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The Mesoproterozoic sub-Lifjell unconformity, central Telemark, Norway

Kauko Laajoki

Department of Geosciences, University of Oulu, P.O. Box 3000, FI-90014 University of Oulu, Finland

Abstract

The sub-Lifjell unconformity subdivides the traditional Seljord group of the Telemark supracrustals, south Norway, into the Vindeggen and Lifjell groups. It is defined by an *in situ* weathering breccia and an angular unconformity above quartzites of the <1 500 – > 1155 Ma old Vindeggen group and by a volcaniclastic palaeoregolith developed above the 1155±2 Ma old porphyry of the Brunkeberg formation. Due to the complex deformation of the Vindeggen and Lifjell groups this unconformity has often been sheared or cut by faults, which impedes its use as a lithostratigraphic boundary. Dated porphyries under and above the Lifjell group define the age of the sub-Lifjell unconformity between 1155±2 Ma and 1145±4 Ma indicating that the part of the unconformity developed above the Brunkeberg formation represents a relatively short time gap (<10 Ma). The part of the unconformity developed above the Vindeggen group represents a substantially larger time gap, for the Vindeggen group was folded before the extrusion of the Brunkeberg porphyry. This time duration cannot be, however, approximated more closely as the ages of the sedimentation and folding of the Vindeggen group are not known. In the terms of sequence stratigraphy, the sub-Lifjell unconformity defines the lower bounding surface of an extensive Mesoproterozoic beach-shallow self sequence.

Key words: metasedimentary rocks, lithostratigraphy, unconformities, deformation, Mesoproterozoic, Lifjell, Telemark, Norway

e-mail: klaajoki@sun3.oulu.fi

1. Introduction

Unconformities represent substantial breaks or gaps in geological record caused either by nondeposition, erosion or deformation (tilting, folding, faulting, uplift) or their combinations. Their importance is measured by the time span they represent, which may vary greatly along their strike. Geological history during formation of an unconformity cannot be studied or dated directly, as it represents a lost rock record. Study of unconformities within the frames of regional structural and lithostratigraphic settings gives, however, important knowledge of the weathering, erosional and tectonic history of both the underlying and overlying sequences in question and is of first-order importance in lithostratigraphic classification. Dons (1960a, b) used unconformities for the latter purpose in his subdivision of the Mesoproterozoic supracrustal rocks in Telemark, south Norway, into the traditional Rjukan, Seljord, and Bandak groups. Recent studies (Laajoki et al., 2002; Laajoki, 2002, in press; Laajoki & Lamminen, 2006) have shown that this subdivision was right in principal points, but that the Telemark sequence includes other significant lithostratigraphic breaks. Laajoki et al. (2002) used one of them for reclassifying Dons' Seljord group into the Vindeggen and Lifjell groups. This paper gives a comprehensive field documentation of this important unconformity. Special emphasis is laid on (a) the primary features of the unconformity itself and the overlying rocks by the aid of which it can be identified from other unconformities in the area and (b) how it has been folded and faulted by the Sveconorwegian orogeny.

2. Geological setting and regional lithostratigraphy

The study area is located in the northern part of the Sveconorwegian Telemark sector (or block, Andersen, 2005a) of the Southwest Scandinavian Domain (Gaál & Gorbatschev, 1987) of the Fennoscandian (Baltic) Shield (Fig. 1). Most of the Precambrian crust in South Norway has been affected by Sveconorwegian deformation and metamorphism (1.2–0.9 Ga), which have obliterated primary stratigraphic relationships (e.g. Starmer, 1993). The northern part of the Telemark sector forms, however, an exception, as it is underlain by rather well preserved volcanic and sedimentary formations known as the Telemark supracrustals (Sigmond et al., 1997) whose history spans from c. 1.5 Ga to <1.12 Ga. The belt comprises two major lithostratigraphic entities: the Vestfjorddalen (c. 1.5 Ga to <1.155 Ga) and Sveconorwegian (c. 1.155 Ga – 1.0 Ga) supergroups separated by the sub-Svinsaga unconformity (Laajoki, in press). They consist of several groups and formations distributed within different lithostratigraphic-structural domains (Figs. 2 & 3, for the definitions of the domains see Laajoki, in press).

The *Vestfjorddalen supergroup* forms the core of the Telemark belt within the domains A & B in Fig. 2. It comprises two groups: (1) the Rjukan group, which consists of (a) the Tuddal formation of c. 1.5 Ga felsic volcanites (Dahlgren et al., 1990; Sigmond, 1998, Dons et al., 2004; Bingen et al., 2005) and (b) the basaltic Vemork formation, and (2) the Vindeggen group with several quartzite and two mudstone formations (Laajoki, in press).

The *Sveconorwegian supergroup* rims the Vestfjorddalenian core in the west, south and east. It is various consisting of diverse sedimentary and volcanic units within different domains as follows: In the southwest and west (domains E and F), the oldest Sveconorwegian unit is (1) the Oftefjell group, which starts with (a) the Svinsaga quartzite formation overlain by (b) the 1155±3 Ma porphyry of the Ljosdalsvatnet formation (Laajoki et al., 2002), (c) several quartzite and porphyry units and (d) the extensive Bergsvatnet basaltic formation (topmost). The sub-Røynstaul unconformity (Laajoki & Lamminen, 2006) separates the Oftefjell

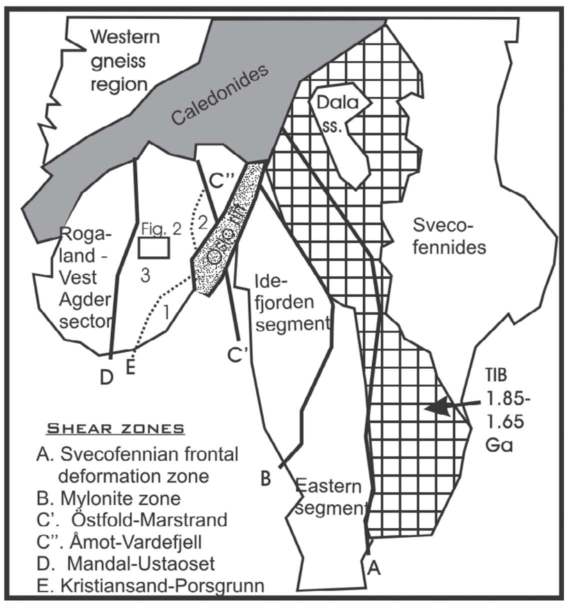


Fig. 1. Sketch map of the Sveconorwegian province (modified from Bingen et al., 2001). The area covered by Fig. 2 is framed. Numbered sectors west of the Oslo rift: (1) Bamble, (2) Kongsberg, (3) Telemark. TIB = Transscandinavian Igneous Belt.

group from the overlying (2) Høydalsmo group, which starts with (a) the quartzitic Røynstaul formation overlain by (b) the basaltic Morgedal formation, (c) the 1150±4 Ma old Dalaå porphyry formation (Laajoki et al., 2002), and (c) the basaltic Gjuve formation. The topmost unit is the <1118±38 Ma old Eidsborg formation (de Haas et al., 1999), which may overlie unconformably the Høydalsmo group.

In the south and southeast (domain G), the oldest unit is the 1155±2 Ma old Brunkeberg formation (Laajoki et al., 2002), whose depositional basement is not known. Within the error limits, its age is identical to that of the Ljosdalsvatnet porphyry (see above), but as it cannot be included by lithostratigraphic methods into the Oftefjell group it is kept separately. Around and east of Brunkeberg, the Lifjell group overlies unconformably the Brunkeberg formation, whereas SW of this town, a thin quartzite unit separates the latter from the complexly folded Transtaulhøgdi supracrustals of problematic stratigraphic position. A small, but critical part of the Lifjell group overlies the Vindeggen group at the eastern margin of the domain B in Heksfjellet. In the east (domain H), the Lifjell group is overlain unconformably by (a) the 1145±4 Ma old Skogsåa porphyry (Laajoki et al., 2002) and (b) the <1121±15 Ma old Heddal group (Bingen et al., 2003). The southern contact of the Telemark supracrustals is tectonic being separated by the Åseå thrust from the Bø granite (Fig. 2, section 4).

The unconformity under the Lifjell group within the domains B and G and its likely correlative at boundaries of domains B and E and D and E (Fig. 2) is the main target of this study. All the rocks have been metamorphosed in greenschist facies and so the meta-prefix should be used in the rock names, but for simplicity's sake their protolith names are used in this paper.

3. Previous studies

No proper documentation of the sub-Lifjell unconformity can be found in older literature, but Werenskiold (1910) classified the quartzites in east Telemark into the Svartdal quartzite (older) and the Lifjeld (Lifjell) and Blefjeld (Blefjell) quartzites (younger), of which the last named was said to lie discordantly over a "granulite" (porphyry in recent nomenclature) (cf. Andersen et al., 2004). Bugge (1931) wrote that the Seljord quartzite near Brunkeberg lies discordantly

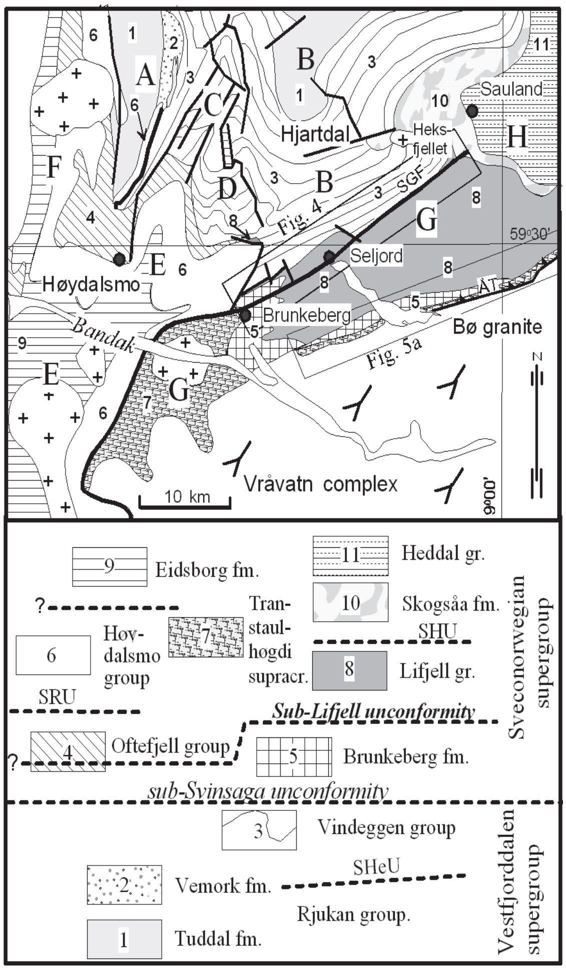


Fig. 2. Simplified geological map of the southern part of the Telemark supracrustals (in part after Dons & Jorde, 1978). Area of Figs. 4 & 5a are framed. Thick lines on the map and hatched lines in the legend refer to a major fault or shear zone and an unconformity, respectively. Unconformities: SHeU = sub-Heddersvatnet, SHU = sub-Heddal, SLU = sub-Lifjell, SRU = sub-Røynstaul. Note that the sub-Lifjell unconformity may continue within the Oftefjell group (see section 10 in the text). SGF = Slåkådalen-Grunningsdalen fault. ÅT = Åseåa thrust. Capital letters A – H refer to the lithostratigraphic-structural domains discussed in the text.

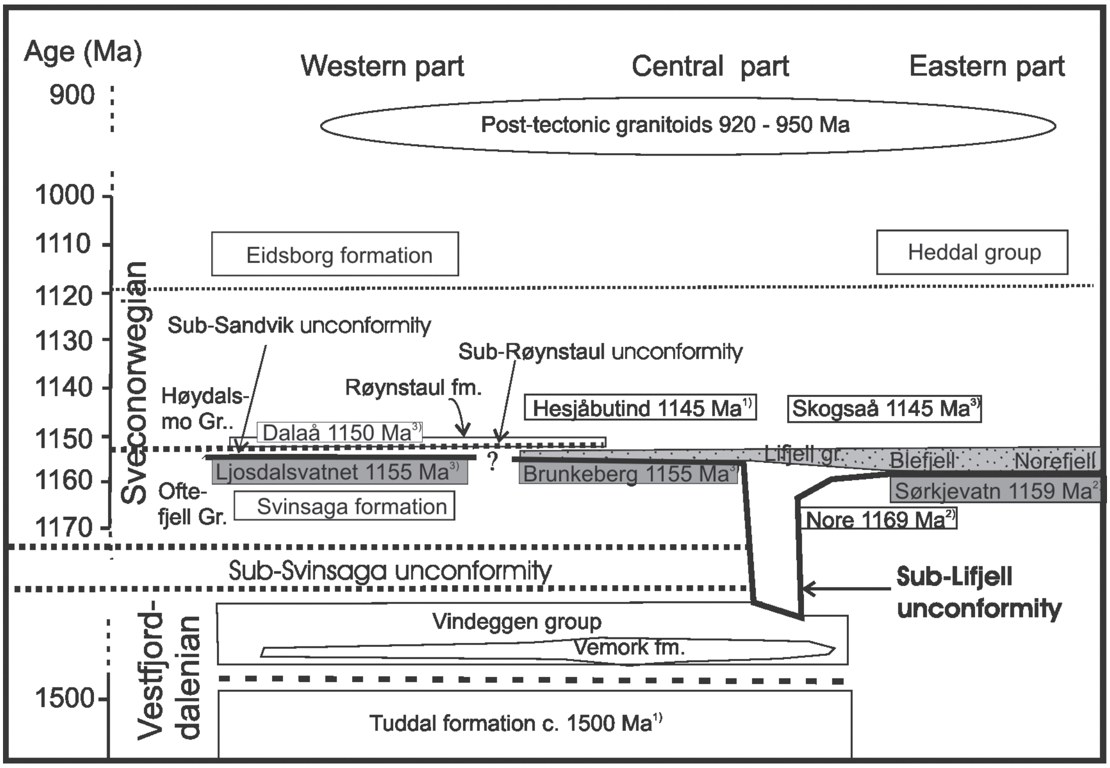


Fig. 3. Schematic chronostratigraphy of the dated igneous and associated sedimentary units in the southern part of the Telemark supracrustals discussed in the text. Note how the sub-Lifjell unconformity (heavy line) erodes the c. 1155 Ma volcanic porphyry units (dark grey) and the Vindeggen group and is overlain by the Lifjell-Blefjell-Norefjell quartzites (grey). Other unconformities are shown by dashed lines. Age references. 1) Dahlgren et al. 1990, Sigmond, 1998. 2) Bingen et al. 2003. 3) Laajoki et al. 2002. Limits of error c. ±2–8 Ma.

on a porphyry (Brunkeberg formation in this study), which he included into his Bandak formation. Dons (1960a, b) demonstrated that bulk of Bugge's Bandak formation overlies the Seljord quartzite and ranked it as the Bandak group, whereas Bugge's Seljord quartzite and Werenskiold's Lifjeld and Svartdal quartzites were all treated under the Seljord group. The Brunkeberg porphyry was correlated conditionally with the Tuddal formation of the Rjukan group. The relative young age of the Brunkeberg formation (Laajoki et al., 2002) proved that it could not be correlated with the Tuddal formation indicating that Werenskiold's concept of two main quartzite units was in principle right. As a consequence, Dons' (1960a, b) Seljord group was subdivided into the Vindeggen and Lifjell groups separated by the sub-Lifjell unconformity (for a more detailed discussion of the history of the lithostratigraphic nomenclature see Laajoki et al., 2002). The present paper is a complementary to this work and uses present informal lithostratigraphic nomenclature and scheme (Fig. 3).

4. Structural and lithostratigraphic features of the study area

Dons (1960b, p. 8) noted that the Telemark supracrustals north of the line Seljord-Brunkeberg have N-S fold axes as opposed to E-W fold axes in the area south of this line and that along this boundary complicated tectonic deformations have taken place. Recent studies have shown that this deformation zone characterized by several ENE trending faults continues from Seljord to Heksfjellet and is named informally the Brunkeberg - Heksfjellet tectonic zone

(Figs. 4a, b). The areas north and southeast of it are underlain mainly by the Middle and Upper Brattefjell formations of the Vindeggen group (domains B & D in Fig. 2) and the Lifjell group (domain G in Fig. 2, Kolltveiteggi, Årnotra and Lifjell ranges in Fig. 4a), respectively. Within the zone itself, the Brunkeberg formation and overlying basal conglomerates of the Lifjell group are exposed in the SW whereas the Heksfjellet conglomerate occurs in the NE. NW trending later faults subdivides the zone into several subareas. The Brunkeberg formation and the overlying conglomerates are most widely exposed SW of the Ubydalen fault (Fig. 4a), where they have been folded and faulted with SE vergence. The identified faults include the Grenjusnetten, Jåfjell, and Vigdesjå faults (Figs. 4a, c). The area NE from the Ubydalen fault to the Seljord city is mainly covered by the alluvium of the Bygdaråi river valley (Fig. 4b). The existence of the Bygdaråi fault along the southern margin of the valley is inferred by the higher degree of deformation of the Brunkeberg formation and associated rocks north of the fault in comparison with the gently folded quartzites of the Årnotra range in the south (Fig. 4b). The Brunkeberg formation and the overlying rocks exposed in the Seljord city and Bjørgenuten are structurally so different (e.g. opposite vergences) that they may be separated by a hidden NW trending fault ("proposed fault" in Fig. 4a). NE of the Borkebudalen fault, the unexposed Slåkådalen-Grunningsdalen fault separates the Vindeggen group in the north from the Lifjell group in the south and only a narrow slice of the Brunkeberg formation occurs in the SW part of Grunningsdalen. Farther to NE, the basal Heksfjellet conglomerate of the Lifjell group occurs from north of Nordfjell to Heksfjellet (Fig. 4a).

Conflicting interpretations regarding the relationship between the Telemark supracrustals and the granites and gneisses in the south appear in the literature (for discussion see Richards, 1998). Recent mapping has shown that this contact is tectonic consisting of the narrow, fault-bounded, SSE-SSW trending Åsekollen and Gardvik tectonic units separated by an inferred fault or a shear zone (Fig. 5a). The former unit consists mainly of gneissic quartzite separated by the Åseåa thrust from the Bø granite (Figs. 5b & c). The latter unit is made up mainly of the Brunkeberg formation with small relics of the overlying Vallar bru formation. West of Seljordsvatnet, the Gravalifjellet (Fig. 5d) and Båstjørnhovet faults (Fig. 5a) separate it from the tectonically overlying quartzites of the Årnotra and Kolltveiteggi ranges, respectively. Its contact with the quartzites of the Lifjell range has not been found exposed east of Seljordsvatnet, but is most likely tectonic. Consequently, the southern part of the Telemark supracrustals occupied by the Brunkeberg formation and the Lifjell group can be described as a minor fold and thrust belt instead of a rather simple synclinorium (Siggerud, 1954; Richards, 1998).

Most of the several faults of the area are unexposed following river valleys covered by alluvium or forest. This causes uncertainties when the sub-Lifjell unconformity is correlated from a place to another. That is why it was necessary to study carefully not only the unconformity itself, but also the rocks under and above it. Table 1 gives a brief description of lithologies across the unconformity in different subareas to be treated in the following.

5. Sub-Lifjell unconformity above the Vindeggen group

The Vindeggen group occupies the northern part of the study area. Its primary upper contact with the Lifjell group, the sub-Lifjell unconformity, is exposed in Heksfjellet and Nystaulvatnet-Grenjusnetten area in the NE and SW, respectively (Fig. 4a). Between these areas about 25 km apart the contact of these groups is either tectonic being defined by the Grunningsdalen, Jåfjell and Grenjusnetten faults and inferred faults south of Skorve and Hattefjell (Fig. 4a) or has not been found exposed.

5.1. Heksfjellet

The best locality where the sub-Lifjell unconformity lies without doubt on the Vindeggen group is the

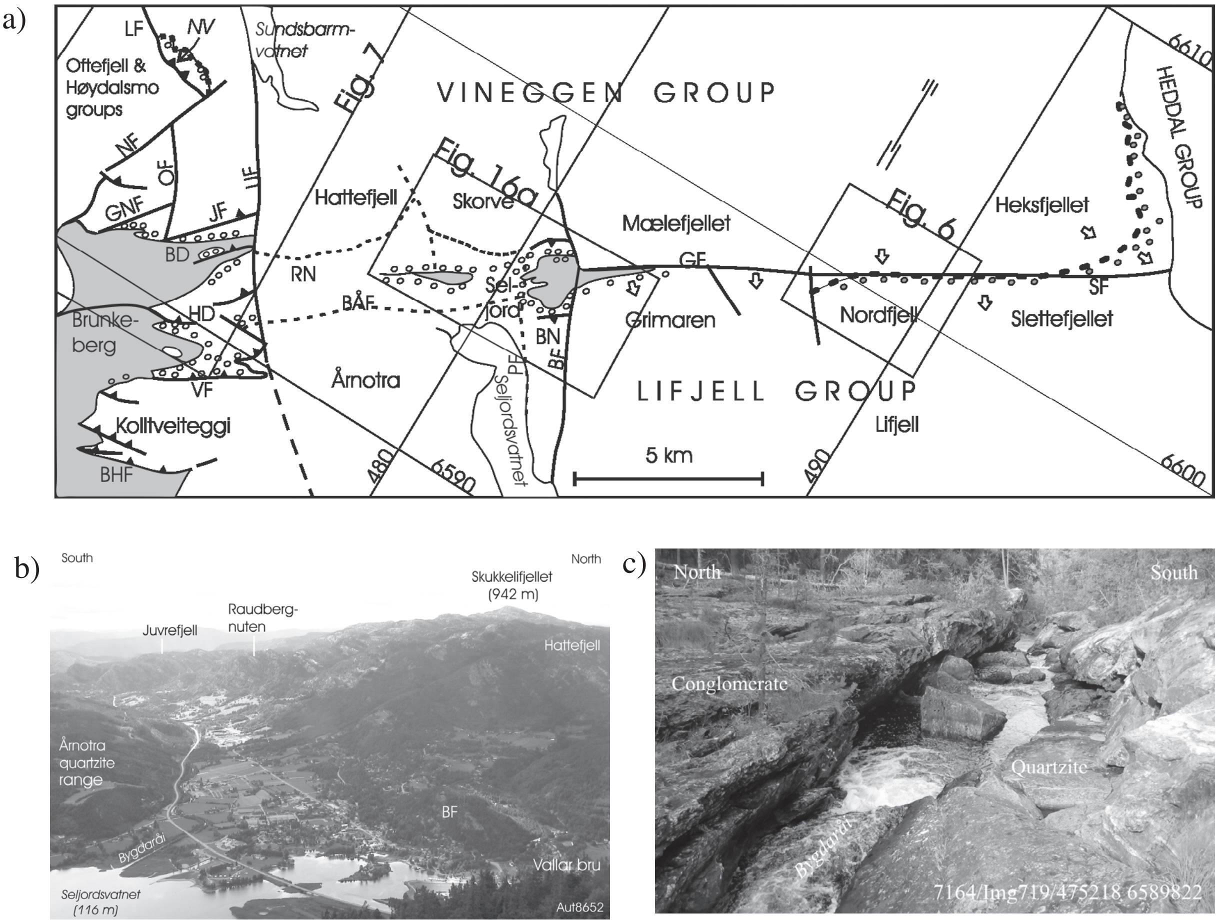
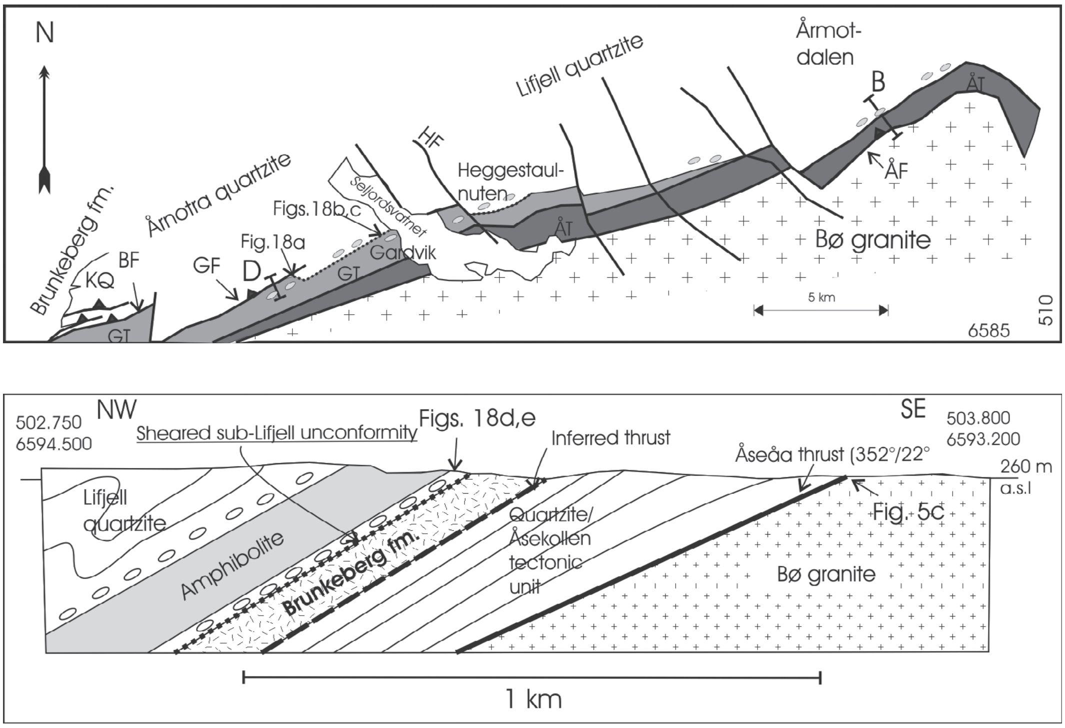


Fig. 4. a) Major faults in the Brunkeberg – Heksfjellet tectonic zone. Gray = Brunkeberg formation. Distribution of the Heksfjellet (in NE) and Vallar bru-type conglomerates are shown by gray and white balls, respectively. Sub-Lifjell unconformity above the Vindeggen group in Heksfjellet and Nystaulvatnet (NV in the left upper corner) areas is shown by a dashed line. Arrows indicate top directions. Major faults discussed in the text (teeth indicate dip direction): BF, BHF, BÅF, GF, GNF, JF, LF, NF, OF, PF, SF, UF and VF = Borkebudalen, Båstjörnhovet, Bygdaråi (inferred, Fig. 4b), Grunningsdalen, Grenjusnetten, Jåfjell, Lier, Nonnetten, Ordalen, "Proposed", Slåkådalen, Ubydalen, and Vigdesjå (Fig. 4c) faults, respectively. Geographic localities: BD = Bjørndalen, BN = Bjørgenuten, HD = Hesteskodiket, RN= Raudbergnuten. Areas of Figs. 6, 7, & 16a are framed. UTM coordinates are used (Also in all other maps and cross sections). b) View from Bjørgenuten to Juvrefjell along the Bygdaråi valley, which most likely represents a major thrust along which the quartzites in the north were thrust above the Årnotra quartzite range. BF marks the hill in the Seljord City consisting of a porphyry of the Brunkeberg formation. c) The Vigdesjå thrust dipping 35–55° to NW between a highly deformed Vallar bru conglomerate and a quartzite of the Kolltveiteggi range. Upper reaches of the Bygdaråi river.

a)



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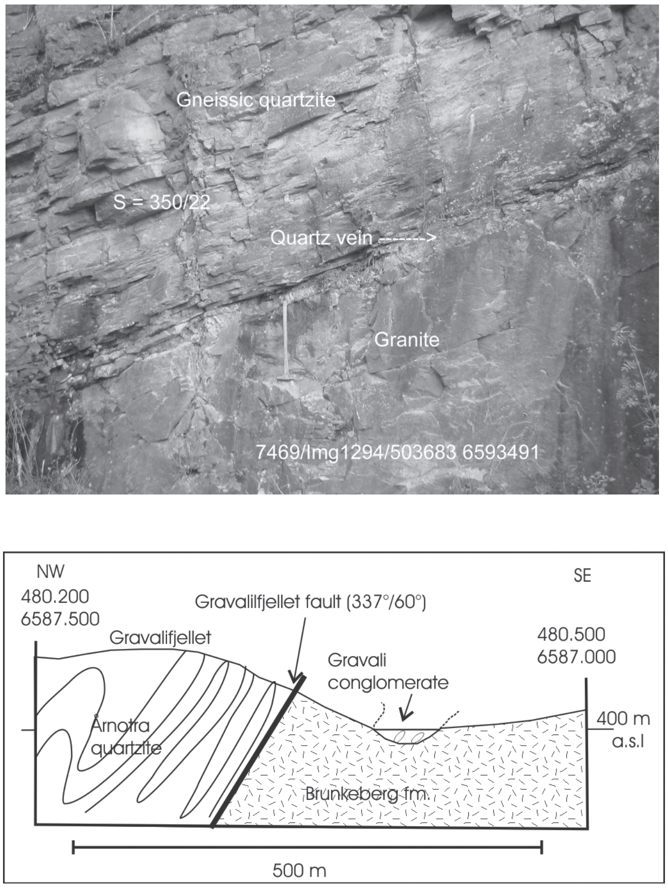


Fig. 5. a). Simplified geological map of the SE margin of the Telemark supracrustals. Small ellipsoids indicate Vallar bru-type conglomerates. Stippled lines indicate places where the sub-Lifjell unconformity has been preserved relatively well (Gardvik and Heggestaulnuten). GT, ÅT & KQ = Gardvik and Åsekollen tectonic units, and Kolltveiteggi quartzite, respectively. BF, GF, HF, & ÅF = Båstjørnhovet, Gravalifjellet, Heggenes, and Åseåa faults, respectively. Thick lines indicate faults. Their verified dip directions are indicated by black teeth. Cross sections in Figs. 5b & 5d are indicated by B & D. Locations of Figs. 18a-c are shown. b) Cross section along Årmotdalen. Locations of Figs. 5c, 18d-e are shown. c) The Åseåa thrust intruded by thin quartz vein above the Bø granite. Station number, file number, and UTM coordinates are give in the lower margin of this and all other outcrop photograph. Road to Årmotdalen. d) Cross section across Gravalifjellet. Note the Vallar bru-type Gravali conglomerate lying on the Brunkeberg formation.

Table 1. Schema of lithostratigraphic units across and nature of the sub-Lifjell unconformity in different subareas.

Heksfjellet-Nordfjell	**Nystaulvatnet**	**Brunkeberg-Grunnings-dalen**	**Gardvik tectonic unit**
Folded ortho-quartzites of the Lifjell range with a minor heterolith unit.	Høydalsmo group: - Morgedal fm. - Røynstaul fm.	Folded orthoquartzites of the Lifjell range and the hills between Seljord and Hesteskodiket.	Folded orthoquartzites of the Lifjell range with minor heterolith units in lower parts
-- Slåkådalen fault--	*-- Lier fault --*		
	Vallar bru formation		
		Quartzite-clast conglomerate	
	Nystaulvatnet mb. Sericite quartzite - orthoquartzite with solitary quartzite pebbles or quartzite-clast beds. Detrital garnet. Lies locally directly on the Vindeggen group	Sericite quartzite – orthoquartzite often with quartzite pebbles or quartzite-clast beds. In Bjørndalen, epidote-bearing sericite schists and graded bedded quartzite-mudstone layers.	Sericite quartzite with solitary quartzite cobbles and boulders
Heksfjellet conglomerate: Lover part contains both felsic volcanite and quartzite clasts. Passes upwards to quartzite-clast conglomerate with quartzite interbeds	Vatnelian mb. Vallar bru-type conglomerates with epidote and felsic volcanic material. Garnet-bearing mica-schist units.	Vallar bru conglomerate: Lover part contains both felsic volcanite and quartzite clasts in felsic volcanic matrix. Passes upwards to a quartzite-clast conglomerate with quartzite interbeds.	Amphibolite (metadiabase)
		Hesteskodiket conglomerate: Solitary felsic volcanite and quartzite clasts in volcanic matrix. Gradual contacts with the Brunkeberg fm. & the overlying conglomerate.	Hesteskodiket-type conglomerate
--- sub-Lifjell unconformity ---			
In situ breccia	*In situ* breccia or sharp angular unconformity	Palaeoregolith	
Upper Brattefjell fm. - wave rippled – parallel laminated orthoquartzite with low-angle cross-bedding	Upper Brattefjell fm. (see adjacent column) and .Middle Brattefjell fm. - cross-bedded quartzite with mudstone caps and rippled quartzite.	Brunkeberg formation	

eastern flank of Heksfjellet (Figs. 2 & 4). As this key occurrence has already been described in detail (Laajoki 2002; Laajoki et al., 2002) only some most important facts are repeated here:

1. An *in situ* breccia developed above the orthoquartzite of the Upper Brattefjell formation of the Vindeggen group (Figs. 9 & 10a in Laajoki, 2002; Fig. 6d in Laajoki et al., 2002).

2. The 1498 ± 6 Ma old porphyry clast (Laajoki et al., 2002) in the Heksfjellet conglomerate, the basal unit of the Lifjell group, has most likely been derived from the Tuddal formation indicating that the basement of the Vindeggen group was exposed at the beginning of the deposition of the Lifjell group. As the Vindeggen group is at least 9 km thick (Laajoki, in press), this suggests a significant pre-Lifjell uplift and erosion of the Vestfjorddalen supergroup.

The sub-Lifjell unconformity has not been found exposed SW of Heksfjellet, but the Heksfjellet conglomerate and the quartzites interbedded with it can be mapped along Slåkådalen to north of Nordfjell (Fig. 4a), where an Upper Brattefjell quartzite dipping shallowly to the SE underlies them (Fig. 6). This indicates that the unconformity may continue this far, but it may have been sheared along the unexposed Slåkådalen - Grunningsdalen fault and is separated by the inferred Nordfjell fault from the sub-Lifjell unconformity above the Brunkeberg formation in the SW end of Grunningsdalen (section 6.5).

5.2. Nystaulvatnet area

This area is located about 25 km SW of Heksfjellet (Fig. 4a). It comprises a pervasively deformed area between the Hovundvarden and Bandak domains (Figs. 7 & 8). Here an unconformity is exposed above the Middle Brattefjell formation of the Vindeggen group. The main problem is should it be correlated with the sub-Svinsaga unconformity (Laajoki, in press) which is exposed only 3 km to the west (Fig. 8) or does it represent the sub-Lifjell unconformity. That is why the geology of the area must be treated in some detail.

Geology: Neumann and Dons (1961) included the conglomerates and quartzites exposed between the Vindeggen group and the Morgedal formation in the Nystaulvatnet area in the Røynstaul formation, whereas Nielsen and Dons (1991) and Dons (2003) correlated them with the Svinsaga formation exposed immediately in the west, north of Lake Liervatnet (Figs. 7 & 8). The lithostratigraphic sequences of these two areas are, however, so contrasting (Table 2) that they cannot be correlated readily, but are most likely separated by a fault (Lier fault in Fig. 8).

The bedrock around and SE of Lake Liervatnet forms a minor syncline, where a lithostratigraphy typical to the Bandak domain can be read from the sub-Svinsaga unconformity upwards (Fig. 5n in Laajoki, in press). The Kleiv marmor, which Nielsen and Dons (1991) and Dons (2003) considered as part of their Ofte formation, occupies the Ljosdalsvatnet formation/the Røynstaul formation contact. In this paper, it is included in the Røynstaul formation, as it is associated with a polymictic conglomerate with both quartzite and felsic volcanite cobbles and boulders and has an analogous lithostratigraphic position

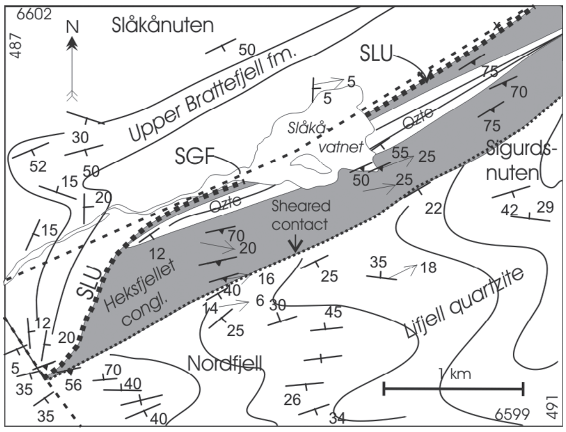


Fig. 6. Simplified geological map around Slåkåvatnet showing the foliated and stretched Heksfjellet conglomerate (gray) between folded Upper Brattefjell formation and the Lifjell quartzites. SLU = inferred sub-Lifjell unconformity. SGF = inferred Slåkådalen-Grunningsdalen fault. Note how the Upper Brattefjell formation continues across the SGF and how bedding is preserved in the quartzite interbed in the Heksfjellet conglomerate. For structural symbols see Fig. 10a. Lineations within the conglomerate and quartzites indicate stretching lineation and intersection lineation, respectively.

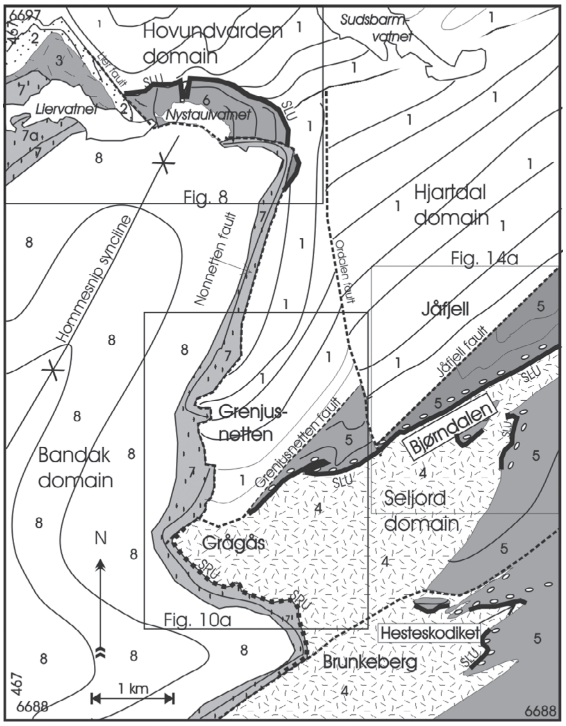


Fig. 7. Simplified geological map of the Brunkeberg-Nystaulvatnet area. Bedding is shown by form lines. Lithostratigraphic units: 1. Vindeggen group. 2. Svinsaga formation. 3. Ljosdalsvatnet formation. 4. Brunkeberg formation. 5. Lifjell group (ellipsoids = Vallar bru-type conglomerate). 6. Vatnelian and Nystaulvatnet members of the Nystaulvatnet area (see section 5.2 in the text). 7 & 7a. Quartzite and Nielsen's & Dons' (1991) unit 20 mafic metalava of the Røynstaul formation, respectively. 8. Morgedal and Dalaå formations. Dashed lines = inferred faults. Thick and dotted lines around the Brunkeberg formation indicate relatively well-preserved parts of the sub-Lifjell (SLU) and sub-Røynstaul (SRU) unconformities, respectively. Areas of maps in Figs. 8, 10a, and 14a are framed and the location of the Hesteskodiket outcrop (Fig. 13a) is shown.

with the basal Kultankriklan conglomerate of the Røynstaul formation in Fjellet (Laajoki & Lamminen, 2006). The presence of carbonates can be attributed to a local facies change.

The bedrock immediately north of Nystaulvatnet and around Nystaul (Fig. 8) is highly tectonized with subhorizontal, N-S trending stretching lineation, sheath folds, folded/destroyed bedding, subhorizontal foliation, and mylonitic metabasites at its northern margin. It is subdivided informally from the north to south into (1) the Vatnelian, and (2) Nystaulvatnet members (Tables 1 & 2).

The Vatnelian member consists of a handful of small breccia and conglomerate outcrops close to or at the contact with the Middle Brattefjell formation of the Vindeggen group. The main problem is does the quartzite-clast conglomerates represent the Vallar bru formation or the basal Svinsaga conglomerates. A highly stretched quartzite-clast conglomerate with subhorizontal foliation is exposed at station 1537 (Fig. 9a, for the UTM coordinates of the stations discussed see the photographs referred to). It is overlain and underlain topographically by an orthoquartzite and dark-laminated sericite quartzite, respectively. At station 1460, just south of the Vindeggen group, a similar, highly stretched conglomerate also occurs. Micaceous matrix contains clastic epidote, quartz-phenocryst clasts, abundant green tourmaline, and garnet porphyroblasts. Nd-isotope mass-balance model (Andersen & Laajoki, 2003) confirms the presence of relatively large amount of volcaniclastic material in the rock. On the basis of the felsic volcanic material, it cannot be correlated with the nearby basal Svinsaga conglomerate; whose matrix is orthoquartzitic and which was deposited before the 1155 Ma felsic volcanism in the area. Andersen and Laajoki (*op. cit.*) correlated it with the Vallar bru formation. A micaceous quartzite with epidote patches and mica schist with subhorizontal foliation occurs at station 3533 (Fig. 9b). Its pervasive deformation indicates the nearness of the Lier fault, for west of it rather well preserved quartzites and conglomerates of the Svinsaga formation occur. These highly foliated rocks of the Vatnelian member represent a deformation zone between the Vindeggen group and the Nystaulvatnet member. Unconformity observations given below indicate that they were deposited unconformably on the former.

The Nystaulvatnet member overlies conformably the breccias and conglomerates of the Vatnelian member or lies unconformably directly on the Middle Brattefjell formation. It is made up mainly of grey sericite quartzite containing solitary quartzite pebbles and often also hematite laminae. Thin interbeds of

Table 2. Comparison of the lithostratigraphies of the Brunkeberg and Ljosdalsvatnet (simplified) areas across the Bandak domain using the upper surfaces of the 1155 Ma porphyries as a reference level. For the geology of the Ljosdalsvatnet area see Laajoki & Lamminen (2006). Gray and black = felsic and basaltic volcanic units, respectively.

Ljosdalsvatnet area (Domain F in Fig. 2)	**Bandak area (Domain E in Fig. 2)**	**Brunkeberg area (Domain G in Fig. 2)**
HØYDALSMO GROUP	**← c. 15 km →**	
Sub-Røynstaul unconformity	Rustfjellet fault; Nonnetten fault	
Bergsvatnet fm.		
(metabasaltic)		
Breidlansnutane fm. (porphyry)		
Hovdevatnet fm. (pebbly quartzite)		Present erosional level
Unnamed metabasaltic fm.		LIFJELL GROUP - Quartzite - Vallar bru congl.
Sandvik pebbly quartzite		
Sub-Sandvik unconformity	? Correlative?	***Sub-Lifjell unconformity***
Ljosdalsvatnet fm. (1155 ± 3 Ma)		Brunkeberg formation (1155 ± 2 Ma)
Svinsaga formation		Basement unknown
Sub-Svinsaga unconformity		
VINDEGGEN GROUP		

strained quartzite-clast conglomerates occur in lower parts. Similar rocks occur within the quartzites overlying the Vallar bru conglomerates in the Åmtveit and Brunkeberg areas (Table 1) c. 5 km to the SE. That is why this member is considered as a part of the Vallar bru formation moved by the Nonnetten fault to the north (Fig. 7).

<u>*Røynstaul formation:*</u> Around Nystaul, SE of Nystaulvatnet, a light brown, feldspathic quartzite with polymictic conglomerate beds with both quartzite and felsic volcanic clasts represents the Røynstaul formation. In comparison with the Nystaulvatnet member, the structure of this part is relatively simple and bedding and top observations indicate that it belongs structurally to the Hommesnip syncline of the Bandak domain (Fig. 7). The contact between it and the Nystaulvatnet member is occupied by a mylonitic sericite quartzite with foliation dipping shallowly to the south indicating that the contact is most likely a fault, which may represent the northern, folded extension of the Nonnetten fault and which may be connected with the Lier fault (Fig. 8).

<u>*Sub-Lifjell unconformity:*</u> As the Vatnelian and Nystaulvatnet members are included into the Vallar bru formation their contact with the Middle Brattefjell formation is considered as part of the sub-Lifjell unconformity. The nature of the unconformity varies from place to place. At station 1990, an *in situ* quartzite breccia (Fig. 9c) with scanty muscovite-rich matrix (Fig. 9d) is exposed. This is similar to the breccia at the contact between Vindeggen and Lifjell groups at Heksfjellet (Fig. 6d in Laajoki et al., 2002). At station 4307, a sericite quartzite lies unconformably on a folded Middle Brattefjell quartzite (Fig. 9e). The gray colour and abundant micas distinguish the rock from the pink, orthoquartzitic Svinsaga formation quartz-

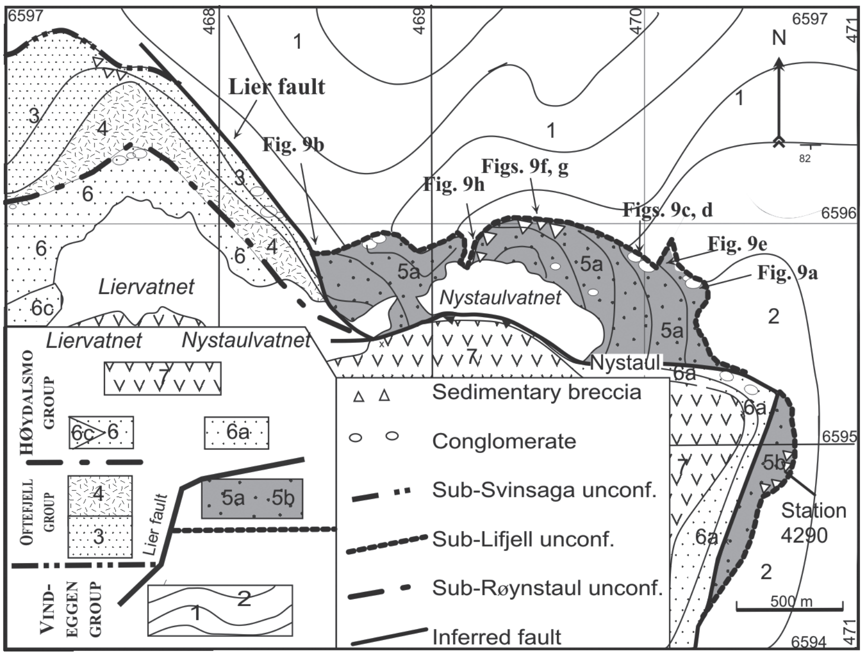
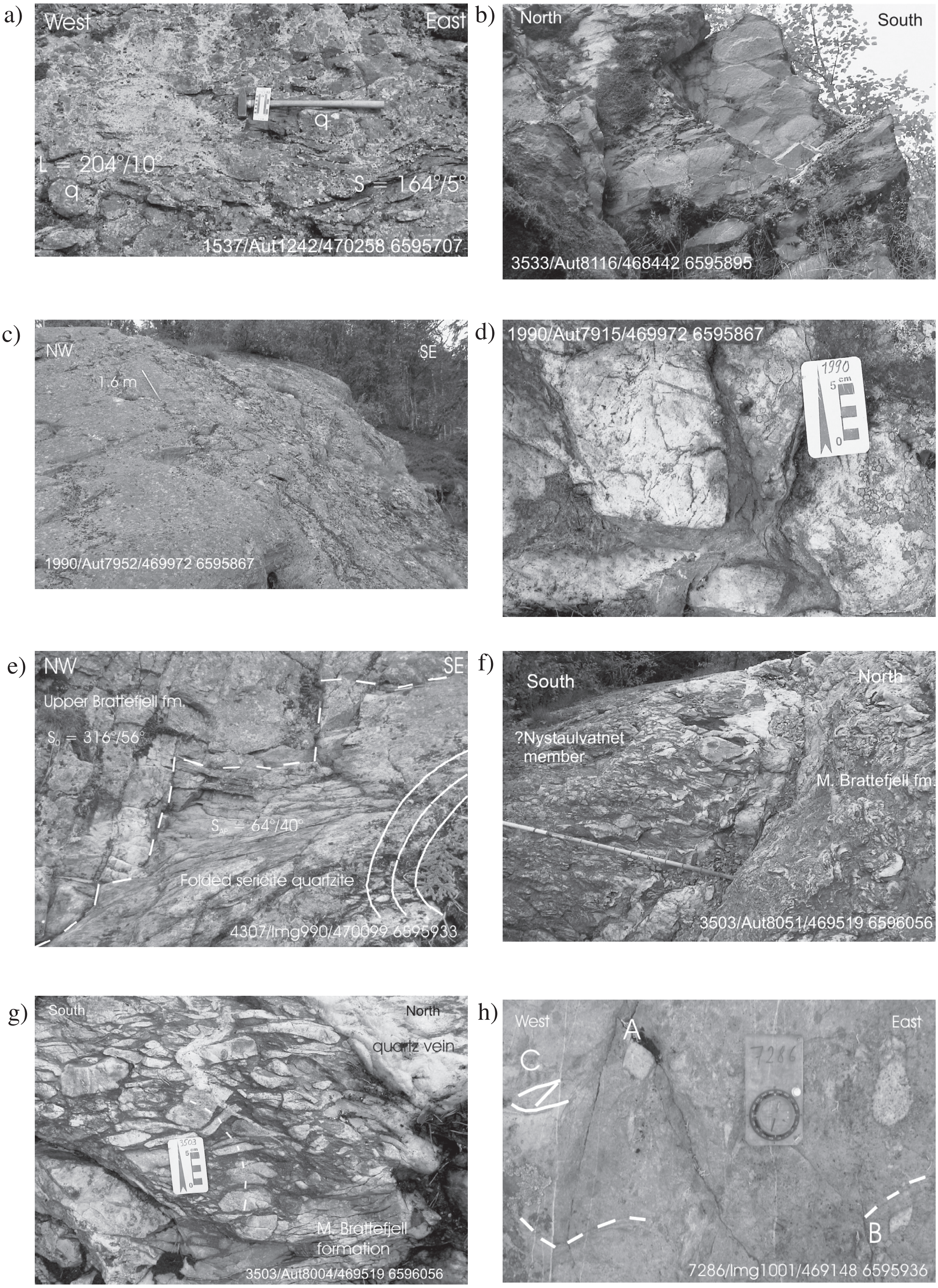


Fig. 8. Geological map of the Nystaulvatnet area. Lithostratigraphic units: 1 & 2. Middle and Upper Brattefjell formations of the Vindeggen group, respectively. 3 & 4. Svinsaga and Ljosdalsvatnet formations of the Oftefjell group, respectively. 5a & 5b. Vatnelian and Nystaulvatnet members and Kortkardsnuten breccia (exposed only at Station 4290 in the right lower corner) of the Vallar bru formation, respectively. 6, 6a & 6b. Quartzite, Nystaul member, and Nielsen's & Dons' (1991) unit 20 mafic metalava of the Røynstaul formation, respectively. 7. Morgedal formation. Locations of photographed outcrops in Fig. 9 are shown. Form lines give bedding.

ites. These features together with the accessory garnet connect it more likely with the Vallar bru quartzites in the Bjørndalen area. The folding of the sericite quartzite indicates that this stepped unconformity is overturned to the SSE. It is possible that the outcrop in Fig. 9a also represents an overturned, but pervasively foliated unconformity, for the distance between these outcrops is only 150 m and the quartzite topographically under the station 1537 conglomerate resembles the station 4307 quartzite.

The nature of the unconformity is more complicated west of the outcrops described above. At sta-

Fig. 9. Photographs of the sub-Lifjell unconformity and basal parts of the Vallar bru formation in the Nystaulvatnet area. For locations see Fig. 8. a) Stretched and foliated quartzite-clast (q) conglomerate, Section is vertical to the foliation and stretching lineation. For discussion see the text. b) Foliated (S = 0°/22°) micaceous quartzite – mica schist with epidotized domains (light areas). c) *In situ* breccia of the Vatnelian member above the Middle Brattefjell formation. The unconformity dips about 40° to the south. Note: this photograph appears erroneously as Fig. 13b in Laajoki 2002. d) Close up of the breccia in Fig.9c with muscovite schist (mudstone) filling breccia fractures. e) Stepped angular unconformity (stippled line) between the Upper Brattefjell quartzite and a sericite quartzite overturned towards the viewer. Axial plane foliation and folding of bedding (curves on the right) in the latter are shown. f) Deformed contact (dips about 70° to the south) between the Middle Brattefjell formation and the breccia under the Nystaulvatnet member. White irregular patches are quartz veins. g) Detail of the breccia in Fig. 9f. Note the knife-sharp sides of the fragments subparallel to the local foliation (c. 260°/75°), layer-like organization of the fragments (dashed line), and sharp, fragmented contact of the quartzite (lower right corner). h) Sericite quartzite above basal breccia with solitary sharp-edge quartzite fragments (A & B). Note relict lamination (dashed lines) and overturned cross-lamination (C).


a)
West
East
q
L = 204°/10°
q
S = 164°/5°
1537/Aut1242/470258 6595707
b)
North
South
3533/Aut8116/468442 6595895
c)
NW
SE
1.6 m
1990/Aut7952/469972 6595867
d)
1990/Aut7915/469972 6595867
1990
5 cm
0
e)
NW
SE
Upper Brattefjell fm.
S_0 = 316°/56°
S_{AP} = 64°/40°
Folded sericite quartzite
4307/Img990/470099 6595933
f)
South
North
?Nystaulvatnet member
M. Brattefjell fm.
3503/Aut8051/469519 6596056
g)
South
North
quartz vein
3503
M. Brattefjell formation
3503/Aut8004/469519 6596056
h)
West
East
A
C
7266
B
7286/Img1001/469148 6595936

tion 3503, the Vatnelian member starts with a quartzite breccia, which has a fault-like, quartz-veined boundary with the Middle Brattefjell formation (Fig. 9f). The angular quartzite fragments occur in dark opaque-pigmented sericite quartzite rich in accessory apatite, zircon and clastic tourmaline. The fragments are interpreted as quartzite interbeds or fragments of quartzite beds cut tectonically into pieces since their sharp sides are parallel to the local foliation and seem to define relict bedding (Fig. 9g). At Station 7286, the breccia is overlain by a laminated or rippled – cross-bedded sericite quartzite with solitary quartzite cobbles and pebbles some of which clearly represents sharp-bounded fragments (Fig. 9h). The rather well-preserved primary structures in the host rock indicate that the quartzite fragments were fragmented before the deposition of the rock. The *in situ* breccia at station 1990 indicates that weathering processes were capable to produce significant amounts of angular fragments from the Upper Brattefjell quartzite supporting that these western occurrences are sedimentary *in situ* – basal breccias deformed intensively by the Sveconorwegian orogeny and that they mark a continuation of the angular unconformity shown in Fig. 9e.

5.3. Grenjusnetten

Grenjusnetten is a fault-bounded mountain c. 5 km south of Nystaulvatnet. It consists of Upper Brattefjell quartzite of the Vindeggen group with quartzite breccias and conglomerates on it southern flank (Fig. 10). The lithostratigraphic position of the quartzite immediately west of Grenjusnetten has been problematic. It has been mapped either as the Svinsaga or Røynstaul formation (Neumann & Dons, 1961; Dons, 2003, respectively). Recent studies proved that the latter choice is valid and that a poorly exposed tectonic zone, named the Nonnetten fault (Fig. 10), separates the Røynstaul formation from the Upper Brattefjell formation exposed at Grenjusnetten. The steep quartzite wall of the Upper Brattefjell formation indicates the presence of the Nonnetten fault, on which patches of highly deformed quartzite breccias are locally preserved (Figs. 11a & b). The main difficulty in this area is to separate deformed sedimentary breccias from real tectonic breccias. Three breccia types occur:

(1) At station 4388, just east of the Nonnetten fault, a tightly packed quartzite breccia with angular fragments of parallel laminated quartzite of the Upper Brattefjell formation occurs. The breccia can be followed about 50 m along the strike of the bedding in the Upper Brattefjell formation. The size of the fragments varies from a few centimetres up to boulder size (Fig.11c). A few well-rounded quartzite pebbles also occur (marked by e in Fig. 11c) proving that the breccia is sedimentary, likely a talus. The dark, scanty matrix consists of sericite quartzite rich in opaques and enriched in accessory detrital zircon and apatite relative to the orthoquartzite fragments. Close to the breccia/quartzite contact quartzite fragments up to 10 m long and 1 m thick occur and some of the breccia fragments seem to form fold-like patterns. These may represent parts of the Upper Brattefjell formation folded and faulted before the sedimentary breccia was formed.

(2) At station 4360, an *in situ* breccia and conglomerate occur upon an Upper Brattefjell formation quartzite. The conglomerate/quartzite contact is gradual starting with a fracture zone in quartzite, which passes to a conglomerate (Fig. 11d), whose matrix is similar to that of the station 4388 breccia.

(3) The third type, the Kortkardsnuten breccia, flanks the Nonnetten fault. It occurs as relatively thin (20 – 50 cm), highly deformed relics attached to the Upper Brattefjell quartzite and has a fault contact with the Røynstaul formation (Figs. 11a & b). It resembles a tectonic breccia near the quartzite (Fig. 11e), but at a short distance from it both angular and well-rounded clasts of different quartzite types occur (Fig. 11f). The dark sericite-quartzite matrix is similar to the matrices in the breccias described above and fills fractures in the underlying quartzite. These features indicate a transition from *in situ* breccia to a basal conglomerate. This type may represent more deformed part of the station 4360 breccia and conglomerate. A similar brec-

a)

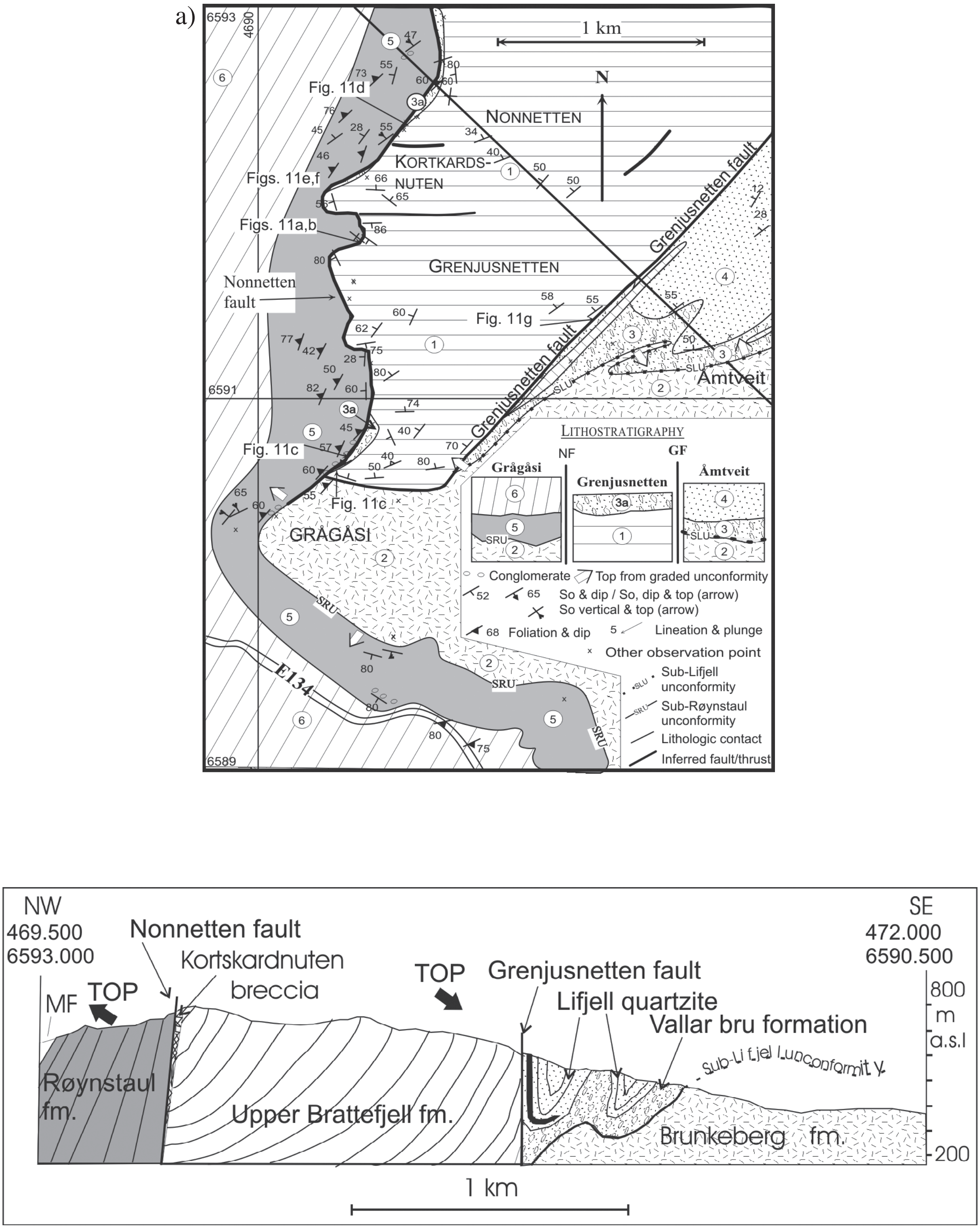
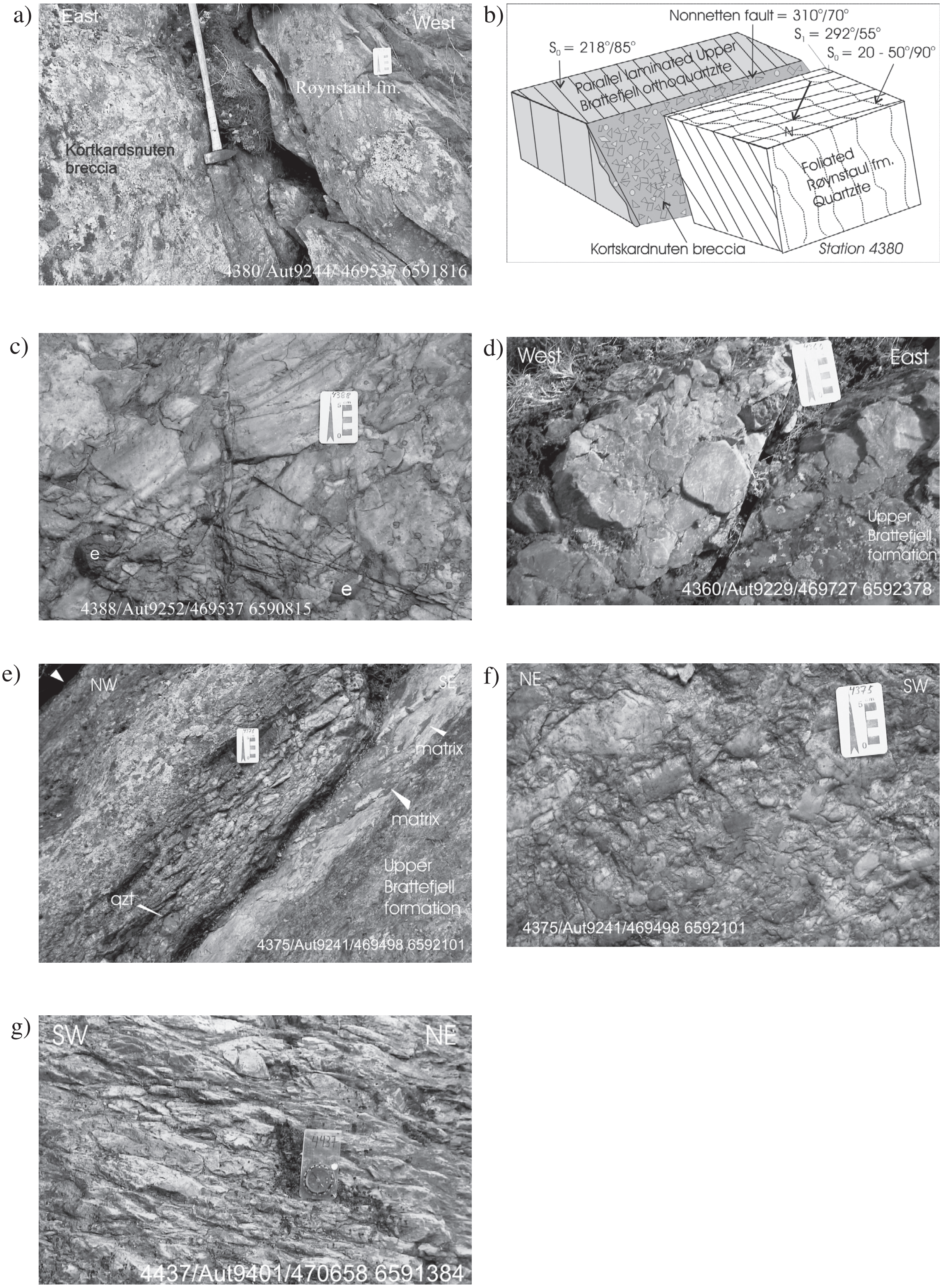


Fig. 10. a) Geological map with lithostratigraphic columns of the Grenjusnetten area. Lithostratigraphic units: 1. Upper Middle Brattefjell formation of the Vindeggen group. 2. Brunkeberg formation. 3. Vallar bru formation. 3a. Kortkardsnuten breccia. 4. Lifjell quartzite. 5. Røynstaul formation. 6. Morgedal formation. Locations of outcrops in Fig. 11 are shown. The diagonal line shows the location of the cross section in Fig. 10b. b) Cross section across Grenjusnetten along the line in Fig. 10a. MF = Morgedal formation.

a) b) c) d) e) f) g)


East
West
Røynstaul fm.
Kortkardsnuten breccia
4380/Aut9244/469537 6591816
Nonnetten fault = 310°/70°
S_1 = 292°/55°
S_0 = 218°/85°
S_0 = 20 - 50°/90°
Parallel laminated Upper Brattefjell orthoquartzite
N
Foliated Røynstaul fm. Quartzite
Kortskardnuten breccia
Station 4380
e
e
4388/Aut9252/469537 6590815
West
East
Upper Brattefjell formation
4360/Aut9229/469727 6592378
NW
SE
matrix
matrix
Upper Brattefjell formation
qzt
4375/Aut9241/469498 6592101
NE
SW
4375/Aut9241/469498 6592101
SW
NE
4437/Aut9401/470658 6591384

cia occurs as a thin layer also on the NW flank of the Grenjusnetten fault (Fig. 11g), which looks like a tectonic breccia. However, its scanty matrix is rich in muscovite, opaques and accessory zircon like in the cases above and so it may be consider as a tectonized sedimentary breccia.

As the conglomerates and breccias can be followed about 2 km along Grenjusnetten and they cut the bedding in the Upper Brattefjell formation at various angles (Fig.10a) they most likely represent the southern, sheared extension of the angular unconformity exposed north of Nystaulvatnet (Figs. 9c, e), but the bedrock between these two areas is covered and may be faulted.

5.4. Vindeggen group/Lifjell group boundary between Grenjusnetten and Seljord

South of Grenjusnetten and Jåfjell, Upper Brattefjell quartzites are separated from the Vallar bru formation by faults named after these hills (Figs. 7 & 10). East the Ubydalen fault, a deformed Lifjell group quartzite with quartzite-clast conglomerates underlies Raudbergnuten (for location see Figs. 4a, b). A less deformed Upper Brattefjell quartzite of the Vindeggen group occurs north of it (Fig. 12a). The contact between the quartzites is not exposed, but a tightly packed quartzite breccia (Fig. 12b) similar to the one at Station 4388 in Grenjusnetten area (Fig. 11c) occurs near it. The breccia is underlain topographically by a more deformed breccia conglomerate with rounded, but stretched quartzite-pebbles in a quartzite matrix (Fig. 12c) and a quartzite-matrixed quartzite-clast conglomerate similar to those in the Vallar bru formation. These observations indicate that an *in situ* breccia was developed upon the Upper Brattefjell formation, but the unconformity itself cannot be located due to missing outcrops. Quite likely it has been sheared and overturned. That is why an inferred fault is marked to run from southern flank of Hattefjell to south of Skorve in Fig. 4a. In the latter place, a mylonitic metadiabases topographically above the Vallar bru formation indicates a tectonic contact.

6. Sub-Lifjell unconformity above the Brunkeberg formation

Although the sub-Lifjell unconformity above the Brunkeberg porphyry is exposed only in a few outcrops and has been folded and faulted, it can be mapped rather accurately with the aid of the distinctive Hesteskodiket- and Vallar bru- type conglomerates (Fig. 4a, Table 1). The outcrops where the sub-Lifjell unconformity is exposed will be described starting from the Brunkeberg and Transtaulhøgdi areas, where the sub-Lifjell unconformity overlies the dated part of the Brunkeberg formation and is relatively little deformed. After these, more deformed occurrences in the Seljord city, Bjørgenuten and in Grunningsdalen and within the Gardvik tectonic unit will be described.

6.1 Hesteskodiket

This is the classical locality (Figs. 4 & 7) where the Vallar bru type conglomerate was first described (We-

Fig. 11. Photographs of basal breccias and conglomerates around Grenjusnetten (for locations see Fig. 10a). a) Outcrop photograph (hammer handle = 60 cm) and b) structural sketch of a fault contact between the Upper Brattefjell formation of the Vindeggen group and the Røynstaul formation of the Høydalsmo group with the Kortkardsnuten breccia attached to the former. c) Quartzite breccia with fragments of the near-by Upper Brattefjell quartzite and a few exotic, well-rounded quartzite pebbles (e). Scale in cm. d) *In situ* breccia above the Upper Brattefjell quartzite. e) View across the Upper Brattefjell quartzite/Kortkardsnuten breccia contact within the Nonnetten fault zone. Note how the matrix enters into the quartzite (arrows on the right) and solitary well-rounded quartzite pebbles (qzt). The arrow in the left upper corner points to the surface presented in Fig. 11f. f) View of the Kortkardsnuten breccia vertical to the Nonnetten fault surface. Presence of both angular and well-rounded clasts of diverse quartzites indicates that this part represents a transition to a real conglomerate. g) Tectonized quartzite breccia on the NE flank of the Grenjusnetten fault.

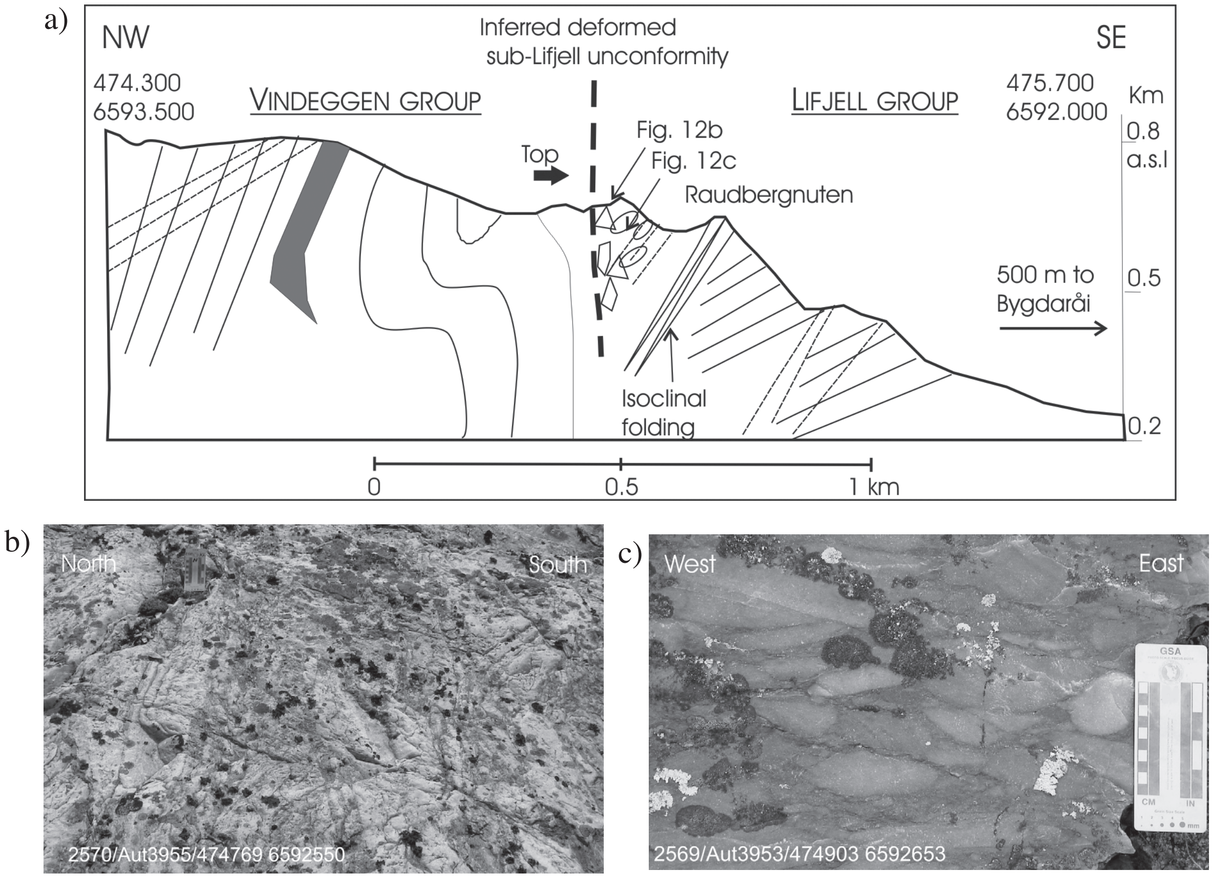


Fig. 12. Cross-section of and breccias at Raudbergnuten. a) Geological cross section across the Vindeggen group/ Lifjell group boundary. Dashed and solid lines indicate foliation and bedding, respectively. Gray = metadiabase. b) Lichen-covered quartzite breccia with randomly orientated fragments. c) Quartzite breccia with rounded quartzite clasts in quartzite matrix.

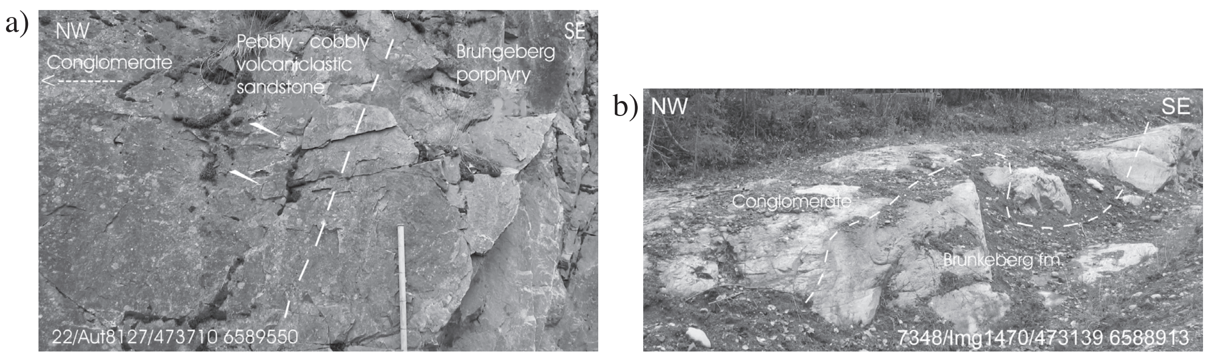


Fig. 13. Photographs of the sub-Lifjell unconformity in the Hesteskodiket area. a) Type outcrop of the sub-Lifjell unconformity showing gradual change from the Brunkeberg formation via its detritus with solitary quartzite pebbles (arrows) to a Vallar bru-type conglomerate. Hesteskodiket (for location see Fig. 7). Dashed line shows approximated bedding position. Stick = 50 cm. b) Openly folded sub-Lifjell unconformity (dashed line) above the Brunkeberg formation. Axial plane foliation 337°/80°. 0.5 km SW of Hesteskodiket.

renskiold, 1910; Bugge, 1931; Dons 1960a, p. 19). It serves as the type locality for the part of the sub-Lifjell unconformity developed above the Brunkeberg formation (Laajoki et al., 2002). Unfortunately, the pollution caused by the passing traffic has stained the road cut. The unconformity cannot be seen as a sharp boundary, but a Brunkeberg formation porphyry passes gradually to a felsic volcanic detritus with solitary quartzite clasts (Fig. 13a): this part is called for simplicity's sake the Hesteskodiket conglomerate, although it consists mostly of a pebbly volcaniclastic sandstone. No hints of primary structures are visible in it. The pebbly unit passes to a Vallar bru-type conglomerate, which contains quartzite clasts and less abundant felsic volcanite clasts in scanty volcaniclastic matrix. The volcanic clasts disappear rapidly upwards in the stratigraphy. Laajoki et al. (2002) considered the contact as a palaeoregolith indicating an erosional break between the Brunkeberg volcanism and the beginning of the deposition of the Lifjell group. Main petrographic differences between the porphyry and its detritus are abundant euhedral plagioclase phenocrysts in the former and their lack in the latter indicating that the role of chemical weathering was rather significant. The contact zone often is epidotized masking the transition between the porphyry and its detritus. The transition porphyry→ Hesteskodiket-type conglomerate → Vallar bru-type is so regular that it can be used as a top determination criterion.

A similar transitional contact between the Brunkeberg and Vallar bru formations is also exposed in nearby outcrops, but it often is folded (Fig. 13b).

6.2. Bjørndalen and Åmtveit

A good place to study the Hesteskodiket type conglomerate is Bjørndalen, c. 3 km NW from Hesteskodiket, where a folded part of the Vallar bru formation has been preserved above the Brunkeberg formation. Structurally, it represents a minor synclinorium cut by the Jåfjell fault (Figs. 14a & b). Here an about 3 m high vertical section shows how a well-preserved porphyry of the Brunkeberg formation passes to a rock with a few feldspar grains representing most likely xenocryst clasts and this to a Hesteskodiket-type conglomerate with solitary stretched quartzite and felsic vulcanite clasts (Figs. 14c & d). A new feature is that the rock contains homogeneous sandstone stripes subparallel to the foliation (Fig. 14d), which could not be sampled by a hammer. They may represent transposed bedding or foreset laminae. This is supported by the fact that primary bedding is locally visible in nearby Hesteskodiket-type conglomerate outcrops. Upwards the amount and size of the quartzite clasts increase abruptly and the upper part is occupied by a Vallar bru-type clast-supported cobble-boulder conglomerate. This transitional contact can be followed over 10 km to the NE in Bjørndalen. It also occurs in Åmtveit, west of the Ordalen fault, but is folded (Figs. 10a & b). In the Hill 657, between Bjørndalen and Hesteskodiket, the Vallar bru formation lies unconformably on the Brunkeberg formation (Figs. 14a & b), but the unconformity is locally sheared (Fig. 14e).

6.3. Transtaulhøgdi

In a small outcrop, 4 km SW of Brunkeberg, a nicely porphyric, mica-poor porphyry of the Brunkeberg formation passes gradually within 2 – 3 m to a muscovite schist with microcline porphyroblasts Fig. 15. The abundance of muscovite in the schist indicates that it represents a weathering product of the porphyry and may be considered as a more metamorphosed part of the transitional unconformity exposed in Hesteskodiket. The Tveitgrendi quartzite overlies the schist sharply (Fig. 15b). As the schist is intensely sheared and the contact is approximately parallel to the local S_2 foliation (Fig. 15b), this part may represent a shear zone developed above the Brunkeberg formation. This could explain the lack of the Hesteskodiket- and Vallar bru-type conglomerates and the thinness (< 10 m) of the Tveitgrendi quartzite. Neumann and Dons (1961) and Nilsen and Dons (1991) included the Tveitgrendi quartzite into the Røynstaul formation and the Vemork formation, respectively, but its presence above the Brunkeberg formation and orthoquartzitic nature support the Lifjell

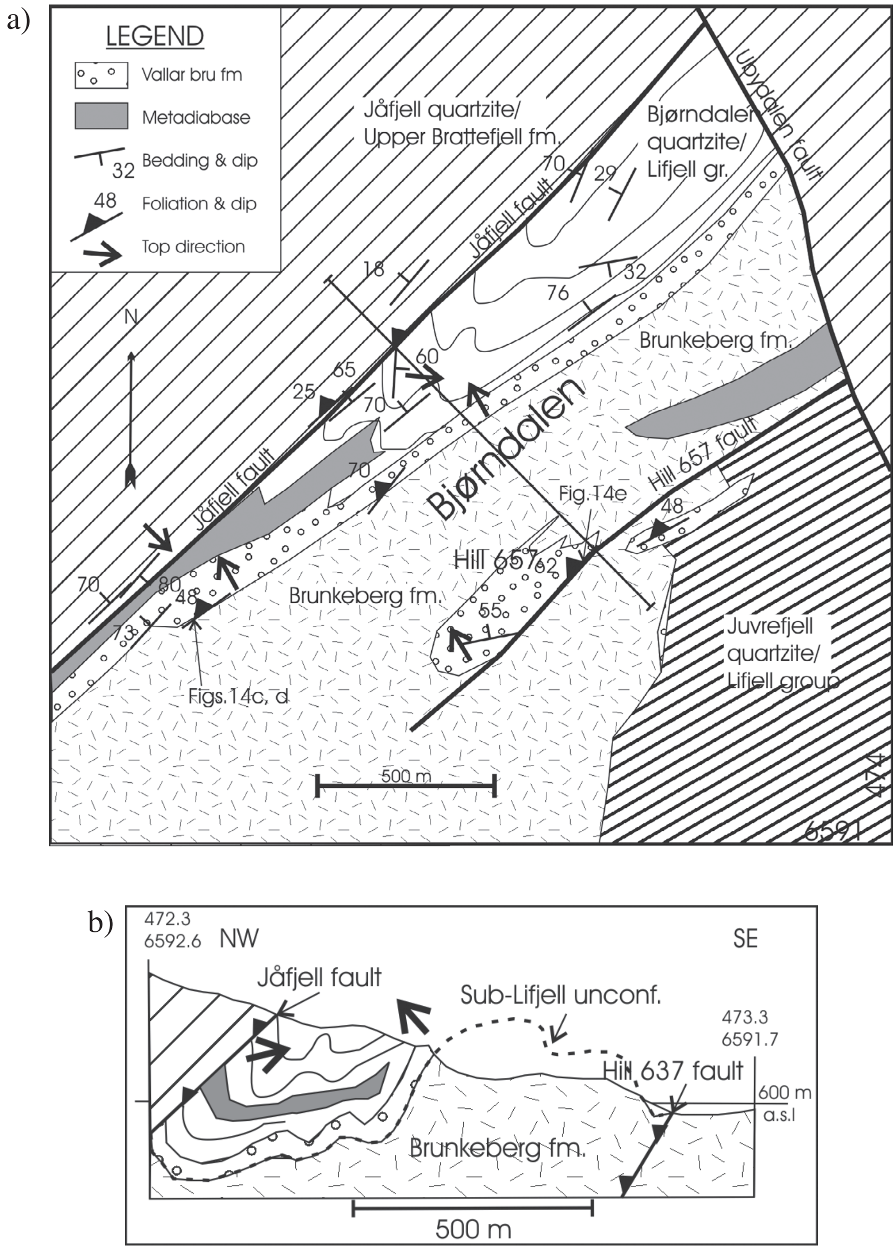
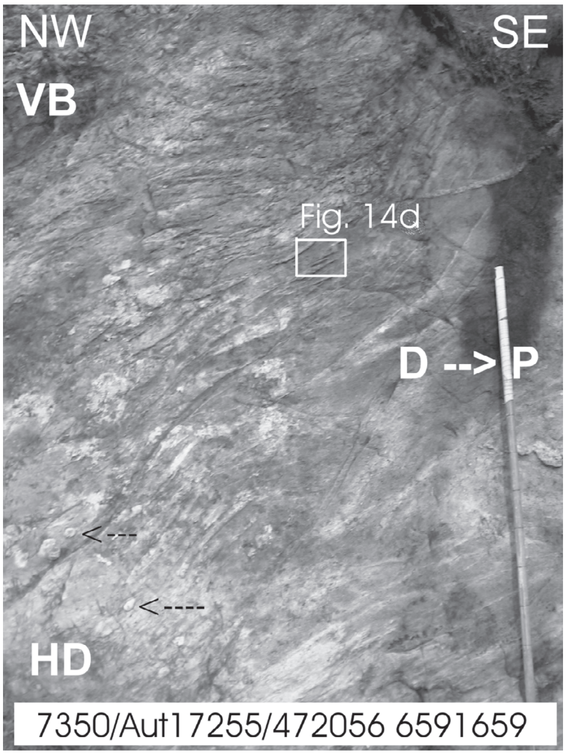
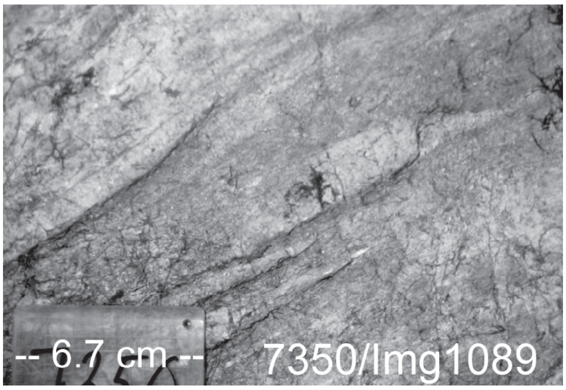


Fig. 14. Geological map (a), cross section (b) and outcrop photographs (c-e) of the Bjørndalen area. a) Geological map with locations of cross section in Fig. 14b and outcrops in Figs. 14c-e. b) Cross section across Bjørndalen along the line in Fig. 14a. c) Contact zone above the Brunkeberg formation. D→ P = volcanic detritus passes to porphyry. HD = Hesteskodiket-type conglomerate – pebbly sandstone with solitary quartzite pebbles (black arrows). VB = Vallar bru-type, clast-supported conglomerate. Fig. 14d gives a detail of the striped zone in the middle. d) Close-up of sandstone stripes in volcanic detritus with tiny feldspar-xenocryst clasts (in upper right corner). e) Sheared contact between the Brunkeberg porphyry, its detritus and the Vallar bru formation. Quartz vein in the upper margin of the photograph is parallel to the schistosity. Note mylonitic seams in the lower part of the figure indicating top to SE movement. The compass palate is 6.5 x 12.5 cm. Hill 657.

c)



d)



e)

group. The rocks above the Tveitgrendi quartzite comprise diverse mafic volcanic rocks, mica schists and thin quartzite units (Fig. 15a, see also Nilsen & Dons, 1991) and cannot be correlated with other areas without additional work.

6.4. Seljord city

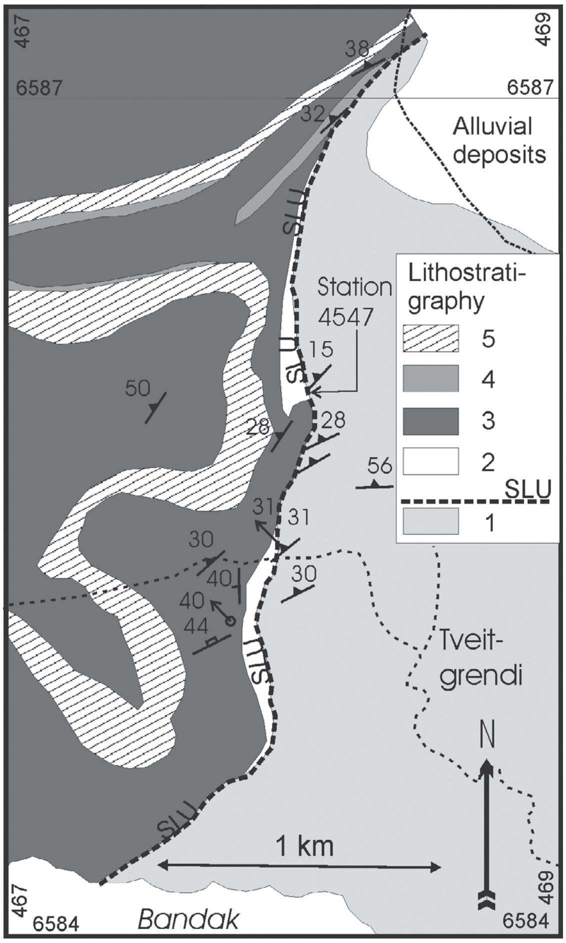
The narrow body of the Brunkeberg formation midst the settlement of the Seljord city is rimmed on both sides by intensely deformed Vallar bru conglomerates indicating that it represents an anticline (Fig. 16a). The sub-Lifjell unconformity is exposed in one outcrop, where it is both folded and faulted (Fig. 17a). The porphyry shows F_2 folded epidote banding, foliation, and thin quartz and pegmatite veins following the contact. Locally, a 10 – 30 cm thick layer of a conglomerate containing solely felsic volcanite clasts occurs above the porphyry (Fig. 17b). Many of the clasts are angular. This part passes abruptly to a typical Vallar bru conglomerate.

In the classical Vallar bru conglomerate locality (Dons 1960b), the unconformity cannot be seen, for a fault separates the conglomerate from the Brunkeberg formation.

6.5. Bjørgenuten and Grunningsdalen

Bjørgenuten, east of the Seljord city (Fig. 16a), has been long known for highly strained Vallar bru conglomerates and a complex structure (Dons 1960a, b). The steep topography, the settlement on the western flank of Bjørgenuten, and relatively few outcrops make the study of the sub-Lifjell unconformity difficult. It is, however, evident that the Brunkeberg formation and the overlying Vallar bru conglomerates have been folded, faulted, and thrust to the NW in Bjørgenuten itself, (Fig. 16). The sub-Lifjell unconformity is also here gradational being defined by a regolith with felsic volcanite clasts overlain by a Vallar bru-type conglomerate. It is, however, intensively deformed (Figs. 17c & d). Importantly, the sub-Lifjell unconformity seems not to have acted as a detachment surface, but thrusts have originated within

a)



b)

Fig.15. a) Geological map of the Transtaulhøgdi area (modified after Nilsen & Dons, 1991). Lithostratigraphic units: 1. Brunkeberg formation. 2. Tveitgrendi quartzite. 3. Mafic metasupracrustals. 4. Quartzite. 5. Biotite schist. Location of the station 4547 (Fig. 15b) is shown. SLU = sheared sub-Lifjell unconformity (see the text). b) Contact between the sericite schist above the Brunkeberg porphyry and the Tveitgrendi quartzite. This may be a fault, but the sericite schist is considered as part of the weathering crust above the Brunkeberg formation.

the Brunkeberg formation (Figs. 16b & 17c). The relationship between Bjørgenuten and Seljord city occurrences is problematic, for the latter occur at much lower altitude (c. 150 m vs. 800 m) and the steep topography hampers mapping. A proposed NW trending fault following the steep western flank of Bjørgenuten (postulated in Fig. 16a) could explain the opposite vergences and the significantly greater distribution of the Brunkeberg formation in Bjørgenuten.

In Grunningsdalen, NE of the Borkebudalen fault, only a thin slice of the Brunkeberg formation has been preserved. The sub-Lifjell unconformity is similar to that at Bjørgenuten, but is intruded by quartz veins and is epidotized. It is more sheared than in Bjørgenuten with shear indicators showing top-to-the-north movement (Fig. 17e).

6.7. Gardvik tectonic unit

Small relics of a Vallar bru-type conglomerate lie unconformably above the Brunkeberg formation SE of the Gravalifjellet fault (Fig. 5d). In an unnamed rivulet, a porphyry passes gradually to its quartzitic detritus overlain by a Vallar bru-type conglomerate (Fig. 18a). On both sides of Seljordsvatnet, the Vallar bru formation is folded, but the Hesteskodiket-type transitional unconformity can locally be seen (Figs. 18b & c). In spite of tight folding, the Vallar bru formation is relatively well preserved and its transitional lower contact can also be mapped in Heggestaulnuten, NW side of the Heggenes fault (Fig. 5a). Farther to the NW, the Brunkeberg/Vallar bru contact is pervasively foliated and the clasts in the overlying conglomerate are extremely strained. A good outcrop in Årmotdalen proves, however, that it represents a Hesteskodiket-type unconformity (Figs. 18d & e).

7. Tectonic contact of the Vindeggen group with the Lifjell group.

The Slåkådalen-Grunningsdalen fault separating the Vindeggen and Lifjell groups is unexposed, but mappable (Laajoki, 2002). It is relatively young, for it cuts the folded sub-Lifjell unconformity (Fig. 4a).

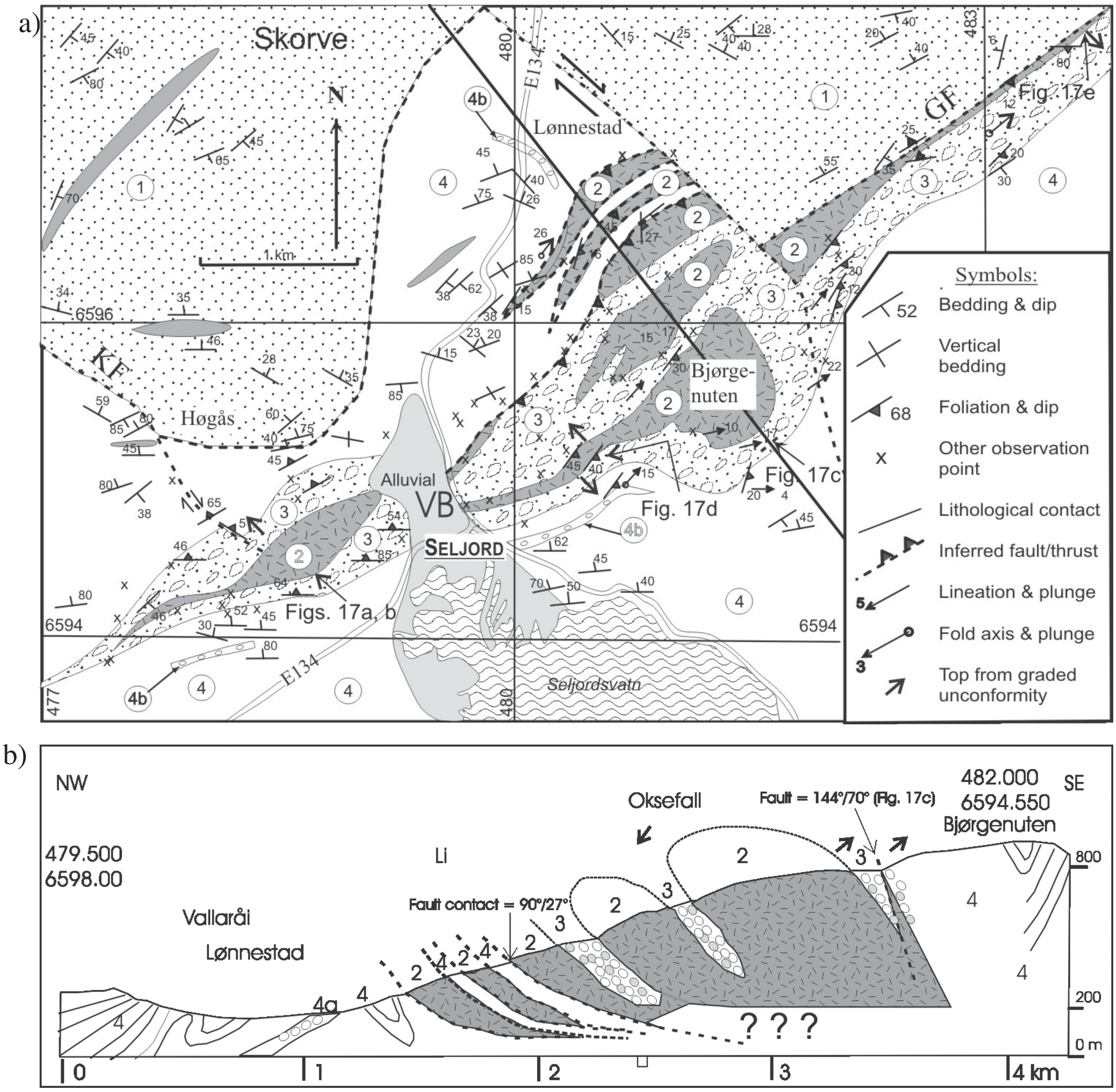


Fig. 16. a) Geological map of the Seljord-Bjørgenuten-SW Grunningsdalen area. Locations of the cross section in Fig. 16b (thick diagonal line) and photographs in Fig. 17 are shown. Lithostratigraphic units: 1. Upper Brattefjell formation of the Vindeggen group. 2. Brunkeberg formation. 3 – 4b Lifjell group: 3. Vallar bru formation. 4. Lifjell quartzite, 4 b. Quartzite-clast conglomerate interbed in the former. Dark gray = metadiabase. VB = Vallar bru. Inferred faults: BF = Borkebudalen, GF = Grunningsdalen, KF = Kievledalen. PF = proposed fault along the western flank of Bjørgenuten. b) Geological cross section of Bjørgenuten. Unit numbers as in Fig. 16a. Note the thin, fault-bounded slices of the Brunkeberg formation in the centre and the minor fault on the right (Fig. 17c). White and grey ellipsoids = quartzite and felsic volcanite clasts in conglomerates, respectively. Black arrows give the top direction.

The Borkebudalen fault offsets dextrally the Vindeggen/Lifjell contact to the NW, near the SE corner of Skorve, for a Lifjell group conglomerate interbed occurs in Lønnestad (unit 4a in Fig. 16). From there the Vindeggen/Lifjell contact is drawn via a mylonitic metabasite near Høgås (Fig. 16a) and Raudbergnuten (Fig. 12a). In the Brunkeberg area, the Ubydalen and Ordalen faults offset the Vindeggen/

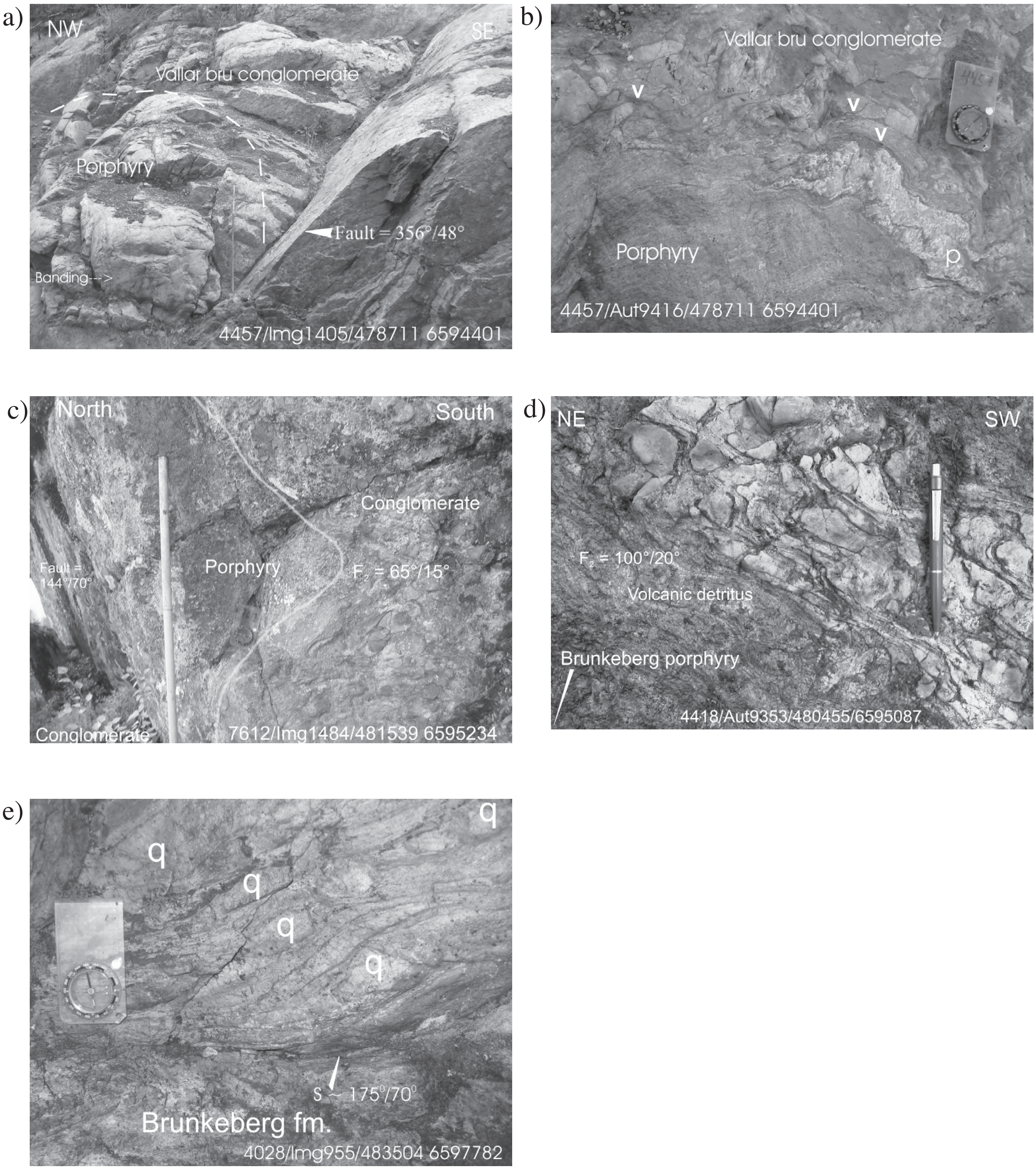


Fig. 17. Photographs of the sub-Lifjell unconformity in Seljord city (a & b), Bjørgenuten (c & d) and in Grunningsdalen (e). a) Folded sub-Lifjell unconformity (dashed line) cut by a minor fault subparallel to S_2 axial plane foliation. Note the banding in the porphyry defined by epidote. b) Close-up of the unconformity in Fig. 17a showing F_2-folded foliation and minor pegmatite-quartz veins (p). Felsic volcanic clasts (v) near the porphyry. c) F_2-folded sub-Lifjell unconformity between the Brunkeberg formation and a Vallar bru-type conglomerate. The clasts in the conglomerate near the unconformity (line) include felsic volcanite, but quartzite clasts are dominant farther from it. Note, that the minor post-F_2 fault on the left does not follow the unconformity, but cuts the porphyry. d) Brunkeberg formation passes via a volcaniclastic detritus and volcaniclastic conglomerate to a quartzite-clast conglomerate folded twice. e) Sheared sub-Lifjell unconformity showing top to N movement. q = quartzite clast.

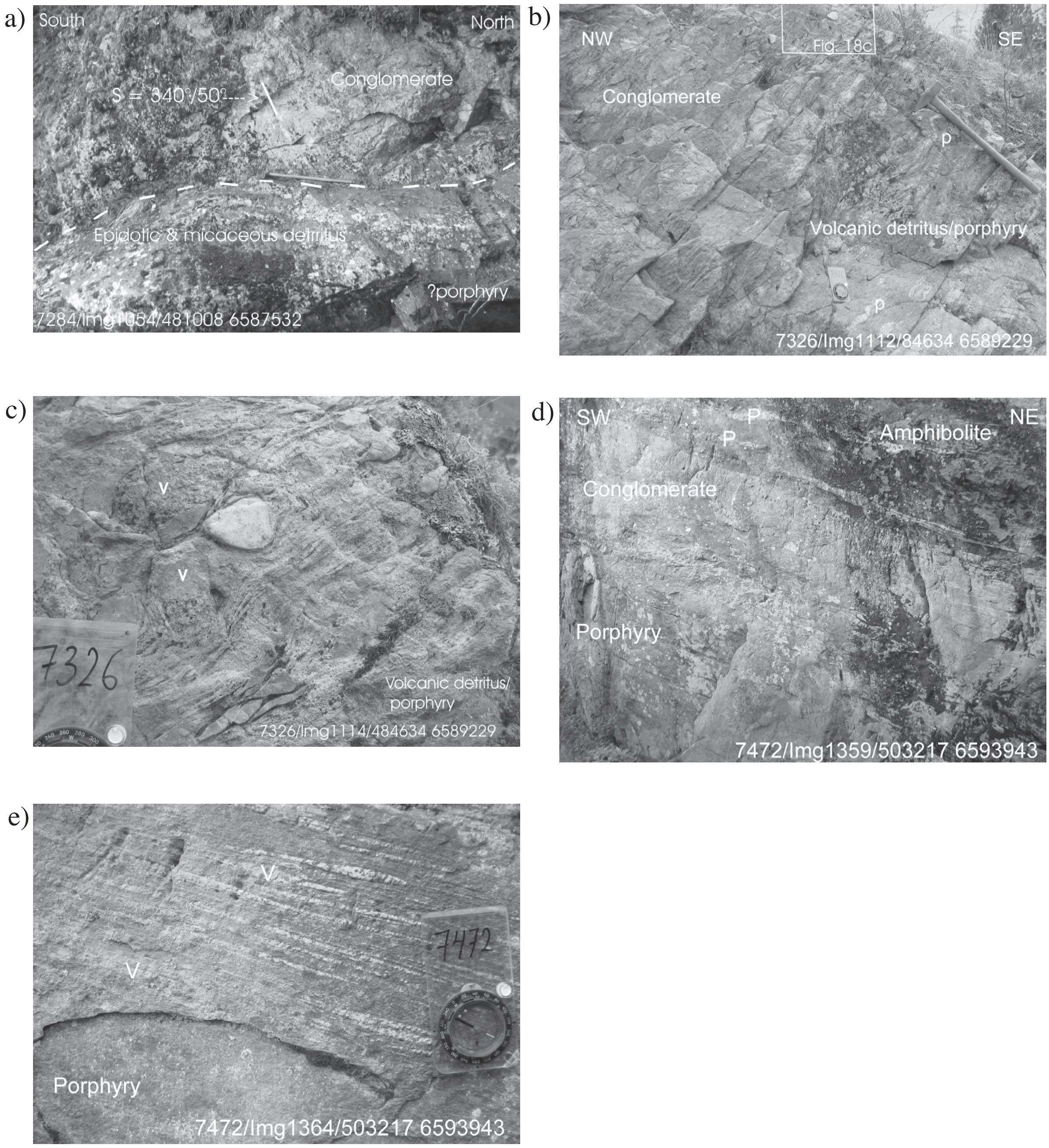


Fig. 18. Photographs of the sub-Lifjell unconformity within the Gardvik tectonic unit. For locations see Figs. 5a & b. a) A Vallar bru-type pebble conglomerate (lower contact dashed) lying subhorizontally on the transitional quartzitic detritus above the Brunkeberg formation. The hammer is 65 cm long. The solid line indicates the pervasive foliation visible in all the units. A lichen covered outcrop in an unnamed creek N of Gravalifjellet. b) Foliated transitional unconformity between the Brunkeberg porphyry and a Vallar bru-type conglomerate. Thin pegmatite veins (p) occur within the porphyry. Close-up in Fig. 18c is framed. Gardvik. c) Close-up of the unconformity in Fig. 18b. The conglomerate contains both quartzite (white) and felsic volcanite (V) clasts in volcanic detritus. d) Intensely strained Hesteskodiket-type conglomerate between the Brunkeberg formation and the overlying intensively foliated amphibolite with thin pegmatite veins (p). The section is about 5 m high. Årmotdalen. e) Close-up of the conglomerate in Fig. 18d with extremely strained quartzite clasts (white stripes) and a fewer felsic volcanite clasts (V).

Lifjell contact to follow the Jåfjell and Grenjusnetten faults, respectively (Figs. 4, 7 & 14a). It is possible that the sheared Vatnelian member/Vindeggen group contact in the Nystaulvatnet area represents the same zone offset dextrally by the Nonnetten fault. Deformation is most intensive between Bjørndalen and Hesteskodiket (Fig. 4a) where the Vallar bru formation conglomerates are highly stretched and the sub-Lifjell unconformity often is mylonitized (Fig. 14e).

8. Deformation of the sub-Lifjell unconformity

Description of the sub-Lifjell unconformity in the previous section proves that it has been folded and faulted everywhere. Two major fault systems occur within the study area (Figs 4 & 5a): (1) ENE trending faults and thrusts, which may counterpart Richards' (1998) D_3 structures and (2) NW trending late, most likely near-vertical faults of which the Ubydalen and Borkebudalen faults are most important. These faults cut the D_3 structures and the sub-Lifjell unconformity at a high angle. Their exact sense of movement is not known, but they seem to have a significant dextral component.

Although the Nystaulvatnet area is highly tectonized, the Vindeggen group/Lifjell group contact is locally so well preserved that it clearly represents an angular unconformity overturned to the south (Figs. 9c-e). In other outcrops, the deformation has been so intense that the primary features of the unconformity have been destroyed (Figs. 9f & g). The unconformity and the overlying breccias and conglomerates on the western margin of Grenjusnetten have been sheared by the Nonnetten fault (Figs. 11a-f). East of this locality, up to Heksfjellet, the Vindeggen/Lifjell contact is defined by diverse ENE trending faults (section 7), which causes that evidence of the existence of the sub-Lifjell unconformity has been destroyed or has not been found. As the Brunkeberg volcanics occur only SE of the Slåkådalen-Grunningsdalen-Jåfjell-Grenjusnetten fault zone (Fig. 4a) this may represent a syn- Brunkeberg fault reactivated by Richards' (1998) late D_4 Sveconorwegian faulting and folding, which he attributed to transpressional deformation.

Richards (1998) considered the ENE trending D_3 thrusts minor and interpreted them to have formed when folds locked up during amplification and thrust out to accommodate further shorting. This seems to be valid in the Brunkeberg area, where the Brunkeberg formation and the overlying Vallar bru formation have been folded openly together (Figs. 10b, 13, & 14b), but have also been locally moved along faults parallel to the regional axial plane foliation (Richards' S_3) (Fig. 14e). The situation is similar in the southern part of Bjørgenuten (Figs. 16b, 17c), but there the vergence is to the opposite direction. Starmer (1993, p. 127) interpreted this as core-crumpling within his second-order, major F_6 antiform. Richards (1998) connected the folding of the unconformity to lower order folds associated with his Lifjell anticline. North of Bjørgenuten, the Brunkeberg porphyry and the Lifjell quartzite occur, however, as thin fault-bounded slices without basal conglomerates in between representing a minor thrust pile. (Fig.16). In Grunningsdalen, the Brunkeberg/Lifjell contact is sheared (Fig. 17e), but may still be classified as an unconformity as the original stratigraphic order can be read from the Brunkeberg formation upwards. At Heksfjellet, the sub-Lifjell unconformity has been folded together with Vindeggen group (Laajoki, 2002).

In the southern margin of the study area, the Åseå thrust and the Gravalifjellet and Båstjörnhovet faults prove that the Åsekollen quartzite and quartzites of the Årnotra and Kolltveiteggi have been thrust, respectively, above the Bø granite and the Gardvik tectonic unit (Fig. 5) and that the sub-Lifjell unconformity has been preserved only locally within the latter unit (Fig. 18). It is a matter of definition how the upper contact of the Brunkeberg formation in Figs.18d & e is called. Without doubt it lies within a ductile shear zone, but seems not to have served as a detachment surface in contrast to the Åseåa thrust. That is why it is considered as a highly sheared unconformity within a thrust sheet.

The thrust tectonics has caused that the lithostratigraphic order has been disturbed significantly in the southern margin of the Telemark supracrustals. For instance, it is not known which quartzite unit the Åsekollen quartzite should be correlated with and do all the quartzites of the Lifjell, Årnotra and Kolltveiteggi ranges really belong to the Lifjell group. On the other hand, it also is difficult to separate the Vindeggen and Lifjell groups in the north. For instance, the quartzites on both sides of the Jåfjell fault in Fig. 14a are lithologically identical. The one SE of the fault belongs to the Lifjell group, for it has a sedimentary contact with the underlying Vallar bru-type conglomerate (Fig. 14b), whereas the one on the NW side is part of the extensive Jåfjell range included into the Vindeggen group (Fig. 7). The effect of thrust tectonics on the lithostratigraphy will be discussed closer in a separate paper after additional mapping.

9. Age of the sub-Lifjell unconformity

The ages of the Brunkeberg and Skogsåa formations (Laajoki et al., 2002) define the age of the part of the sub-Lifjell unconformity developed upon the former unit between 1155 ± 2 Ma and 1145 ± 4 Ma indicating that the time gap it represent is rather small (<10 Ma). As the ages of the sedimentation and folding of the Vindeggen group are not known, no lower age limit can be given to the part of the sub-Lifjell unconformity above this group. The time gap it represent, must be, however, much larger than in the previous case, for the Vestfjorddalenian basement was folded and eroded deeply (section 5) before its formation.

10. Discussion

Three subjects deserve closer discussion: (1) Do the unconformities above the Vindeggen group and the Brunkeberg formation represent both the sub-Lifjell unconformity, (2) primary nature of the sub-Lifjell unconformity, and (3) its regional correlation and stratigraphic-sedimentological significance.

(1) As the parts of the unconformities above the Vindeggen group and the Brunkeberg formation are faulted, their correlation with each other may be questioned. The key area is Grunningsdalen, where the Heksfjellet conglomerate as well as the Vallar bru conglomerate underlie the Lifjell quartzite (Fig. 4a), but they overlie, respectively, the Vindeggen group (Fig. 6), and the Brunkeberg formation (Fig. 16a). This indicates that the conglomerates represent same stratigraphic level and consequently the unconformities under them are correlative. However, the inferred Slåkådalen-Grunningsdalen fault seems to cut obliquely both the Brunkeberg formation and the Heksfjellet conglomerate. The intense stretching of both conglomerates and the northern vergence in the units south of the fault indicate that the Lifjell group could have been thrust above the Vindeggen group. However, no distinctive detachment surface has been found. This problem calls for additional structural geological studies.

Other areas important in this respect are Nystaulvatnet and Bjørndalen, where the sericite quartzite lying unconformably on the Vindeggen group (Fig. 9e) can not be correlated with the Svinsaga quartzite north of Liervatnet, but with the similar quartzite lying above the Vallar bru-type conglomerate in Bjørndalen and Åmtveit (section 5.2, Table 1).

(2) Laajoki (2002, in press) and Köykkä and Laajoki (2006) attributed *in situ* breccias on sub-Svinsaga and sub-Heddersvatnet to frost action. It is logical to apply a similar explanation to occurrences in the Nystaulvatnet area (Figs. 9c & d).

The gradational unconformity above the Brunkeberg formation is problematic. It must indicate erosion of the porphyry, for its material occurs both as matrix and clasts in the overlying conglomerate. However, no clear erosional surface can be seen. This and increase of muscovite away from the porphyry indicate that the transitional zone represents an *in situ* weathering crust into which solitary quartzite and felsic volcanite pebbles were deposited by a low energy sedimentary process, e.g. by falling from nearby rock faces or from a waning current. The sandstone stripes in Bjørndalen points to the latter possibility (Fig. 14d). As the contact zone is often epidotized it is possible that its primary features were obliterated. A geochemical study across the zone could enlighten this problem

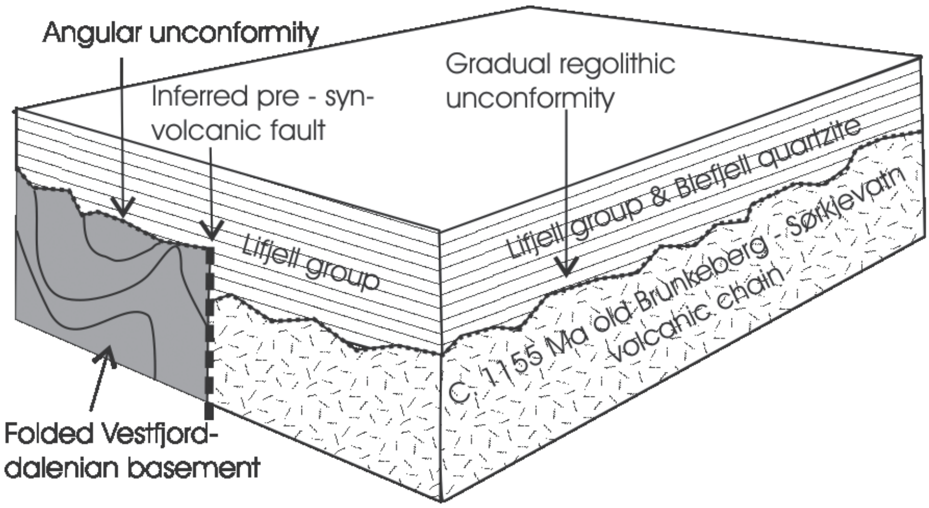


Fig. 19. Sketch of the sub-Lifjell unconformity showing its angular and gradual nature above the folded Vindeggen group and the Brunkeberg formation, respectively, with a hypothetical pre - syn-volcanic fault (Slåkådalen – Grenjusnetten fault zone) in between.

(3) The complex deformation of the area impedes some uncertainties in correlating the sub-Lifjell unconformity from place to place and its use as a lithostratigraphic marker. Lithological and structural proofs why it is not correlated with the nearby sub-Svinsaga unconformity in the Nystaulvatnet area were given in section 5.2. Its relationship with the sub-Heddal unconformity north of Heksfjellet is somewhat problematic. The Lifjell quartzite is missing and the Skogsåa porphyry is in contact with the Vindeggen group (Fig. 11 in Laajoki, 2002). This contact was interpreted as part of the sub-Heddal unconformity eroding progressively deeper levels from the present south to the north. It can be, however, speculated, that the sub-Heddal unconformity joins the sub-Lifjell unconformity and so the *in situ* breccias in the Moltelia and Skårsetvatnet road outcrops (Figs. 12, 13a, c & d in *op. cit*) could, in fact, represent the sub-Lifjell unconformity.

The sub-Lifjell unconformity cannot be mapped west of the Brunkeberg-Nystaulvatnet line, as it is cut by the Nonnetten and Lier faults. It may reappear, however, in the Ljosdalsvatnet area (domain F, Fig 2) where a gradual weathering crust, named informally as the sub-Sandvik unconformity, occurs between the 1155 ± 3 Ma Ljosdalsvatnet formation and the overlying Sandvik quartzite of the Oftefjell group. This Sandvik quartzite is overlain by a thick sedimentary-volcanic sequence of porphyries, quartzites and basalts (Table 2), which is in strong contrast with the simple conglomerate-quartzite sequence above the sub-Lifjell unconformity in the Brunkeberg - Bjørgenuten area. It may be comparable with the Transtaulhøgdi supracrustals above the Tveitgrendi quartzite (section 6.3). The ages of the Brunkeberg and Ljosdalsvatnet porphyries are identical within error limits (Laajoki et al., 2002) indicating that the unconformities above them could be correlative. The differences in the overlying sequences may be due to that the Ljosdalsvatnet and Brunkeberg areas represent, respectively, a rift valley with bimodal volcanism and fluvial sedimentation and a fault-bounded horst or highland facing a shallow sea (Laajoki & Lamminen, 2006). This would mean that the Lifjell group and the part of the Oftefjell group above the Ljosdalsvatnet formation and even the Transtaulhøgdi supracrustals were coeval. In this case, it could also be possible, that the sub-Lifjell unconformity in the

Grenjusnetten-Nystaulvatnet area was developed on re-exposed sub-Svinsaga palaeosurface. This would mean that the sub-Lifjell unconformity joins the sub-Svinsaga unconformity. There is no evidence that the Svinsaga, Ljosdalsvatnet and Brunkeberg formations were folded before the formation of the sub-Sandvik and sub-Lifjell unconformities, which means that the lithostratigraphic break they represent seems to be modest.

Richards (1998) described basal quartzite-clast conglomerate overlain by pure white quartzite of the Seljord group in the Central Numedal area, about 70 km north of Heksfjellet. As this sequence resembles the Lifjell group it is possible that also here an unconformity could separate the traditional Seljord quartzite into two separate units.

Andersen et al. (2004) correlated the regolith above the 1159±8 Ma Sørkjevatn formation at Blefjell, about 25 km to NNE from Heksfjellet, with the sub-Lifjell unconformity (Fig. 3). They also correlated the Blefjell quartzite with the quartzite of Nordgulen's (1999) Hallingdal complex (Norefjell in Fig. 3) (cf. Bingen et al., 2005). If this is correct, the sub-Lifjell unconformity must continue under the latter an additional 80 km to the NNE. This would mean that it represents the basal bounding surface of an at least 150 km wide Mesoproterozoic beach – shallow shelf complex, which overlapped the about 1155 Ma old, slightly eroded Brunkeberg-Sørkjevatn volcanic chain in the present south and the folded and deeply eroded Vestfjorddalenian basement in the north (Fig. 19). Before the role of the sub-Lifjell and other unconformities in the area can be understood more deeply, more reliable regional sedimentological and especially, structural studies and complimentary dating of detrital (cf. Andersen, 2005b) and igneous zircons are needed from the whole distribution area of the Telemark supracrustals and even from the neighbouring Sveconorwegian sectors. These works are necessary for evaluating the correlation schemes and diverse tectonic models proposed to these formations in recent literature (e.g. Falkum & Pedersen, 1980; Starmer, 1983; de Haas et al., 1999; Bingen et al., 2001; 2003; 2005; Brewer et al., 2004; Andersen, 2005a).

Acknowledgements

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