fig. 11). This deepening takes place in a stepwise manner along 10 – 20 m long, NW-SE directed sharp boundaries. These structures resemble the fault-like parts of the sub-Heddal unconformity on the Lislestul outcrop (surfaces B and D in Fig. 9) in the sense that they do not seem to continue into the Upper Brattefjell formation or the overlying Skogsåa porphyry, do not deform their surroundings, and cut the bedding in the Upper Brattefjell formation at high angles. They may represent minor, fracture-controlled erosional palaeosurfaces.

Mjoltelia outcrop

The sub-Heddal unconformity is exposed three-dimensionally at station 3442, which is located on the eastern flank of a small hill of Mjoltelia, 200 m southwest of the Skårsetvatnet road (Fig. 11). The outcrop shows a unique, rugged, palaeoweathered surface. It is c. 15 m wide and 8 m high and its exposed upper surface is c. 5 x 10 m in size. The contact with the nearby Skogsåa porphyry is covered. The most eye-catching feature of the outcrop is two irregular channels, which have been excavated into the parallel-laminated Upper Brattefjell orthoquartzite (Fig. 12a). Outside the channels, the unconformity surface is very rough due to an irregular fracture framework (Fig. 12b). Mosaic breccia may occur in this part (Fig. 12c).

The substratum is visible at the upper surface of the outcrop, but is covered by lichen. It can be seen, however, that the underlying rock is Upper Brattefjell orthoquartzite with locally preserved parallel lamination. It is overlain erosively by a conglomerate, which contains quartzite pebbles and cobbles in a quartzitic matrix. It cannot be seen how the conglomerate is related to the rugged sub-Heddal palaeosurface, except that it underlies the latter. The conglomerate may be a small pocket of the Heksfjellet conglomerate.

The main channels are irregular in geometry, margin shape and width (20 cm to 1 m). Their depths cannot be measured accurately as they are cut obliquely by the recent erosion surface. The formation of the gutters seems to have been controlled by fracturing as they branch and die out into thin fractures at their bottoms (Fig. 12b). The curved 'sub-channel' fractures continue only some 10 – 20 cm into the underlying quartzite, and some of them are clear continuations of the of channel margins. At the bottom of the southern channel there are quartzite pebbles derived probably from the underlying conglomerate. Otherwise the channels are filled by a foliated muscovite schist, which in this case is more pelitic than the muscovite schists in the Lislestul and Gvammen outcrops. The schist is composed almost totally of opaque-pigment laminated mus-

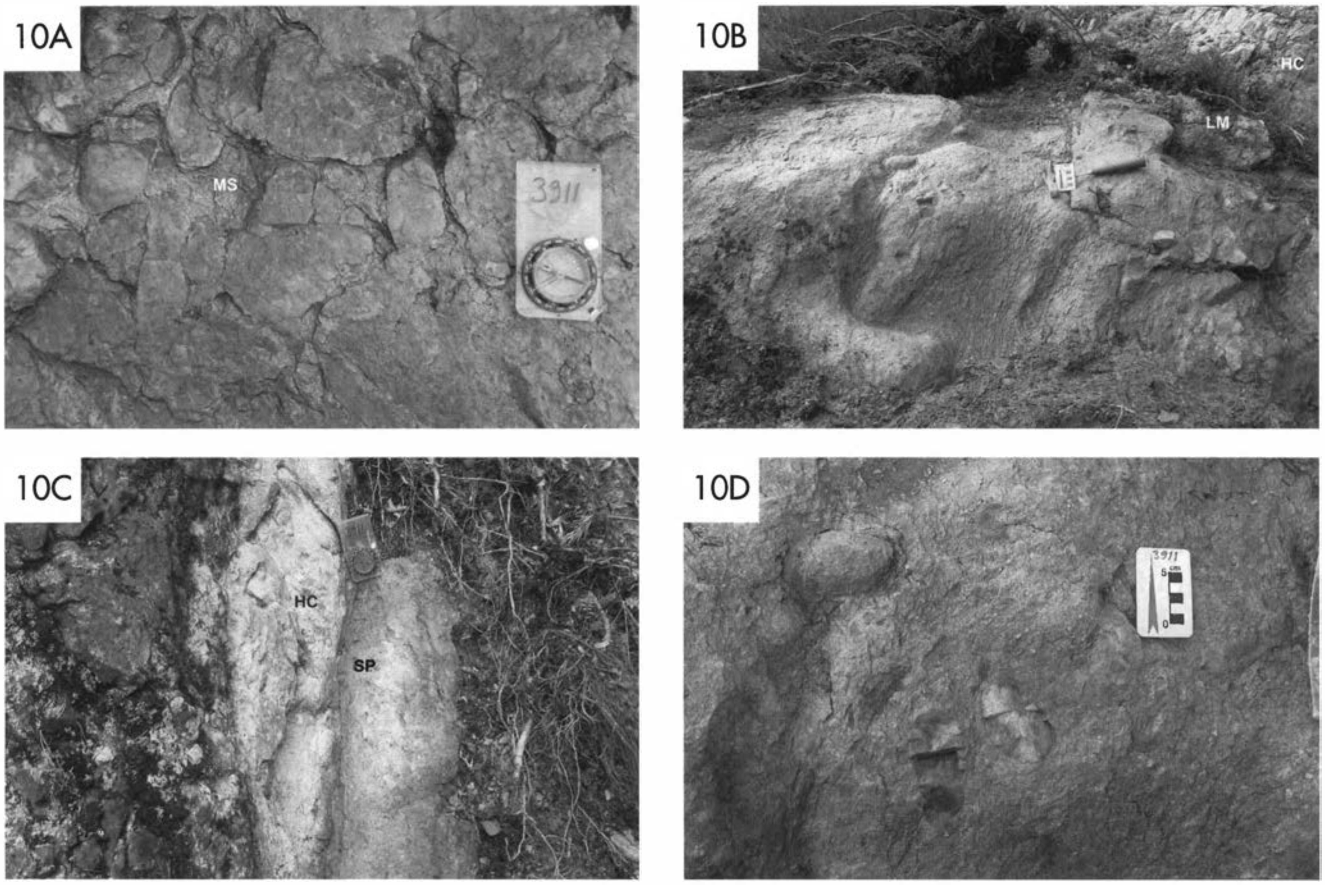

Fig. 10. Photographs of the Lislestul outcrop (for locations see Fig. 9). (A) Sub-Lifjell in situ breccia. Structureless Upper Brattefjell orthoquartzite occupies the lower part. The matrix (MS) is scanty but rich in muscovite. (B) View of the sub-Heddal unconformity between the Heksfjellet conglomerate (HC) and the basal, conglomeratic Lislestul member (LM) of the Heddal group. Note that the amount of the quartzite clasts decreases upwards and the rock passes gradually to the Skogsåa porphyry. (C) Sub-Heddal unconformity between the Heksfjellet conglomerate (HC) and the Skogsåa porphyry (SP) following a minor syn-sedimentary fault?/erosional scarp. (D) Close-up of the upper part of the Lislestul member showing solitary quartzite clasts in a matrix rich in volcanic detritus.

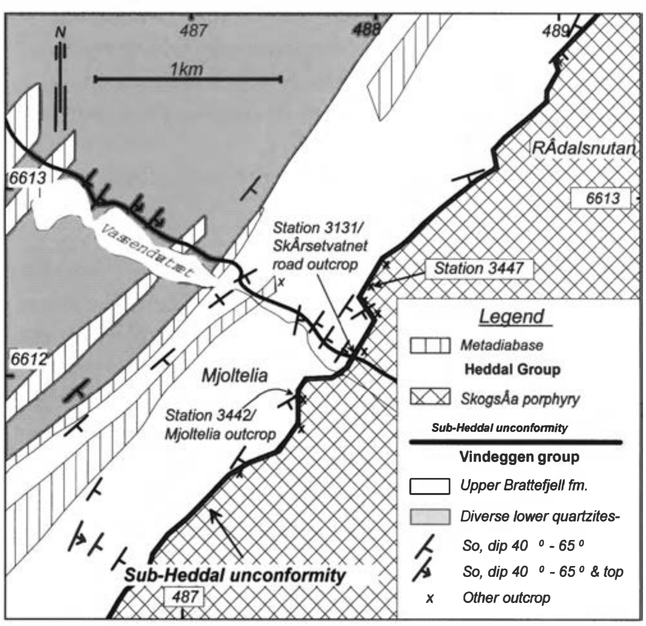

Fig. 11. Detailed map of the sub-Heddal unconformity in the Mjoltelia area. Locations of the stations discussed in the text are indicated

covite with only minor amounts of quartz and feldspar. Microcline and biotite porphyroblasts are absent indicating a lower degree of metamorphism than in Lislestul. Similar schist with variable amounts of clastic quartz and feldspar occurs as fracture fill everywhere in the outcrop. The fracture framework starts with solitary thin fractures subparallel to the bedding in the Upper Brattefjell formation. Their number, width, and curvature increase upwards with the consequence that the unconformity seems bulbous (Fig. 12b).

Skårsetvatnet road outcrop

An easily accessible outcrop of the sub-Heddal unconformity is located on the north side of a private road (locked by a bar) to the cottage settlement of Lake Skårsetvatnet. It is located only some 500 m northeast of the previous outcrop (station 3131 in Fig. 11). The bedding in the underlying parallel-laminated Upper Brattefjell orthoquartzite dips about 50° to the southeast. The sub-Heddal unconformity is subparallel to this (Fig. 13a) and resembles the Mjoltelia outcrop except that no channels are visible. The closest Skogsåa porphyry outcrop occurs a few metres to the east. Also in this case the amount and width of the fractures increase gradually upwards within the fracture framework (Figs. 13b & c). The lowermost parts may show mosaic breccia (Fig. 13c). The fractured zone is 2 - 4 m thick and contains in its lower part boulder-size (over 1 m long) quartzite bodies which are partly attached to their substratum and each other (Figs. 13c & d). The fractures are up to 10 cm wide and are filled by a mylonitic muscovite schist with quartz-opaque "augens" and unusually abundant accessory apatite and zircons. The unconformity can be described as an *in situ* breccia framework, where the open fractures were later filled by pelitic material.

North of the Skårsetvatnet road, the sub-Heddal unconformity is exposed at the station 3447 (Fig. 11). Here the muscovite schist lies directly on the Upper Brattefjell orthoquartzite and the fracture surface seems to be missing. The muscovite schist is of the same type as in the Mjoltelia outcrop: relics of replaced quartz occur in fine-grained muscovite host rock.

Raundalskleiva area

The northernmost outcrops studied occur south of the Raundalskleiva mountain (Fig. 4), where the sub-Heddal unconformity is exposed in three small outcrops. In each case, the fracture framework described above is missing and the muscovite schist has been deposited directly on the Upper Brattefjell orthoquartzite. At station 3629 (Fig. 4), the muscovite schist contains solitary, angular orthoquartzite fragments from the underlying Upper Brattefjell formation (Fig. 13e). The orthoquartzite/muscovite schist contact is irregular and muscovite continues into the orthoquartzite along grain boundaries for a short distance.

Discussion

The ages of the Brunkeberg and Skogsåa porphyries limit that of the sub-Heddal unconformity to between 1155 and 1145 Ma, indicating that this unconformity is markedly younger than the ≥1155 Ma old sub-Svinsaga unconformity, but of about the same age as the ≤ 1155 - ≥1150 Ma old sub-Røynstaul unconformity in the type area of the traditional Bandak group (Laajoki et al. 2002). Due to the locations on different sides of the Rjukan rift (Fig. 2), the relationship between the sub-Heddal and sub-Røynstaul unconformities cannot be solved in the field and is kept open (Fig. 3).

Fig. 14 gives a simplified reconstruction of the sub-Heddal unconformity along the mapped part from Gvammen to Raundalskleiva. It was done by supposing that during the deposition of the Heddal group, the

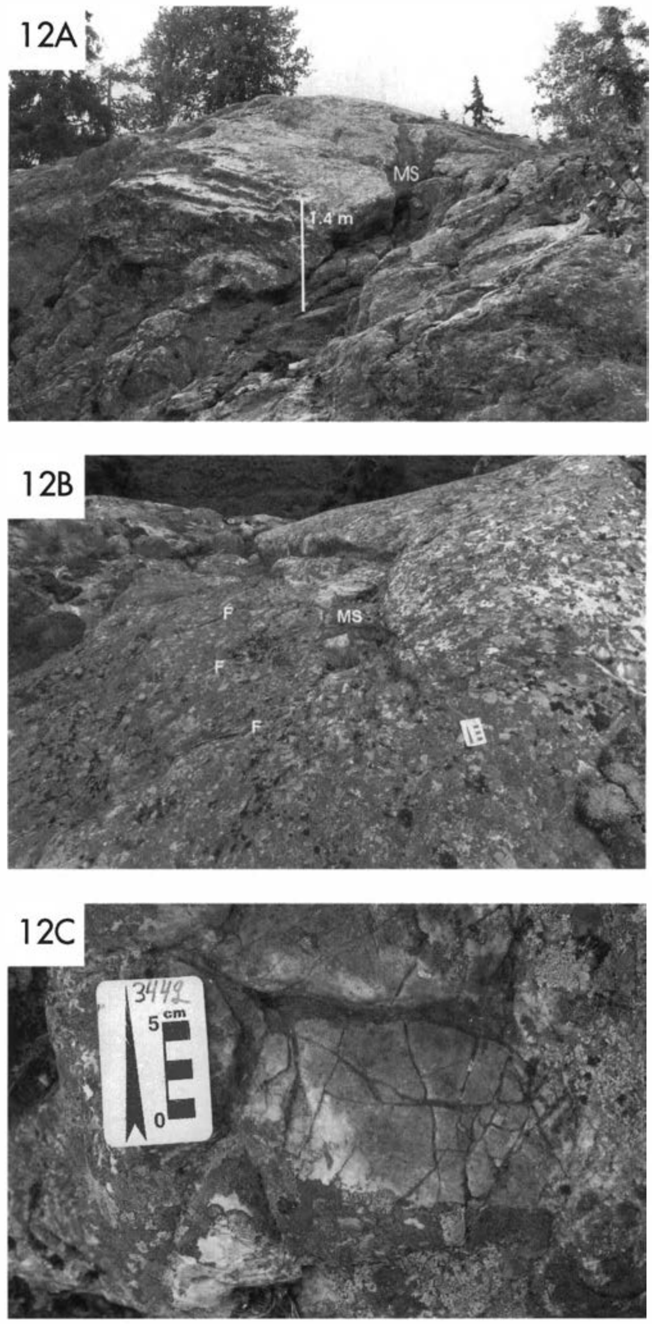

Fig. 12. Photographs of the Mjoltelia outcrop (Station 3442KL-N, UTM 487614/6611906). (A) View of the outcrop from the northeast showing the northern channel and the bulbous appearance of the surface of the sub-Heddal unconformity developed on Upper Brattefjell orthoquartzite. The channel is filled by muscovite schist (MS). The flat surface above the 1.4 m stick is considered as a recent erosional feature. Aut7901. (B) Branching and dying out of the northern channel seen from above. MS = muscovite schist fill. Note the thin fractures (F) subparallel to the bedding in the Upper Brattefjell orthoquartzite (covers main part of the photograph). Aut7896. (C) Mosaic breccia developed upon Upper Brattefjell orthoquartzite. The fractures are filled by muscovite schist. Aut7898.

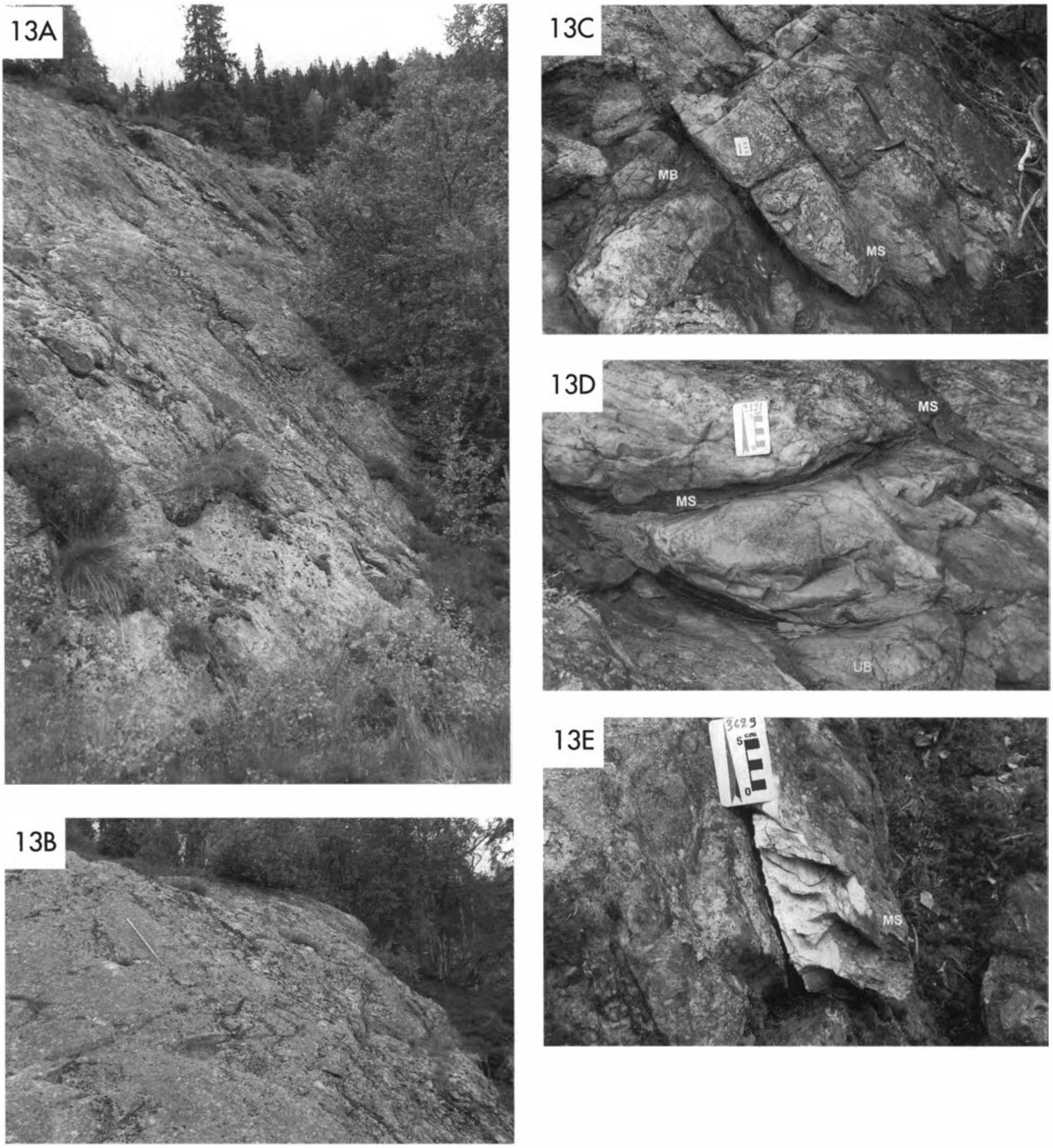

Fig. 13. Sub-Heddal unconformity at the Skårsetvatnet road outcrop (A – D, station 3131KL-N, UTM 487957/6612172) and south of Raundalskleiva (E, station 3629KL-N, UTM 492400/6615664). (A) General view of the basal fracture zone approximately parallel to the regional lineation and perpendicular to bedding in Upper Brattefjell quartzite visible in the lower left. Skogsåa porphyry occurs under the bushes to the right (east). The hammer in the foreground is 30 cm long. Aut4507. (B) General view from above of the fracture framework – in situ breccia developed on Upper Brattefjell formation (left of the 1.4 m long stick). Aut7951. (C) Close-up view of the sub-Heddal fracture zone almost parallel to the regional lineation and perpandicular to bedding in Upper Brattefjell formation. The sparse muscovite schist fill (MS) between in situ quartzite fragments is partly weathered away. Mosaic breccia (MB) is visible on Upper Brattefjell quartzite. Aut4503. (D) Close-up view of the sub-Heddal fracture framework almost perpendicular to the regional lineation. Muscovite schist matrix (MS) between quartzite fragments partially in contact with each other and to the Upper Brattefjell orthoquartzite substratum (UB). Aut4504. (E) Basal in situ breccia (under the scale) upon Upper Brattefjell orthoquartzite overlain by muscovite schist (MS). Station 3629, UTM 492400/6615664. Aut 8404.

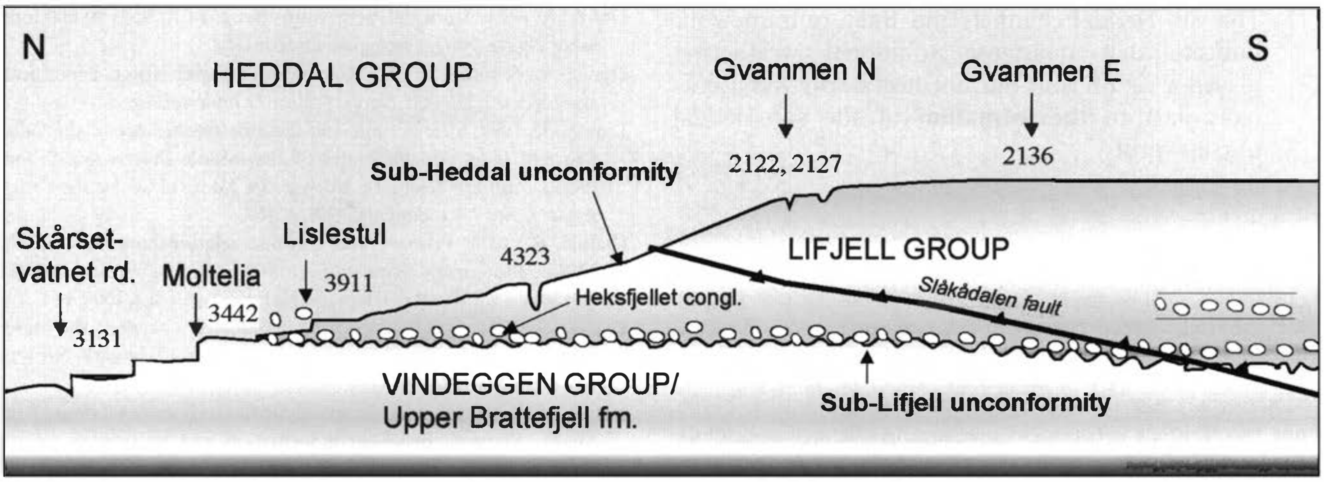

Fig. 14. Conceptual reconstruction of the sub-Heddal unconformity from Gvammen to the Skårsetvatnet road. Not to scale. Numbers refer to the stations discussed in the text.

Vindeggen and Lifjell groups dipped 30° to the present southeast and that the Slåkådalen and Hjartsjåvatnet faults have not drastically affected the stratigraphy. The cross-section indicates that the unconformity surface was smooth in the south; the only locality where fractures were noted in the substratum is shown in Fig. 8b. In contrast, the pre/early-Heddal fracturing and associated? faulting are common in the northern part of the profile, where the unconformity erodes the Upper Brattefjell orthoquartzite. However, it should be noted that the observation points are rather sporadic and that it is not possible to reconstruct the three-dimensional palaeotopography of the unconformity surface.

The irregular geometry of individual fractures and fracture framework in general and associated *in situ* mosaic breccias indicate that break-up of the substratum orthoquartzite was caused by surficial processes. Consequently, their presence strongly suggests that the surface/basal zone mapped is a real palaeoerosional feature. The fact that it was developed on both the Lifjell and Vindeggen groups indicates that the erosion was significant and deep. As fractures are encountered even in the Lifjell orthoquartzite, the latter must have been at least initially lithified before the formation of the unconformity.

The muscovite schist fill of the fractures cannot have been derived from the underlying Lifjell and Brattefjell groups, as weathering cannot produce such a large amount of pelitic material from an orthoquartzite *in situ*. This is confirmed by a whole rock Nd analysis, indicating that the muscovite schist fill in the Skårsetvatnet road outcrop contains a significant amount of volcanic component (sample 3131 in Andersen & Laajoki, subm.). Consequently, the clastic fill does not represent *in situ* regolith, but has been transported from an unknown source. This indicates that the fractures were open (detritus-free) offering accommodation space for the clastic material. This again indicates that the fractures may represent extensional fractures. One possible surficial process, which can produce open fractures unfilled by sedimentary detritus is thaw and freeze. The fact that the amount and width of the fractures increase upwards, and the presence of mosaic breccia, seem to support this interpretation. Another possibility is fracturing of rift shoulders during initial rifting, but no evidence of this kind of tectonism has been detected. It is also possible, that initial Heddal volcanism and/or associated seismic activity deformed the Heddal basement.

The origin of the channels is hard to interpret as they are filled by muscovite schist and are cut obliquely by recent erosion. The irregular geometry of the channels and their margins may suggest solutional weathering. Quartzose karst landforms have been described from present-day tropical regions, or areas believed to have been tropical in the geologically recent past, but the requirement of tropical weathering is not tenable (Wray 1997). The complex fracture framework and the muscovite schist fill indicate that various pedogenic and sedimentological processes took part in the formation of the sub-Heddal palaeosurface.

Conclusions

(1) As the sub-Heddal unconformity incises both the Vindeggen and Lifjell groups, it represents a distinct depositional unconformity. Fractures developed upon the Lifjell orthoquartzite indicate that also this rock was indurated before it was weathered.
(2) In view of its 1155 – 1145 Ma age, the sub-Heddal unconformity cannot be readily correlated with any other known unconformities within the Telemark supracrustals.

(3) The sub-Heddal channels and fracture framework indicate that quartzose solutional weathering played a significant, but not necessarily the dominant part in the formation of the sub-Heddal unconformity.

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