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The Mesoproterozoic sub-Svinsaga unconformity, central Telemark, Norway

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Abstract

The ≥1155 Ma angular sub-Svinsaga unconformity subdivides the Mesoproterozoic Telemark supracrustal belt into the Vestfjorddalen (ca. 1500 - ≥ 1350 Ma) and Sveconorwegian units (ca. 1155 – ≅ 1120 Ma). The former was folded and faulted first time between 1350 Ma and 1155 Ma and was refolded together with the latter during the main Sveconorwegian deformation stage ca. 1000 Ma ago. In the western part of the study area, the sub-Svinsaga unconformity erodes the Vindeggen group of the Vestfjorddalen supergroup progressively from the present north to south down to ca. 4 km palaeodepth, whereas in central and eastern parts it erodes folded middle parts of the Vindeggen group.

Structural mapping and palaeorelief reconstruction indicate that the sub-Svinsaga unconformity represents a high-relief erosional palaeosurface or palaeolandscape carved into a plateau with mountainous topography in the present north.

Key words: Telemark, lithostratigraphy, quartzite, conglomerate, palaeosurface, Sveconorwegian, Vestfjorddalen, Vindeggen, Oftefjell

1. Introduction

Ancient unconformities represent palaeosurfaces. According to Widdowson's (1997b, p. 5) working definition, the term palaeosurface should indicate *"an indefinable topographic surface of either endogenic or exogenic origin, recognizable as part of the geological record or otherwise of demonstrable antiquity, which is, or was, originally of regional significance, and which as a consequence of its evolution, displays the effects of surface alteration resulting from prolonged period of weathering, erosion, or non-deposition."* This definition restricts attention to those surfaces, which have a regional significance whether this be in terms of tectonics, climate, or geomorphology.

In Precambrian folded and metamorphosed bedrock, unconformities are usually preserved fragmentarily and in most cases only cross-sections of ancient palaeosurfaces can be seen. This highly restricts their use in 3D palaeosurface and palaeolandscape studies, which are the main targets of geomorphology (e.g. articles in Widdowson, 1997a; Thiry & Simon-Coinçon, 1999). Since Hutton's time, old unconformities have been used to dividing sedimentary packages into lithostratigraphic units. With the advent of sequence stratigraphy, surfaces of erosion within the geological record have taken increasing importance also in Precambrian regional studies (e.g. Christie-Blick et al., 1988; Strand & Laajoki, 1999). Unconformities representing Precambrian rock-weathering horizons and associated residual deposits have also been studied extensively as they contain important palaeo-environmental information regarding the composition of the Precambrian atmosphere and climate (e.g. Marmo, 1992; Gall, 1999; Yang & Holland, 2003). Geomorphologic studies include for instance river canyon problems.

This study treats an angular unconformity in slightly folded and metamorphosed Mesoproterozoic bedrock in southern Norway. Dons (1960a, b) recognized it long ago, but no closer description was given. In the following, emphasis is laid on its physical appearance and relation to the underlying bedrock.

2. Geological setting

The Southwestern Scandinavian Domain of the Fennoscandian (Baltic) Shield (Gaál & Gorbatschev, 1987) is divided into segments and sectors separated by Sveconorwegian shear zones, some of which have been reactivated as brittle faults in the Phanerozoic (Fig. 1). In the present paper, the regional terminology of Andersen and Knudsen (2000) is used (Fig. 1). This study is concerned with the northeastern part of the *Telemark Sector*, situated in central south Norway. It is separated from the *Kongsberg Sector* in the east and the *Rogaland-Vest Agder sector* in the west by Sveconorwegian shear zones (Fig. 1; Sigmond, 1998; Nordgulen, 1999; Bingen et al., 2001).

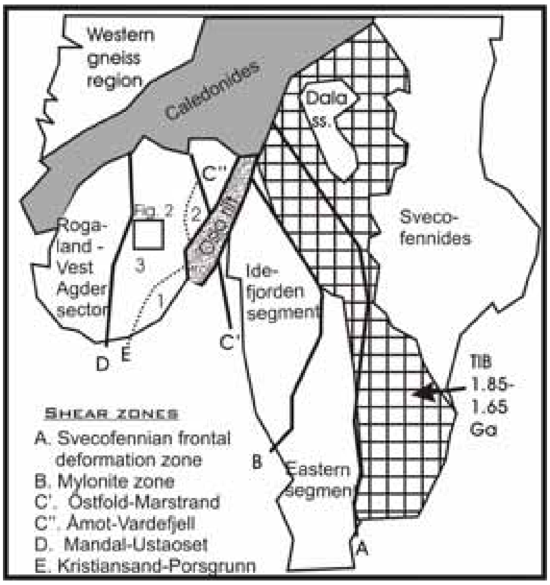

Fig. 1. Sketch map of the Sveconorwegian province (modified from Bingen et al., 2001a). The area of Fig. 2 is framed. Numbered sectors are: (1) Bamble, (2) Kongsberg, (3) Telemark.

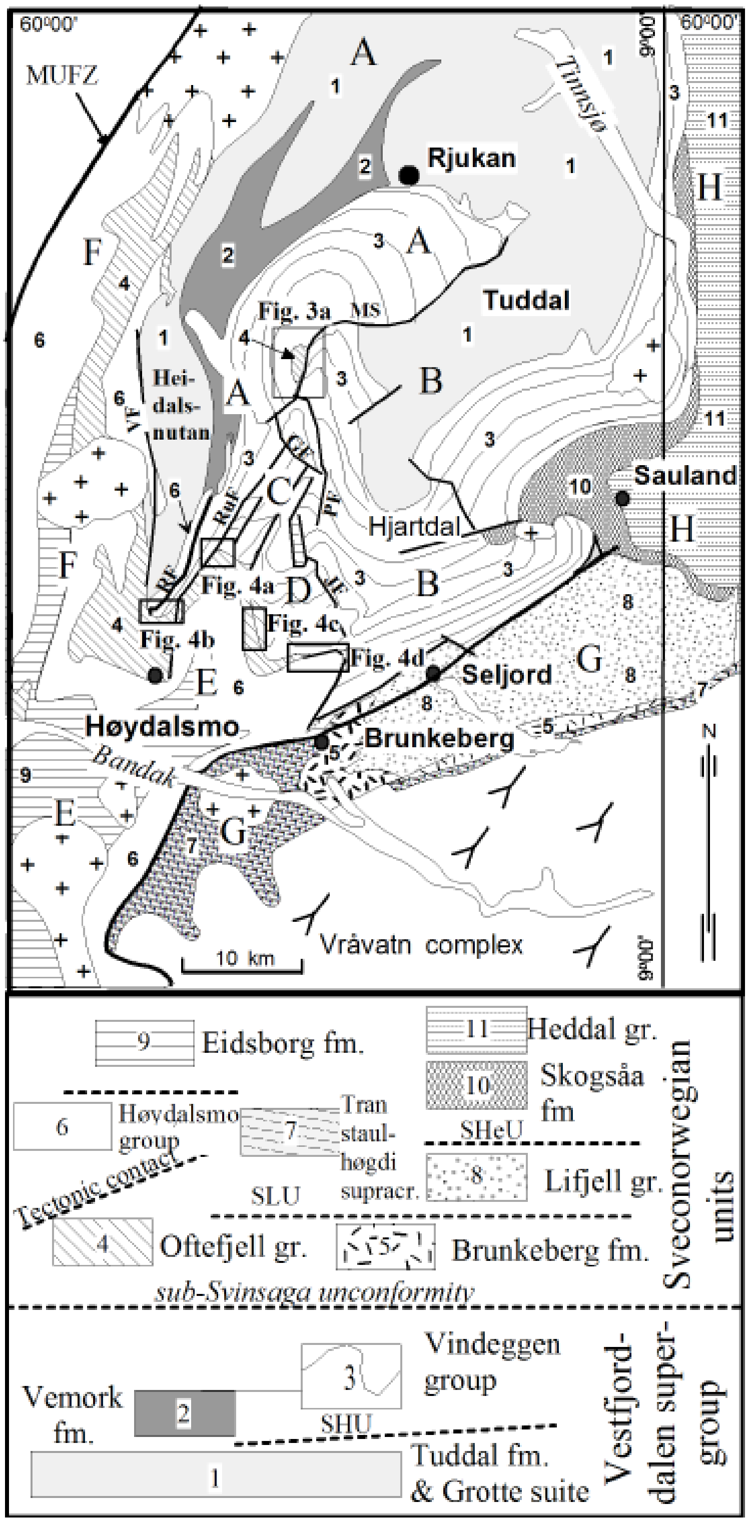

Fig. 2. Simplified geological map of the southern part of the Telemark supracrustals (modified from Dons & Jorde, 1971; Dons, 2003). Areas of Figs. 3a and 4a-d are framed. Lithostratigraphic-structural domains: A = Mefjell, B = Hjartdal, C = Åmotsdal, D = Hovundvarden, E = Bandakian. F = Øyfjell. G = Seljord. H = Sauland. Fault zones (thick lines): GF = Gryvlun, JF = Jaspisfjellet, MF = Marigrønutan, PF = Piggnatten, RF = Raudsinutan, RuF = Rustfjellet, VF = Vikvatnet. Unconformities (in the legend only) SHU, SHeU, SLU, & SRU = sub-Heddersvatnet, sub-Heddal, sub-Lifjell, and sub-Røynstaul, respectively. Crosses = diverse granitoids.

The oldest parts of the Southwestern Scandinavian Domain were formed during the mid-Proterozoic event known as the Gothian or Kongsbergian orogeny, i.e. at ca. 1.75 to ca. 1.5 Ga (Starmer, 1993; Connelly and Åhäll, 1996; Åhäll and Gower, 1997; Åhäll et al., 1998, 2000; Brewer et al., 1998; Andersen et al., 2002, 2004). Later, the Precambrian crust in South Norway was affected by the Sveconorwegian deformation and metamorphism, which obliterated primary stratigraphic relationships (e.g. Starmer, 1993). Northern and central part of the Telemark sector is, however, exceptional, as rather well preserved sedimentary-volcanic units known as the Telemark supracrustals underlie it (Sigmond et al., 1997). These were formed after the Kongsbergian orogeny, but were metamorphosed and deformed by the main Sveconorwegian orogeny at ca. 1000 Ma. Dons (1960a) subdivided them into three groups separated by angular unconformities. Recent studies have shown that their subdivision is more complicated (Laajoki et al., 2002; Bingen et al., 2003, 2005) and is in the study area as follows (see the lithostratigraphic legend in Fig. 2).

The Telemark belt is cored by the ca. 1500 Ma old felsic volcanites of the Tuddal formation and diverse plutonic rocks of the Grotte suite (Dons et al., 2004) (Fig. 2). The Vemork formation (Laajoki and Corfu, 2007) overlies the Tuddal formation W and SW of the Rjukan city. South of the Rjukan city, the quartzite-dominated Vindeggen group (VG) overlies unconformably the Tuddal formation (Laajoki, 2005), but west of this city, the Tuddal formation is overlain by the basalt-dominated Vemork formation (Laajoki and Corfu, 2007). Recent studies (Köykkä, subm) indicate that the Vemork formation and the basal unit, the Heddersvatnet formation, of the Vindeggen group are lateral equivalents and interfinger with each other. These three units are called collectively the Vestfjorddalen supergroup after the valley where the Rjukan city is located. The sedimentary-volcanic Oftefjell group (OG) ($\leq$1153 $\pm$ 3 Ma, Laajoki et al., 2002), which starts with the Svinsaga formation, overlies unconformably the VG in the southwest, whereas the 1155 ± 2 Ma old Brunkeberg formation (Laajoki et al., 2002) and the overlying orthoquartzite-dominated Lifjell group (Laajoki, 2006a, b) comprise the southeastern corner of the Telemark belt. The volcanic-sedimentary Høydalsmo group in the southwest was thought to lie unconformably on the Oftefjell group (Laajoki and Lamminen, 2006), but recent studies (unpublished data) indicate this unconformity is younger and that the Høydalsmo group may have a tectonic contact with the Oftefjell group and the Brunkeberg formation. In the east, the 1145 ± 4 Ma old Skogsåa porphyry (Laajoki et al., 2002; Laajoki 2002) overlies the Lifjell group. The youngest sedimentary units include quartzites and conglomerates of the Eidsborg formation (<1118 ± 38 Ma, de Haas et al., 1999) and the Røynstaul formation (1127 ± 9 Ma, unpublished data.), and the sandstones of the Heddal group (<1121 ± 15 Ma, Bingen et al., 2003), which border the Telemark belt in the southwest and east, respectively. The Mandal - Ustaoset shear zone separates the Telemark belt from the gneisses and granitoids of the Rogaland - Vest-Agder sector (Sigmond, 1985).

This study concentrates on the unconformity, which separates the VG from the OG northeast of Høydalsmo and in the Brattefjell area (Figs. 2 - 4). As it is known to occur only under the Svinsaga formation (SF), it is called the sub-Svinsaga unconformity (SSU) (Laajoki et al., 2002).

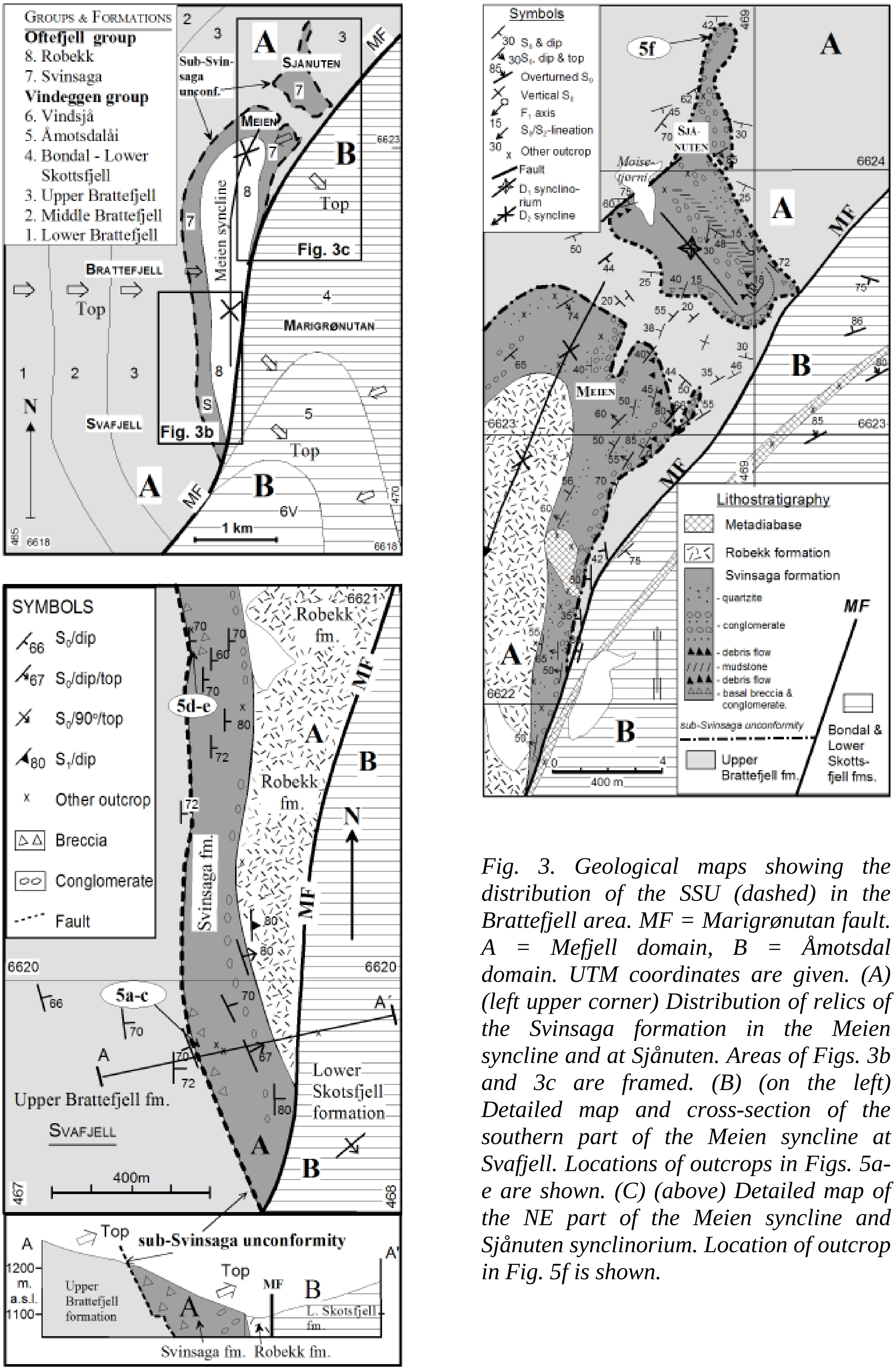

Fig. 3. Geological maps showing the distribution of the SSU (dashed) in the Brattefjell area. MF = Marigrønutan fault. A = Mefjell domain, B = Åmotsdal domain. UTM coordinates are given. (A) (left upper corner) Distribution of relics of the Svinsaga formation in the Meien syncline and at Sjånuten. Areas of Figs. 3b and 3c are framed. (B) (on the left) Detailed map and cross-section of the southern part of the Meien syncline at Svafjell. Locations of outcrops in Figs. 5a-e are shown. (C) (above) Detailed map of the NE part of the Meien syncline and Sjånuten synclinorium. Location of outcrop in Fig. 5f is shown.

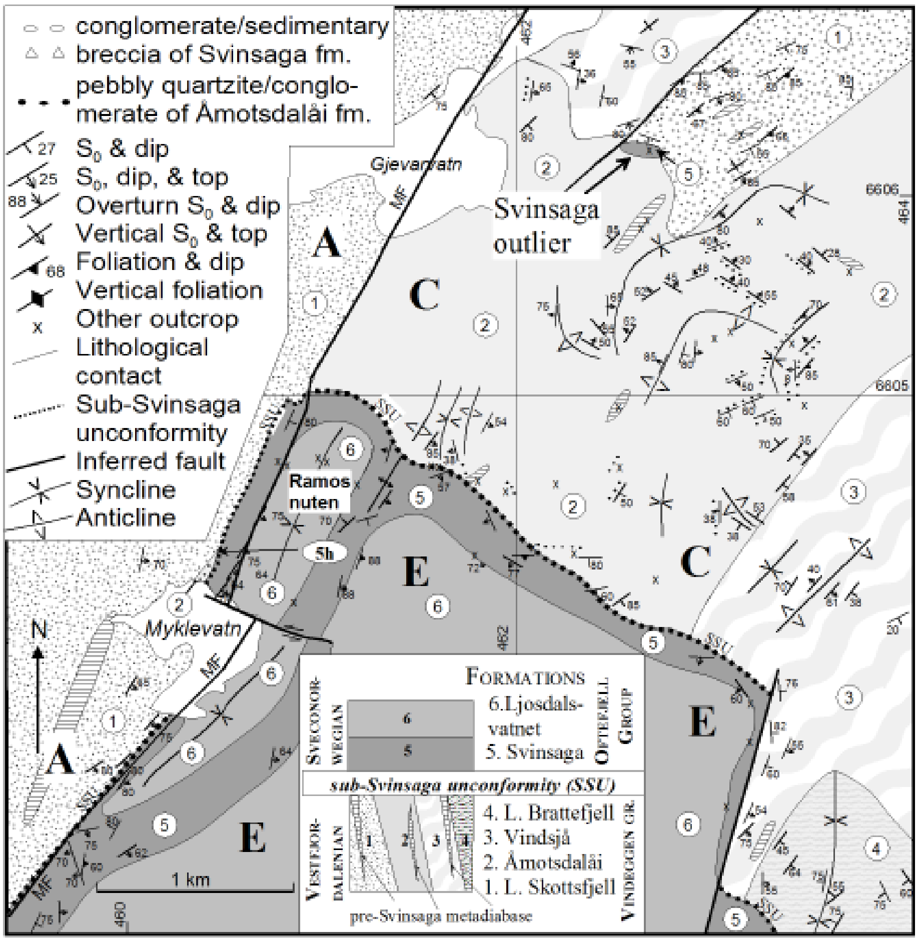

Fig. 4A. For the legend see the next page.

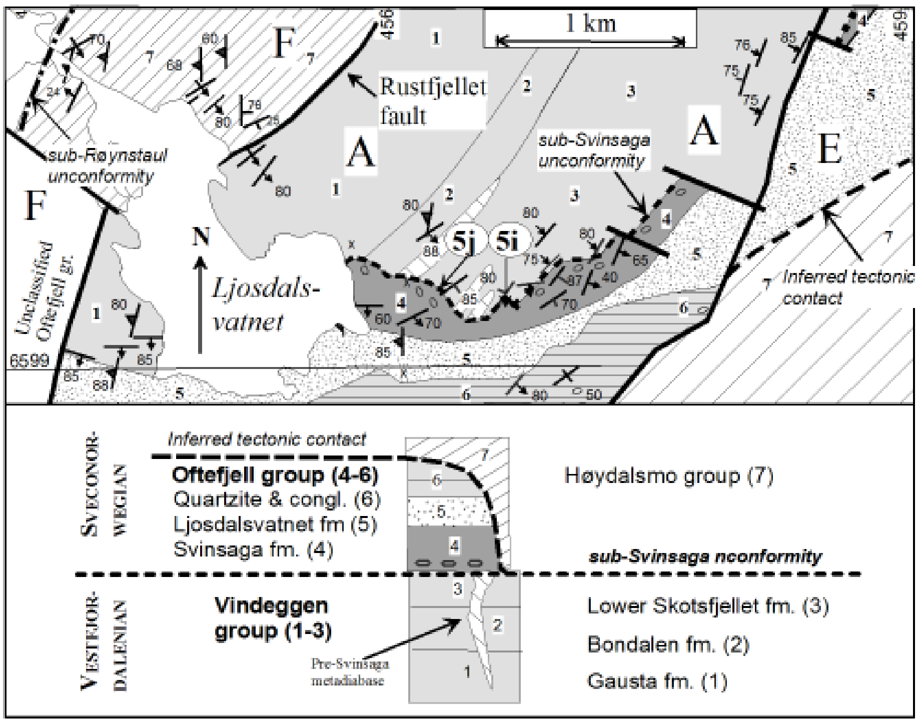

Fig. 4B. For the legend see the next page.

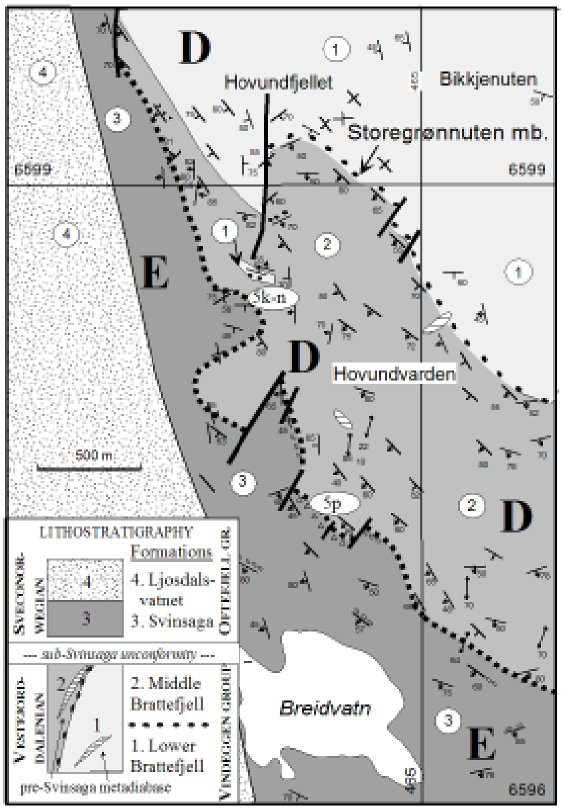

Fig. 4C

Fig. 4. Geological maps (for locations and lettering of domains see Fig. 2) showing the distribution of the SSU (dashed) in northeastern margin of the Bandakian domain. UTM coordinates are given. (A) (On page 8) SSU separating the Svinsaga formation (dark grey) from diverse VG formations around and northeast of Myklevatn. Location of outcrop in Fig. 5g is shown. (B) (On page 8) SSU cutting lower - middle parts of the VG in the Ljosdalsvatnet area. Locations of the outcrops in Figs. 5h & 5i are shown. For symbols see 4a. (C) SSU between the Middle Brattefjell formation (grey) of the VG and the SF (dark grey) in the Hovundvarden area. Locations of the outcrops in Figs. 5k-o are shown. (D) SSU cutting the Middle Brattefjell formation north of Liervatn. Formations: 1. Middle Brattefjell. 2. Upper Brattefjell. 3. Svinsaga, 4. Ljosdalsvatnet, 5 Lifjell group, 6. Røynstaul, 7. Morgedal. Location of the outcrop in Fig. 5p is shown. For additional symbols see 4a.

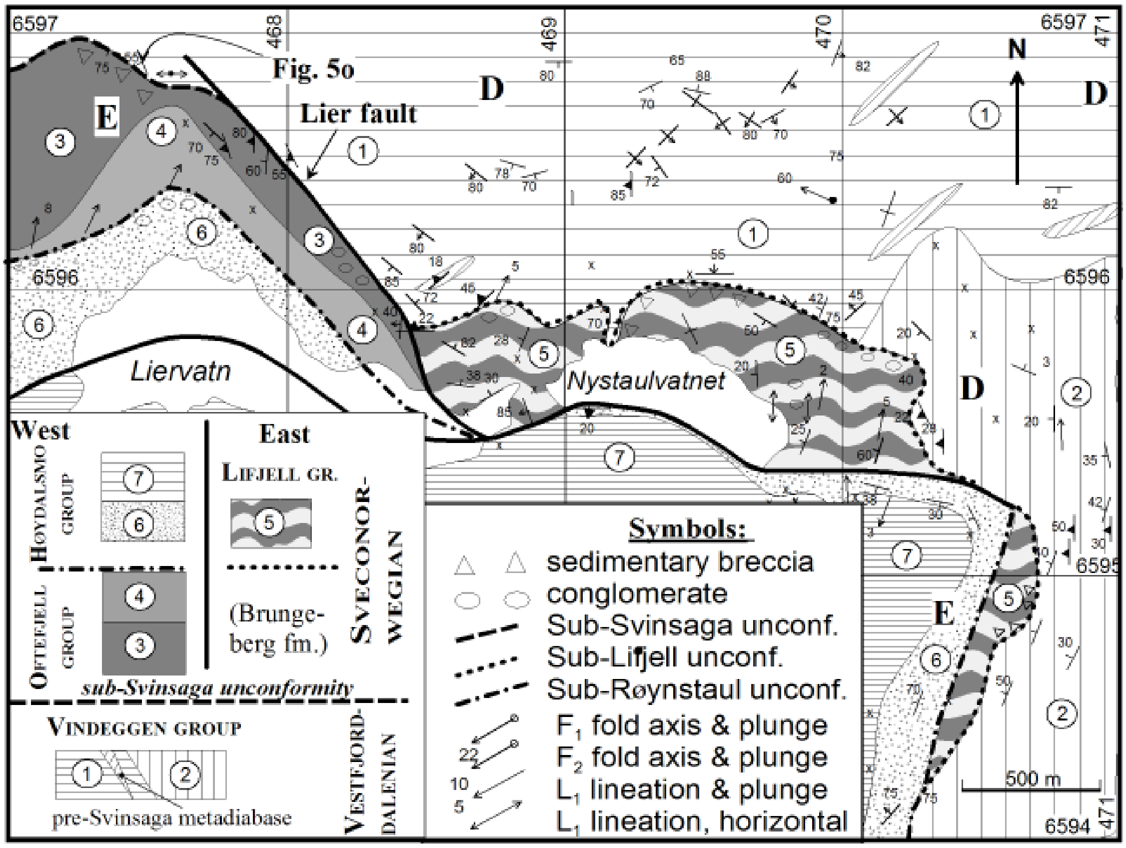

Fig. 4D

3. Lithostratigraphy of the study area

Dons (2003) mapped the southern part of his Seljord group as unclassified. For the purpose of this paper more detailed mapping was carried out. However, the time available did not allowed to establish the lithostratigraphic units formally after the demands of the Stratigraphic Commission of Norway (Nystuen, 1986; 1989). That is why the lithostratigraphic classification and nomenclature in Table 1 is informal. It uses as much as possible Dons' (1960a, b) original formation names. Local lithostratigraphies of the areas where the SSU is best visible are given in the legends in Figs. 3 and 4.

4. Structural-lithological domains of the study area

The SSU is exposed in the area, where several faults subdivide the bedrock into diverse domains. The bounding faults, which are named in Fig. 2, are not exposed as they follow valleys, but they have been located approximately by structural and lithostratigraphic mapping. The lithological contents of the domains and their boundaries are briefly described below.

The Vestfjorddalenian bedrock is subdivided into the following domains (marked by A to D in Fig. 2):

- *Mefjell domain* (A) consists of the Tuddal formation overlain by the Vemork formation and the complete VG. Small relics of the OG have been preserved in the Brattefjell area, where the SSU is well exposed (Fig. 3). The SSU is also exposed along the southern margin of the domain. The Rustfjell-Marigrønutan fault system and the Vikvatnet fault bound the domain in the southeast and west, respectively. The occurrence of the Vemork group is mainly restricted to this domain.

Table 1. Lithostratigraphy above and under the sub-Svinsaga unconformity in domains A, C, D, and E (Fig. 2).

Group/Formation	Approximated thickness (m)	Lithology
Eidsborg Fm. *and* *Røynstaul Fm*		Quartzite and minor conglomerate. Depositional age <1118 ± 38 Ma (de Haas et al., 1999). Debris flow conglomerates and quartzites. Depositional age 1127 +- 9 Ma (unpublished data).
------------ *Sub-Røynstaul unconformity(Laajoki & Lamminen, 2006)* -------------		
Høydalsmo group		
• *Morgedal – Gjuve fms.*		Mixed volcanic-sedimentary. Dalaå porphyry: U-Pb age 1150 ± 4 Ma (Laajoki et al. 2002).
•		- Quartzites and minor conglomerates. - Basal breccias and conglomerates
---------- *Inferred tectonic contact* ----------		
Oftefjell group		
• Several units		Diverse felsic and mafic volcanic units and quartzite – pebbly quartzite units (Laajoki, 2006.).
• b) Robekk fm. • a) Ljosdalsvatnet fm		b) Felsic porphyry (Eeast of Brattefjell Fig. 3) (Dons 1961). A likely time- equivalent of the Ljosdalsvatnet formation. a) Felsic porphyry. U-Pb age 1153 ± 3 Ma (Laajoki et al. 2002).

• Svinsaga fm.	100 - 200	- Fluvial quartzites and conglomerates (Köykkä, 2006). - Basal quartzite breccias and conglomerates
----- ***Sub-Svinsaga angular unconformity*** (this study) -----		
Vindeggen group		
• Upper Brattefjell fm.	1000	- Parallel-laminated – rippled beach orthoquartzite with low angle cross bed units. Typically red. - Basal member: massive – cross-bedded pebbly quartzite.
• Middle Brattefjell fm.	620	- Tidal – shallow marine heteroliths. (Lamminen & Laajoki, 2006) - Basal *Storegrønlinuten member* in the Hovundvarden domain.
• Lower Brattefjell fm.	660	Parallel-laminated – rippled beach orthoquartzite with low angle cross bed units.
• Vindsjå fm.	400	Heterolithic mudstone and quartzite units. Tidal.
• Upper Skottsfjell fm.	100	Tidal – shallow marine heteroliths and quartzites.
• Åmotsdalåi fm. • (Middle Skottsfjell)	400	Trough cross-bedded fluvial blue-grey quartzite, often pebbly with quartzite and siltstone clasts.
• Lower Skottsfjell fm.	500	Several diverse quartzite and siltstone units.
• Bondal & Lauvhov fms.	100-200	Heterolithic mudstones and carbonate-bearing quartzites.
• Gausta fm.	500 - 800	Cross-bedded – rippled, fluvial – shallow marine quartzite.
• Heddersvatnet fm	200 – 400	Basal conglomerates and debris flows with fluvial arkosites. Likely interbedded with the Vemork formation (Köykkä, subm.)
• Vemork fm.	2000	Metabasalt flows with interbedded metasedimentary vocaniclastic units (Laajoki & Corfu, 2007.).
----- Syn-post-Tuddal erosional/angular unconformity (Laajoki, 2005;Laajoki & Corfu, 2007.) -----		
• Tuddal fm.		Felsic volcanites with minor volcanoclastics. Age of volcanism ca. 1500 Ma (Dahlgren et al., 1990) or 1512+9/-8 Ma (Sigmond, 1998). Intruded by the Grotte suite.

- *Hjartdal domain* (B) consists of the Tuddal formation and the overlying VG southeast of the Marigrønutan fault. The SSU does not occur in this domain.
- *Åmotsdal domain* (C) is a NE-SW trending zone between the Mefjell and Hjartdal domains and consists of folded and faulted middle - upper part of the VG, e.g. from the Lower Skottsfjell formation to the Upper Brattefjell formation (UB). The SSU is exposed at the southern margin of the domain north of which a small outlier of the SF occurs (Fig. 4a).
- *Hovundvarden domain* (D) is allochthonous in respect to the Hjartdal domain from which it is separated by the Jaspisnuten fault. The bedrock comprises upper part of the VG from the Åmotsdalåi formation to the UB. Small outliers of the SF occur at the western margin of the domain, where the SSU is locally well exposed.

The bedrock underlain by the Sveconorwegian units is subdivided into the following domains (E – H in Fig. 2):

- *Bandakian domain* (E) consists of the folded OG, Høydalsmo group, the Eidsborg formation and minor parts of the Røynstaul formation. This domain contains most of the SF preserved (Fig. 4) and the SSU is locally well exposed.
- *Øyfjell domain* (F) occurs west of the Mefjell domain and consists of the Oftefjell and Høydalsmo groups and the Eidsborg and Røynstaul formations intruded by post-tectonic granites. Its eastern margin with the Heidalsnutan felsic volcanic complex is defined by the Vikvatnet fault/shear zone (Fig. 2) west of which the rocks are intensively foliated.

- *Seljord domain* (G) consists of the Brunkeberg formation, the Lifjell group, and the Transtaulhøgdi supracrustals. Its boundary with the Vråvatn complex to the south is tectonic (Laajoki, 2006b).
- *Sauland domain* (H) comprises the Skogsåa formation and the Heddal group.

5. Sub-Svinsaga unconformity

The SSU has been found exposed in the southeastern part of the Mefjell domain (Figs. 3 & 4a, b), in southwestern part of the Åmotsdal fault zone (Fig. 4a) and in southwestern margin of the Hovundvarden domain (Figs. 4c, d). These occurrences will be described in this order in the following. Probable occurrence of the SSU in the Øyfjell domain will also be discussed.

Mefjell domain

The SSU is well exposed on the eastern flank of Svafjell (Fig. 3b) and at northeastern part of Meien and at Sjånuten (Fig. 3c). All the localities are west - northwest of the Marigrønutan fault and in all of them the SSU marks the boundary between the SF and the underlying red UB orthoquartzite, the topmost unit of the VG (Table 1). Structurally, the parts of the SSU exposed at Svafjell and Meien belong to the steep western flank and more shallowly dipping northeastern end of the Sveconorwegian D_2 Meien syncline cut by the Marigrønutan fault (Fig. 3a). The Sjånuten area is structurally more complex as the SF was folded twice (Fig. 3c). However, the maps in Figs. 3b and 3c reveal that in all the areas the bedding positions in the UB and the SF are subparallel and both the units face the same direction. This shows that, in contrast to the Hovundvarden area to be described later, the SF was deposited without any greater angular unconformity on the UB. According to *the principle of original horizontality*, this means that the UB was positioned near horizontally during the deposition of the SF.

It is hard to locate the SSU exactly in Svafjell as it does not form any pronounced surface, but starts with a fracture zone, where thin fractures in the UB orthoquartzite are filled by purple mudstone (Figs. 5a-c). The fractures do not have any clear systematics, which indicates that they were not formed by any early Sveconorwegian deformation (for closer details see Köykkä and Laajoki, subm.). This zone passes to a basal *in situ* or slightly reworked Svinsaga breccia with large, sharp-edge, and tightly packed fragments of the UB orthoquartzite (Figs. 5d, e). Size of the fragments degrees and the width of the mudstone-filled inter-fragment spaces widens upwards. The breccia either passes to a conglomerate with angular UB fragments and subordinate, well-rounded, more distant quartzite clasts or is overlain by a massive SF quartzite with solitary UB fragments (Fig. 5d). The fracture - breccia zone is also preserved at Meien and Sjånuten, but often it has been eroded off and the basal SF conglomerate lies with a sharp contact directly on the UB orthoquartzite (Fig. 5f). Köykkä (2006) has described these occurrences more comprehensively.

At Myklevatn, ca. 15 km SSW of Svafjell, the SSU is exposed on one outcrop, where it cuts the basal part of the Åmotsdalåi formation (Fig. 4a). A boulder conglomerate with both local Åmotsdalåi quartzite boulders and subordinate, exotic quartzite pebbles lies sharply upon the underlying quartzite (Fig. 5g). Both the Åmotsdalåi and Svinsaga formations are steeply dipping and face to the east indicating that also here the VG laid subhorizontally during the deposition of the SF. Farther to the south, NE of Ljosdalsvatnet, the SSU represents a high-

Fig. 5A. For the legends see page 18.

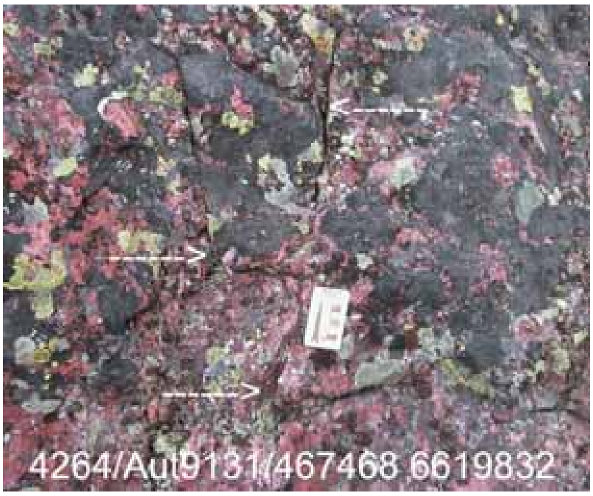

Fig. 5B.

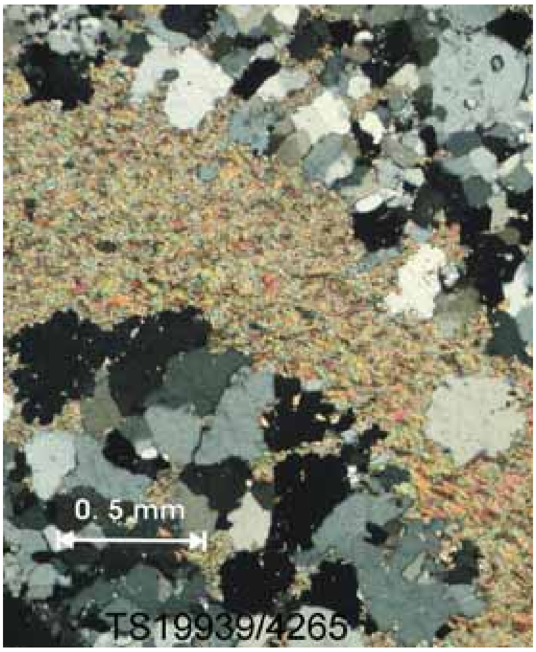

Fig. 5CA.

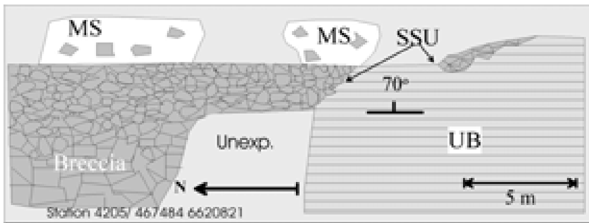

Fig. 5D.

Fig. 5E.

Fig. 5F.

Fig. 5G.

Fig. 5H. For the legends see page 18.

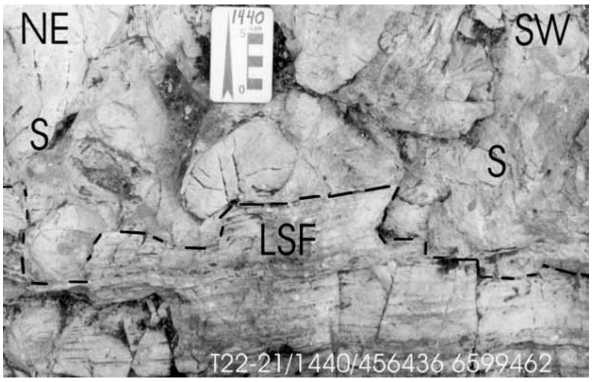

Fig. 5I.

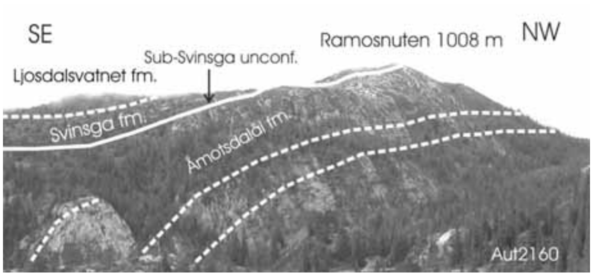

Fig. 5J.

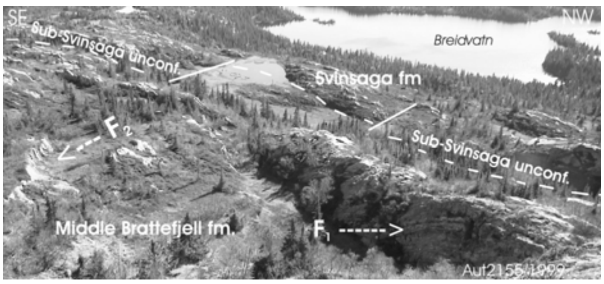

Fig. 5K.

Fig. 5L.

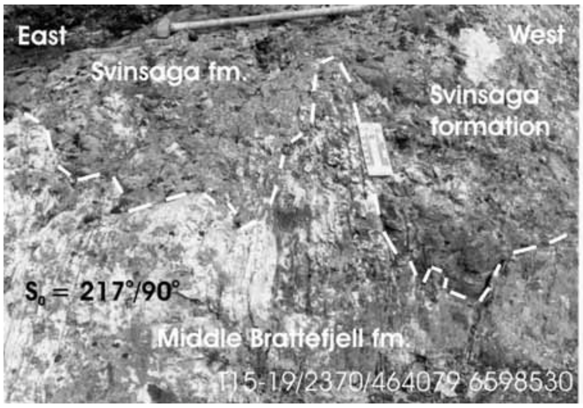

Fig. 5M.

Fig. 5N.

Fig.5O. (On the left)

Fig.5P.

Fig. 5. Field occurrences of the SSU. Number series on photographs give the station number, the file number of the photograph, and UTM coordinates of the outcrop. (A) Basal fracture zone developed into the UB, Svafjell. Oblique view from SE. Pens and markers show mudstone-filled fractures. The handle (70 cm) of the hammer depicts strike of near vertical bedding. (B) Close-up of the fractures (arrows) in Fig. 5a and (C) microphotograph (crossed polars) of their mudstone-fill composed mainly of white mica; the host rock is a blastoclastic, silica-cemented UB orthoquartzite. (D) Plan sketch of an outcrop showing eroded, parallel-laminated UB quartzite overlain by basal Svinsaga breccia and this again by a massive Svinsaga quartzite (MS) with UB fragments (grey). As bedding in UB is steep, the view can be treated also as a primary vertical section. Palaeorelief is at least 7 m. Svafjell. (E) Basal view of the breccia in Fig. 5d. The stick is 1.4 m. Note the irregular fracture network. (F) Svinsaga boulder conglomerate deposited directly on an Upper Brattefjell (UB) quartzite. The 1.4 m long stick leans on a large, parallel-laminated UB quartzite boulder in the SF conglomerate. Sjånuten. (G) Plane view of SSU developed upon Åmotsdalåi formation in Myklevatn. Note the washed-out nature of the unconformity and large Åmotsdalåi boulders (ÅiB) in the conglomerate matrixed by smaller quartzite pebbles. (H) Oblique view of a sub-Svinsaga palaeoweathering horizon/in situ breccia developed on a heterolithic siltstone of the steeply dipping Lower Skottsfjell formation (lower part), NE of Ljosdalsvatnet. (I) Washed-out SSU (dashed) between Lower Skottsfjell (LSF) and Svinsaga conglomerate (S). Note the minor pre-syn-Svinsaga fractures and faults in the LSF. (J) View of an open, Vestfjorddalenian anticline defined by the Åmotsdalåi formation of the Vindeggen group overlain unconformably by the Svinsaga and Ljosdalsvatnet formations of the Oftefjell group. Dashed lines indicate bedding. (K) View of folded and faulted SSU at Hovundvarden seen from NE. Note the Vestfjorddalenian (F_1) and Sveconorwegian (F_2) folds in the Middle Brattefjell formation. Solid lines = faults. (L) Openly folded SSU (dashed) and Svinsaga formation upon vertically dipping Middle Brattefjell formation quartzite. Hovundvarden. Detail of the unconformity is shown in Fig. 5m. The large SF outcrop on the left consists of debris flow(s). (M) Oblique view of high-angle unconformity between the vertically dipping Middle Brattefjell formation and a basal SF conglomerate. (N) Diamictic Svinsaga quartzite

deposited on a deformed Middle Brattefjell quartzite defining a washed-out SSU. Note the pre-Svinsaga fractures in the Middle Brattefjell quartzite along which the Svinsaga quartzite intrudes (left lower corner). Hovundvarden. (O) A knife-sharp SSU between a Middle Brattefjell quartzite and a pebbly, fluvial quartzite of the Svinsaga formation. The stick is 1.4 m. Hovundvarden. (P) Sharp, erosional SSU between a Svinsaga boulder conglomerate and the underlying quartzite of the Middle Brattefjell formation Fjosskorli.

angle unconformity cutting the Lower Skottsfjell and Bondal formations and associated metadiabases and even the Gausta formation (Fig. 4b). This area is characterized by NW-SE trending, steep – vertical, pre-syn-SF faults, which displace the unconformity right-laterally (Fig. 4b). The SSU is exposed on two outcrops. In the first case, an *in situ* breccia has been developed on Lower Skottsfjell heterolith (Fig. 5h). In the second case, the SSU is sharply defined by a SF cobble conglomerate overlying directly the Lower Skottsfjell quartzite (Fig. 5i). The quartzite shows ca. NW-SE trending, vertical pre-Svinsaga fractures and minor faults indicating that the Vestfjorddalenian bedrock was faulted during the deposition of the SF.

The SSU as well as the SF disappear under the Lake Ljosdalsvatnet, west of which they have not been identified reliably (Laajoki & Lamminen, 2006).

Åmotsdal domain.

At the southern margin of this domain, the SSU cuts the openly folded Åmotsdalåi and Vindsjå formations. This is visible both macro- (Fig. 4a) and mesoscopically (Fig. 5j). No fracture zone neither *in situ* breccias occur, but a SF boulder conglomerate or pebbly quartzite lies directly either on an Åmotsdalåi quartzite – pebbly quartzite or on a Vindsjå siltstone. Northeast of Ramosnuten, a small SF conglomerate outlier occurs at the Lower Skottsfjell – Åmotsdalåi boundary (Fig. 4a) indicating an angular unconformity under the conglomerate.

Hovundvarden domain

The western flank of Hovundvarden (Fig. 4c) is the area where the high-angle unconformity between the VG and the SF can be mapped for several kilometres (Dons, 2003). The SSU cuts the Middle Brattefjell formation, which was folded along sub-horizontal, about E-W trending fold axes before the deposition of the SF (Fig. 5k). It was refolded by the Sveconorwegian orogeny together with the SSU and SF (Fig. 5l). The SSU is sharply erosional with the SF conglomerates or debris flows lying directly on the Middle Brattefjell basement without any relics of *in situ* breccia (Figs. 5n,o).

At the southern margin of the domain, north of Liervatn, the geology is more complicated and it is not quite sure how the SSU and the SF continue to the southeast. The outcrop in Fig. 5p, in which a SF boulder conglomerate lies directly on an eroded Middle Brattefjell quartzite, is the southeasternmost case, where the SSU is visible without any doubt. Southeast of it, a typical SF quartzite and the overlying Ljosdalsvatnet porphyry die rapidly out. The SF/Middle Brattefjell contact is not exposed, but structural and metamorphic observations indicate that it could be a fault, named tentatively the Lier fault (Fig. 4d). The SF west of this fault is deformed relatively little, whereas east of it, especially north of Nystaulvatnet, the conglomerates and quartzites are highly deformed containing L-S tectonites and sheath folds. Here micaceous rocks contain garnet and actinolite and metadiabases scapolite, which have not detected west of the Lier fault. Dons (2003) mapped these rocks as part of the SF, but originally they were included into the Røynstaul formation (Neumann & Dons, 1961). In this study, following Laajoki (2006a, b), they are correlated with the basal parts of the Lifjell group as the lowermost conglomerates include felsic volcanic detritus and epidote, which are missing in the SF conglomerates. The volcanic evidence includes embayed quartz clasts and the Nd-isotope mass-balance modelling of a conglomerate sample (Andersen & Laajoki, 2003). Laajoki (2006a) has treated this problem more thoroughgoing.

Øyfjell domain

Dons (2003) included the quartzites and conglomerates rimming the Tuddal acid volcanites west of Heidalsnutan (Fig. 2) into the SF or probable SF indicating that the SSU could have been developed directly upon the Rjukan group. Laajoki & Lamminen (2006, their Fig. 3) included these into the Røynstaul formation except the one in Heimveglinuten (*op. cit.*, Fig. 11a), where a SF-type quartzite occurs between the Tuddal and Røynstaul formations. It is not known, however, does this quartzite counterpart the SF itself or some other quartzite higher in the Høydalsmo group stratigraphy (Laajoki, 2006c). Consequently, its lower contact may represent either the SSU or a younger intra-Høydalsmo group unconformity.

Quartzites included into the traditional Bandak group also occur northwest of Heidalsnutan (Dons et al, 2004), but their closer stratigraphic positions and relations to their basement are not known. Further to the northwest, the rocks are cut by the Mandal-Ustaoset fault zone and are intruded by diverse plutonic rocks (*op. cit.*)

6. Palaeogeomorphologic features

Reconstruction of geomorphologic palaeosurfaces and palaeolandscapes is a complex task (for discussion see Widdowson, 1997b). It is especially difficult in the case of the SSU, because the bedrock is folded and faulted, the unconformity itself has been preserved or is visible only in part, and two-dimensional observations of it can rarely be done. Fortunately, the bedrock under the SSU consists of VG quartzites and siltstones, whose bedding positions and younging directions can easily be determined. On the basis of these and the nature of the lowermost SF breccias and conglomerates an attempt is made to reconstruct the geomorphologic conditions during the formation of the SSU (Fig. 6).

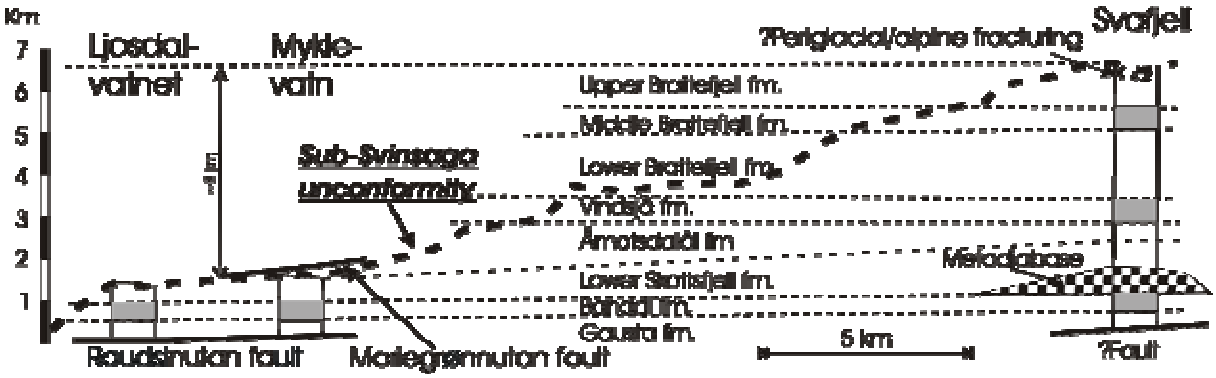

Fig. 6. Reconstruction (see the text) of the SSU along the line from Svafjell to Ljosdalsvatnet.

The main criteria used were:

(1) Structural mapping shows that the VG within the Mefjell domain forms a large hook fold overlain near-conformably by the SF and that both the units face the same direction (Figs. 3 & 4a). This indicates that the VG in this area was horizontal or subhorizontal during the deposition of the SF.

(2) Stratigraphic observations indicate, that the SSU erodes progressively deeper lithostratigraphic levels of the VG when moving from the north to the south within the Mefjell domain; e.g. UB at Sjånuten and Svafjell (Fig. 3), Lower Skottsfjell/Åmotsdalåi boundary zone at Myklevatn (Fig. 4a), and down to the lower part of the Gausta formation at

Ljosdalsvatnet (Fig. 4b). Provided that the VG formed originally a layer cake body, this means that about 5 km thick part of the VG was eroded in the south (Fig. 6).

(3) Such a large amount of erosion of a subhorizontal sedimentary rock pile is not possible without epeirogenic movements. This indicates that the VG of the Mefjell domain rose gradually to a plateau, into which a deep canyon was carved by a fluvial SF system.

(4) As the highest parts of the VG have been preserved at Svafjell, this area may represent the mountainous part of the plateau. This is supported by the basal fracture zone and in situ breccias at Svafjell, which may be attributed to periglacial or alpine physical weathering (cf. breccia in Fig. 5e with the frost-shattered bedrock in Fig. 5 in McEwen & Matthews, 1998) (Köykkä, 2006; Köykkä & Laajoki, 2006, subm.). Consequently, the Myklevatn - Ljosdalsvatnet section may represent ancient canyon wall and bottom, where the preservation of *in situ* breccias and other loose material was poor.

(5) Because only small outliers of the SF occur within the Åmotsdalåi and Hovundvarden domains it is difficult to reconstruct their palaeogeomorphology. However, the high-angle angular unconformity shown in Figs. 5l and 5m proves that the VG was folded within both the domains before the deposition of the SF. This indicates that a major tectonic zone separated these domains from the Mefjell domain, but it was so much reactivated and/or destroyed during the main Sveconorwegian deformation, that it can no more be located. It is possible that this tectonic zone was the site of the SF river system, which carved the canyon referred to above.

On the basis of these criteria a palaeogeomorphologic sketch is presented in Fig. 7. Svafjell is supposed to have acted as a mountainous source area, which produced coarse material to a fault bounded fluvial system.

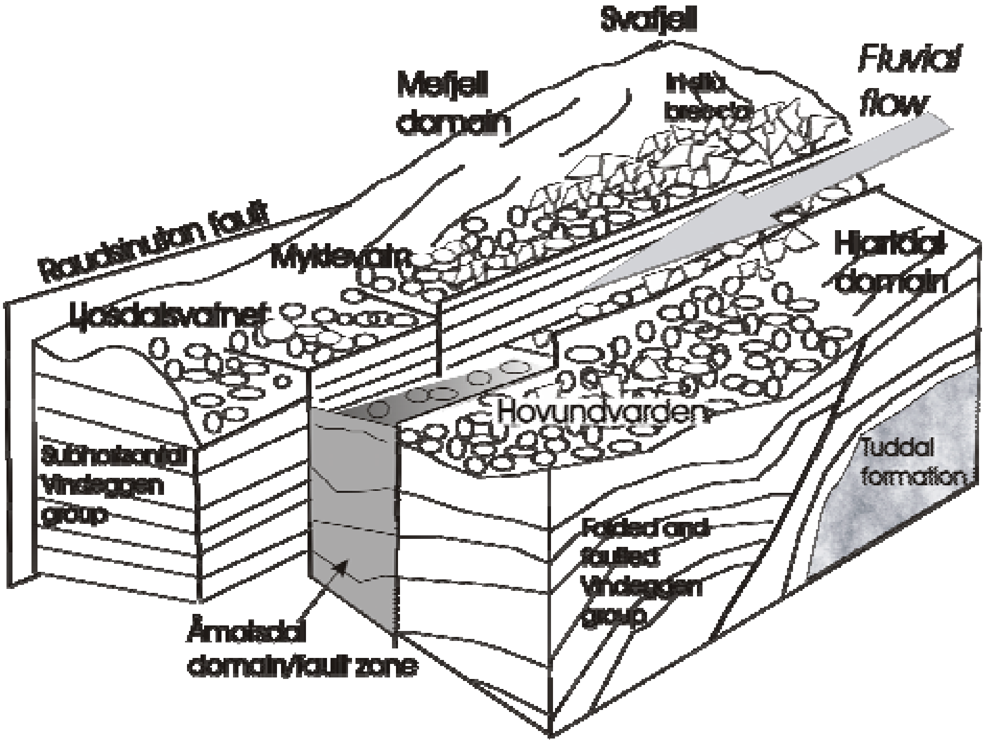

Fig. 7. Sketch of the palaeolandscape defined by the SSU. See the text.

7. Discussion

This study confirms Dons' (1960a, b) idea that the SSU represents an angular unconformity and that the underlying VG (Dons' Seljord) sequence was folded before the deposition of the overlying Oftefjell (Bandak) group. Starmer (1993) stated that the former was folded by the Early Sveconorwegian phase. The ages of the pre-Svinsaga Sandvik metadiabase (Corfu and Laajoki, 2007) and the Ljosdalsvatnet porphyry (Laajoki, et al, 2002) limit the formation of the SSU between ca. 1350 Ma and 1153 Ma (Fig. 8). The time period of ca. 200 million years is, of course, too rough an estimation.

As the SSU is regional and was formed by a prolonged period of weathering and erosion it represents an important palaeosurface (see the introduction). Because it cannot be followed to the south of Liervatnet (Fig. 4d) and its occurrence within the Øyfjell domain is questionable, it is hard to say how extensive this surface was.

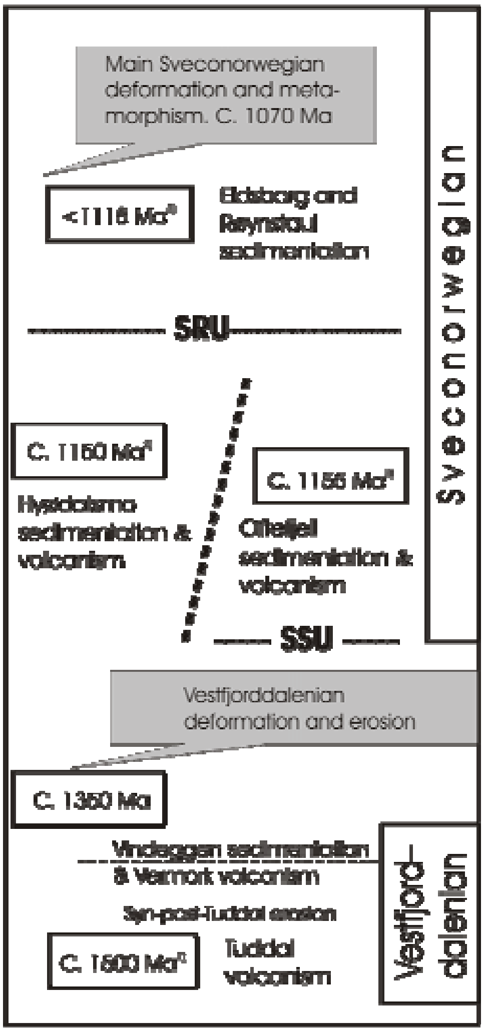

Fig. 8. Diagram showing the relative position of the sub-Svinsaga unconformity (SSU) in relation to the dated Vestfjorddalenian and Sveconorwegian episodes in the study area. SRU = sub-Røynstaul unconformity. References for the ages: 1) Felsic lavas, Dahlgren et al. 1990; Sigmond, 1998. 2 & 3) Ljosdalsvatnet and Dalaå porphyries, respectively, Laajoki et al., 2002. 4) Youngest detrital zircon, de Haas et al., 1999.

Except the *in situ* fracturing and brecciation in the Svafjell (Figs. 5a-e) and Ljosdalsvatnet (Fig. 5h) areas, no evidence of palaeosol profiles associated with the SSU has been detected. This may be a question of preservation or due to the exogenic conditions, which did not allow formation of any thicker palaeosol with horizonation. Deposition of the SF conglomerates directly on the VG basement and into its fractures (Figs. 5f, g, i, m-p) indicates that most of the pre-existing weathering cover was stripped off by fluvial processes.

If the breccias in Svafjell represent the elevated part of the ancient landscape, as is supposed in this study, a question arises; how did they escape later erosion? One explanation is a tectonic collapse along the precursory fault system of the Åmotsdal domain, which separated the subhorizontal western part of the VG from its folded eastern part. It is also possible, that they and the overlying SF were protected under the Robekk volcanics of the Oftefjell group.

8. Conclusions

1. The SSU was carved into the folded and faulted Vestfjorddalenian quartzite plateau, which had a mountainous topography, at least in the surroundings of Svafjell
2. An up to 4 – 5 km thick pile of the quartzite basement seems to have been eroded off in the southern part of the Mefjell domain.
3. Physical weathering processes were significant in forming the SSU, but, expect in a few cases, their products have mostly been washed out and the SSU presents a palaeosurface moulded by ancient fluvial activity.

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REFERENCES

Åhäll, K.-I. & Gower, CA.F. 1997. The Gothian and Labradorian orogens: variations in accretionary tectonism along a late Paleoproterozoic Laurentia-Baltica margin. Gelogiska föreningen i Stockholm förhandlingar 119, 181-191.

Åhäll, K.-I., Cornell, D.H. & Armstrong, R. 1998. Ion probe zircon dating of metasedimentary units across the Skagerrak: New constraints for early Mesoproterozoic growth of the Baltic Shield. Precambrian Research 87, 117-134.

Åhäll, K.-I., Connelly, J. & Brewer, T.S. 2000. Episodic rapakivi magmatism due to distal orogenesis?: Correlation of 1.69-1.50 Ga orogenic and inboard, "anorogenic" events in the Baltic Shield. Geology 28, 823-826.

Andersen, T. & Knudsen, T.-L. 2000. Crustal contaminants in the Permian Oslo Rift, South Norway: constraints from Precambrian geochemistry. Lithos 53, 247-264.

Andersen, T. & Laajoki, K. 2003. Provenance characteristics of Mesoproterozoic metasedimentary rocks from Telemark, South Norway: a Nd-isotope mass-balance model. Precambrian Research 126, 95-122.

Andersen, T., Griffin, W.L. & Pearson, N.J. 2002. Crustal evolution in the SW part of the Baltic Shield: The Hf isotope evidence. Journal of Petrology 43, 1725-1747.

Andersen, T., Griffin, W.L., Jackson, S.E. & Knudsen, T.-L. 2004. Mid-Proterozoic magmatic arc evolution at the southwest margin of the Baltic Shield. Lithos 73, 289-318

Bingen, B., Birkeland, A., Nordgulen, Ø. & Sigmond, E.M.O. 2001. Correlation of supracrustal sequences and origin of terranes in the Sveconorwegian orogen of SW Scandinavia: SIMS data on zircon in clastic metasediments. Precambrian Research 108, 293-318.

Bingen, B., Nordgulen, Ø., Sigmond, E.M.O., Tucker, R., Mansfeld, J. & Högdahl, K. 2003. Relations between 1.19–1.13 Ga continental magmatism, sedimentation and metamorphism, Sveconorwegian province, S Norway. Precambrian Research 124, 215-241.

Bingen, B., Skår, Ø., Marker, M., Sigmond, E. M.O., Nordgulen, Ø., Ragnhildstveit, J., Mansfeld, J., Tucker, R. D. & Liégeois, J.-P., 2005. Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. Norwegian Journal of Geology 85, 87-116.

Brewer, T.S., Daly, J.S. & Åhäll, K-L. 1998. Contrasting magmatic arcs in the Palaeoproterozoic of the south-western Baltic Shield. Precambrian Research 92, 297-315.

Christie-Blick, N., Grotzinger, J.P. & von der Borch, CA. CA. 1988. Sequence stratigraphy in Proterozoic successions. Geology 16, 100-1004.

Connelly, J.N. & Åhäll, K.-I. 1996. The Mesoproterozoic cratonization of Baltica – new age constraints from SW Sweden. In: T.S. Brewer (Editor), Precambrian crustal evolution in the North Atlantic Region. Geological Society Special Publication 112, 261-273.

Dahlgren, S., Heaman, L. & Krogh, T.E. 1990. Geological evolution and U-Pb geochronology of the Proterozoic Central Telemark area, Norway (abstract). Geonytt 17 (1), 38-39.

de Haas, G.J.L.M., Andersen, T. & Vestin, J. 1999. Application of detrital zircon geochronology to assembly of a Proterozoic terrain – an example from the Baltic Shield. Journal of Geology 107, 569-586.

Dons, J.A. 1960a. Telemark supracrustals and associated rocks. In Holtedahl, O. (Ed.) Geology of Norway. Norges geologiske undersøkelse 208, 49-58.

Dons, J.A. 1960b. The stratigraphy of supracrustal rocks, granitization and tectonics in the Precambrian Telemark area. Southern Norway. Norges geologiske undersøkelse 212h, 1-30.

Dons, J.A. 1961. Rjukan. Geologisk kart. Berggrunnskart. Rjukan; 1:100 000. Norges geologiske undersøkelse.

Dons, J.A. 2003. Åmotsdal, berggrunnskart 1514 II, M 1: 50 000, foreløpig utgave. Norges geologiske undersøkelse.

Dons, J. & Jorde, K. 1978. Geologisk kart over Norge, berggrunnskart Skien, 1:250 000. Norges geologiske undersøkelse.

Dons, J.A., Heim, M. & Sigmond, E.M.O. 2004. Frøystaul. Berggrunnskart; Frøystaul; 1514 I, 1:50 000. Norges geologiske undersøkelse

Gaál, G. & Gorbatschev, R. 1987: An outline of the Precambrian evolution of the Baltic Shield. Precambrian Research 35, 15–52.

Gall, Q. 1999. Precambrian palaeosols: a view from the Canadian shield. Special Publications of the International Association of Sedimentologists 27, 207-221.

Köykkä J. 2006: Mesoproterotsooisen Svinsagan muodostuman sedimentologia, Telemark, Etelä-Norja (in Finnish). Unpublished M.Sc. Thesis, University of Oulu, Department of Geosciences, pp. 126.

Köykkä, J, submitted. Lithostratigraphy of the Mesoproterozoic Telemark supracrustal rocks, South Norway: revision of the sub-Heddersvatnet unconformity and geochemistry of basalts in the Heddersvatnet Formation. Norwegian Journal of Geology, Vol. xx, pp. xx – xx.

Köykkä. J & Laajoki, K. 2006. Fracture and talus breccia zone at the base of the Svinsaga Formation, central Telemark, South Norway indicators of Mesoproterozoic frost weathering action. Geological Society of Finland, Special Issue I, 81

Köykkä, J. & Laajoki, K., subm. Mesoproterozoic frost action at the base of the Svinsaga Formation, central Telemark, South Norway. Norwegian Journal of Geology.

Laajoki, K., 2002. The Mesoproterozoic sub-Heddal unconformity, Sauland, Telemark, south Norway. Norsk Geologisk Tidsskrift 82, 139-152.

Laajoki, K. 2005. The Mesoproterozoic sub-Heddersvatnet unconformity, Telemark, South Norway. Bulletin of the Geological Society of Finland 11, 49-63.

Laajoki, K., 2006a. The Mesoproterozoic sub-Lifjell unconformity, central Telemark, Norway. Bulletin of the Geological Society of Finland 78, 41-70..

Laajoki, K. 2006b. Lithostratigraphy of the lower part of the Lifjell group, Telemark, Norway. Res Terrae, Ser. A, No. 23, 47 p

Laajoki, K. 2006ca. Lithostratigraphy of the Oftefjell group, central Telemark, Norway. Res Terrae, Ser. A, No. 24, 36 p.

Laajoki, K. & Corfu, F., 2007. Lithostratigraphy of the Mesoproterozoic Vemork formation, central Telemark, Norway. Bulletin of the Geological Society of Finland, 41-67.

Laajoki, K. & Lamminen, J. T., 2006. The Mesoproterozoic sub-Røynstaul unconformity, central Telemark, Norway. Norwegian Journal of Geology 86, 29-40.

Laajoki, K., Corfu, F., Andersen, T., 2002. Lithostratigraphy and U-Pb geochronology of the Telemark supracrustals in the Bandak-Sauland area, Telemark, South Norway. Norsk Geologisk Tidsskrift 82, 119-138.

Lamminen, J. & Laajoki, K., 2006. The Mesoproterozoic Brattefjell formation, Telemark, South-Norway: a tidally influenced shoreline. Geological Society of Finland, Special Issue I, 87.

Marmo, J. S. 1992. The Lower Proterozoic Hokkalampi palaeosol in North Karelia, eastern Finland. In: Schidlowski, M. ... [et al.] (Editors.) Early organic evolution: implications for mineral and energy resources. Berlin: Springer-Verlag, 41-66.

McEwen. L.J. & Matthews, J.A. 1998. Channel form, bed material and sediment sources of the Sprongdola, Southern Norway; evidence for a distinct periglacio-fluvial system. Geografiska Annaler A80, 17-36.

Neumann, H. & Dons, J.A. 1961. Kviteseid. Geologisk kart. Berggrunnskart. Kviteseid; 1: 100 000. Norges geologiske undersøkelse.

Nilsen, K.S. 1981. Geologiske undersøkelser av Bessefjell- og Bandakgranittene i vest-Telemark deres nærliggende bergarter og mineraliseringer. Unpublished M.SCA. Thesis, University of Oslo.

Nordgulen, Ø. 1999. Geologisk kart over Norge, Berggrunnskart HAMAR, M 1: 250 000. Norges geologiske undersøkelse.

Nystuen, J.P. (ed.) 1986. Regler og råd for navnsetting av geologiske enheter i Norge. Av Norsk stratigrafisk komité. Norsk Geologisk Tidsskrift 66, Suppl. 1, 96 p.

Nystuen, J.P. (ed.) 1989: Rules and recommendations for naming geological units in Norway by the Norwegian Committee on Stratigraphy. Norsk Geologisk Tidsskrift 69, Suppl. 2, 111 p.

Priem, H.N.A., Boelrijk, N.A.I.M., Hebeda, E.H., Verdurmen, E.A.Th. & Verschure, R.H. 1973. Rb-Sr investigations on Precambrian granites, granitic gneisses and acidic metavolcanics in Central telemark: Metamorphic resetting of Rb-Sr whole rock systems. Norges geologiske undersøkelse 289, 37-53.

Sigmond, E. 1985. The Mandal-Ustaoset Line, a newly discovered major fault zone in South Norway. In Tobi, A. CA. (ed.) The deep Proterozoic crust in the North Atlantic provinces. NATO ASI Series. Serie C, 158, 323-331.

Sigmond, E. 1998. Geologisk kart over Norge, Berggrunnskart ODDA, M 1:250 000. Norges geologiske undersøkelse.

Sigmond, E. M.O., Gjelle, S. & Solli, A. 1997. The Rjukan Proterozoic rift basin, its basement and cover, volcanic and sedimentary infill, and associated intrusions. Norges geologiske undersøkelse Bulletin 433, 6-7.

Starmer, I.CA. 1993. The Sveconorwegian orogeny of southern Norway, relative to deep crustal structures and events in the North Atlantic Proterozoic Supercontinent. Norsk Geologisk Tidsskrift 73, 109-132.

Strand, K. & Laajoki, K. 1999. Application of the parasequence concept to the Paleoproterozoic record of the northern Fennoscandian Shield. Precambrian Research 97, 253-267.

Thiry, M. & Simon-Coinçon, R.1999. Paleoweathering, palaeosurfaces and Related Continental Deposits. Special Publication Number 27 of the International Association of Sedimentologists, 404 p.

Widdowson, M. (Editor) 1997a. Palaeosurfaces: Recignition, Reconstruction and Palaeoenvironmental Interpretation. Geological Society Special Publication 120, 330 p.

Widdowson, M. 1997b. The geomorphological and geological importance of palaeosurfaces. Geological Society Special Publication 120, 1-12.

Yang, W. & Holland, D.H. 2003. The Hekpoort Paleosol profile in Strata 1 at Gaborone, Botswana; soil formation during the great oxidation event. American Journal of Science 303, 187-220.