Lithostratigraphy and U-Pb geochronology of the Telemark supracrustals in the Bandak-Sauland area, Telemark, South Norway

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The Mesoproterozoic Telemark supracrustals in southern Norway have been subdivided into four groups: (1) the ca. 1500 Ma volcanic Rjukan group overlain by (2) the quartzite-dominated Seljord group, itself overlain by (3) the ca. 1160 Ma volcanic-sedimentary Bandak group in the west and by (4) the undated Heddal group in the east. New mapping and U-Pb work provide considerable refinement to this stratigraphy. The Ljosdalsvatnet porphyry near the base of the Bandak group has an age of 1155 ± 3 Ma age, but it overlies that part of the Seljord group, which was folded and eroded before deposition of the Bandak group. The Brunkeberg porphyry, which has previously been correlated to the Rjukan group, yields an identical age of 1155 ± 2 Ma. It is unconformably overlain by a quartzite, which has also been included into the Seljord group. This group must, therefore, consist of two separate successions separated by a period of folding, here referred to as the Vindeggen group (older) and the Lifjell group (younger). The former represents a thick, fluvial, shallow sea sandstone - intertidal heterolithic sequence, whereas the latter is composed of a relatively thin and mature beach-shoreline sandstone sequence. The unconformity between the groups is displayed by in situ weathering breccias and quartzite-clast conglomerates at Heksfjellet.

The gneissic and supracrustal rocks southwest of Brunkeberg, previously mapped as the Vemork formation, do not belong to the Rjukan group, as they overlie the 1155 Ma Brunkeberg formation. The traditional Bandak group is subdivided into the Oftefjell (older), and Høydalsmo (younger) groups separated by a major unconformity detected under the Røynstaul formation, and the Eidsborg formation (topmost). The Høydalsmo group comprises the Dalaå porphyry that yields an age of 1150 ± 4 Ma. An unconformity has also been mapped under the Heddal group, which erodes both the Vindeggen and Lifjell groups. The Skogsåa porphyry, at the base of the Heddal group is dated at 1145 ± 4 Ma, bracketing the time of deposition of the Lifjell group between about 1155 Ma and 1145 Ma ago and making the Heddal group younger than the traditional Bandak rocks under the Dalaå formation.

These data reflect a short-lived period of major tectonic activity accompanied by rifting and the generation of A-type intrusive bodies, probably related to an episode of mantle upwelling. There is also evidence for at least two orogenic or major deformation stages: (1) the older phase, which folded the Rjukan and Vindeggen groups prior to 1155 Ma, and (2) the younger phase post-dating 1145 Ma, which folded the Oftefjell, Høydalsmo, Lifjell, and Heddal groups and the Brunkeberg and Eidsborg formations for the first time, and the Rjukan and Vindeggen groups for the second time.

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Introduction

The bedrock of Southwest Scandinavia is a Mesoproterozoic, polyorogenic domain that developed during: (1) the 1.75 – 1.50 Ga Gothian-Kongsbergian (Labradorian-Pinwarian in Laurentia) accretionary orogeny, (2) an intervening stage of crustal stabilization from 1.50 Ga to 1.25 Ga interspersed with periods of high-grade metamorphism and igneous activity, and (3) the 1.25 – 0.95 Ga Sveconorwegian (Elzevirian + Grenvillian) orogeny (e.g. Gaál & & Gorbatchev 1987; Gower et al. 1990; Starmer 1990; Åhäll et al. 1995; Andersson 2001). Both orogenies comprised a number of episodes during which the SW-Scandinavian crust formed and was cratonised. In general, the magmatic and metamorphic evolution of plutonic and high-grade domains has been studied much more intensely than that of supracrustal successions. Recent investigations, especially those using zircon U-Pb geochronology, have substantially increased our understanding of the evolution of Gothian and Sveconorwegian supracrustals (Dahlgren et al. 1990b; Lundqvist and Skiöld 1992; Åhäll et al. 1995; Birkeland et al. 1997; Knudsen et al. 1997; Nordgulen et al. 1997; Åhäll et al. 1998; Andersen & Grorud 1998; de Haas et al. 1999; Sigmond et al. 2000; Bingen et al. 2001a, b). As sedimentation and associated volcanism are as much a part of the orogenic cycle as plutonism and metamorphism, this recent trend is apt to shed new light on the geological evolution of the SW Scandinavian bedrock as a whole.

This paper is one part of our recent studies on the stratigraphy, geochronology and sedimentation of Sveconorwegian supracrustals in south Norway. The Mesoproterozoic volcanic and sedimentary rocks, known collectively as the Telemark supracrustals (Sigmond et al.

1997), were chosen as the study target as they are exceptionally well exposed and preserved in central Telemark in the area between Lake Bandak and the town of Rjukan. They have been metamorphosed to greenschist – lower amphibolite facies and, although folded, their primary features are commonly well preserved. These supracrustals were studied most intensely in the 1960s and 1970s when their stratigraphy was established (Dons 1960a, b) and some aspects of their sedimentology were evaluated (Dons 1963; Singh 1969). Relatively little work has been carried out in more recent decades, apart from geochemistry on the volcanic rocks (Brewer & Menuge 1998 and references therein), preliminary U-Pb geochronology of volcanic and intrusive rocks (Dahlgren et al. 1990a, b; Dahlgren & Heaman 1991), and isotope studies of sedimentary rocks to evaluate their provenance (de Haas et al. 1999).

The main purpose of this study is to clarify the lithostratigraphy and depositional ages of the southern part of the Telemark supracrustals, and to resolve the incongruencies brought to light by detailed mapping and radiometric dating of key volcanic units.

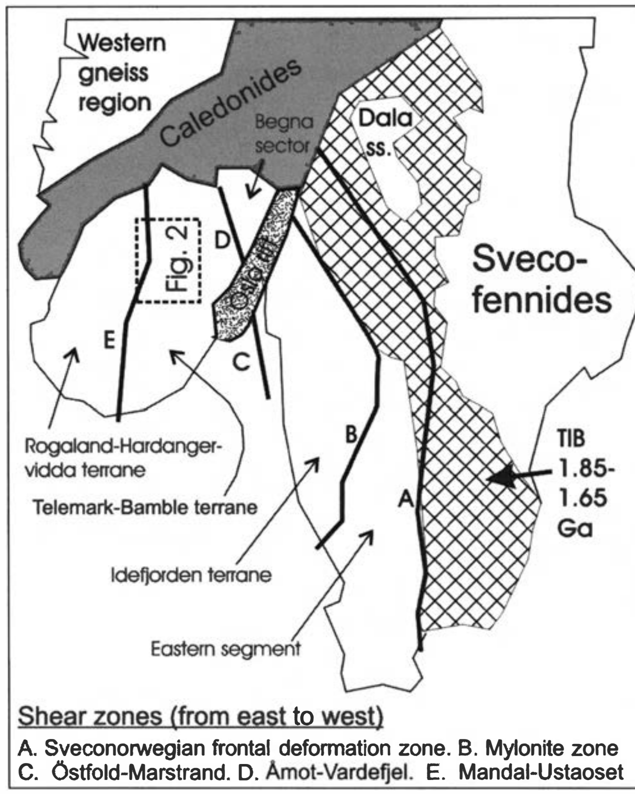

Fig. 1. Sketch map of the Sveconorwegian province (modified from Bingen et al. 2001a). The area covered by Fig. 2 is framed.

Geological setting

The Gothian-Sveconorwegian SW Scandinavian domain occupies the southwestern corner of the Baltic (Fennoscandian) Shield to the west of the 1.90 – 1.80 Ga Svecofennides and the 1.85 – 1.65 Ga Transscandinavian Igneous belt (TIB) (Fig. 1). Four N to NW-trending major shear zones subdivide it into four lithotectonic domains (variably called sectors, segments or terranes) (Bingen et al. 2001a; subm.): (1) The parautochthonous Eastern Segment immediately west of the Sveconorwegian frontal deformation zone is composed mainly of TIB granitoids, reworked by the Sveconorwegian deformation in the north, and penetratively deformed 1.70 - 1.66 Ga high-grade orthogneisses in the south, (2) The Idefjorden terrane, between the Mylonite zone and the Permian Oslo rift in the northwest, represents an allochthonous Gothian terrane, which is composed of the 1.61 Ga Åmål (Lundqvist & Skiöld 1992), 1.64 Ga Horred (Åhäll et al. 1995), and ca.1.60 Ga Stora Le – Marstrand (Brewer et al. 1998) supracrustal belts intruded by voluminous 1.59 Ga calc-alkaline subduction-related and late- and post-Gothian intrusive rocks. The Begna sector is the along strike extension of the Idefjorden terrane to the northwest of the Oslo rift. (3) The Telemark-Bamble terrane consists of the Bamble, Kongsberg, and Telemark sectors, the first two of which are deformed gneissic-plutonic complexes with minor relics of supracrustal belts. The southern part of the Telemark sector is made up mainly of diverse poorly dated gneisses and granitoids (Mitchell 1967; Cramez 1969; Martins 1969; Stout 1972), whereas its northern part comprises the Telemark supracrustals (Sigmond et al. 1997) (Fig. 2). (4) The Rogaland-Hardangervidda terrane west of the Mandal-Ustaoset shear zone comprises migmatites, deformed granitoids of probable Gothian age (Sigmond et al. 2000), the Breive-Valldal and other minor metasupracrustal belts correlated with the Telemark supracrustals (Sigmond 1978), voluminous post-tectonic 1.10 – 0.90 granites, and the 0.93 Ga Rogaland anorthosite complex.

The low-grade metamorphic Telemark supracrustals of the Rjukan palaeorift (Sigmond et al. 1997), the southern part of which is the main target of this study, comprise bimodal volcanic rocks together with clastic and subordinate chemical sedimentary rocks. They were deposited in the period between about 1500 and 1100 Ma (Dahlgren et al. 1990b). Two major fold phases, an earlier W-trending phase and a later and dominant N-trending phase, define the major structures of the area (Dahlgren et al. 1990b; Brewer & Menuge 1998; Starmer 1993). The supracrustal rocks are intruded by granitoid plutons and complexes of various ages (Dahlgren et al. 1990a, b).

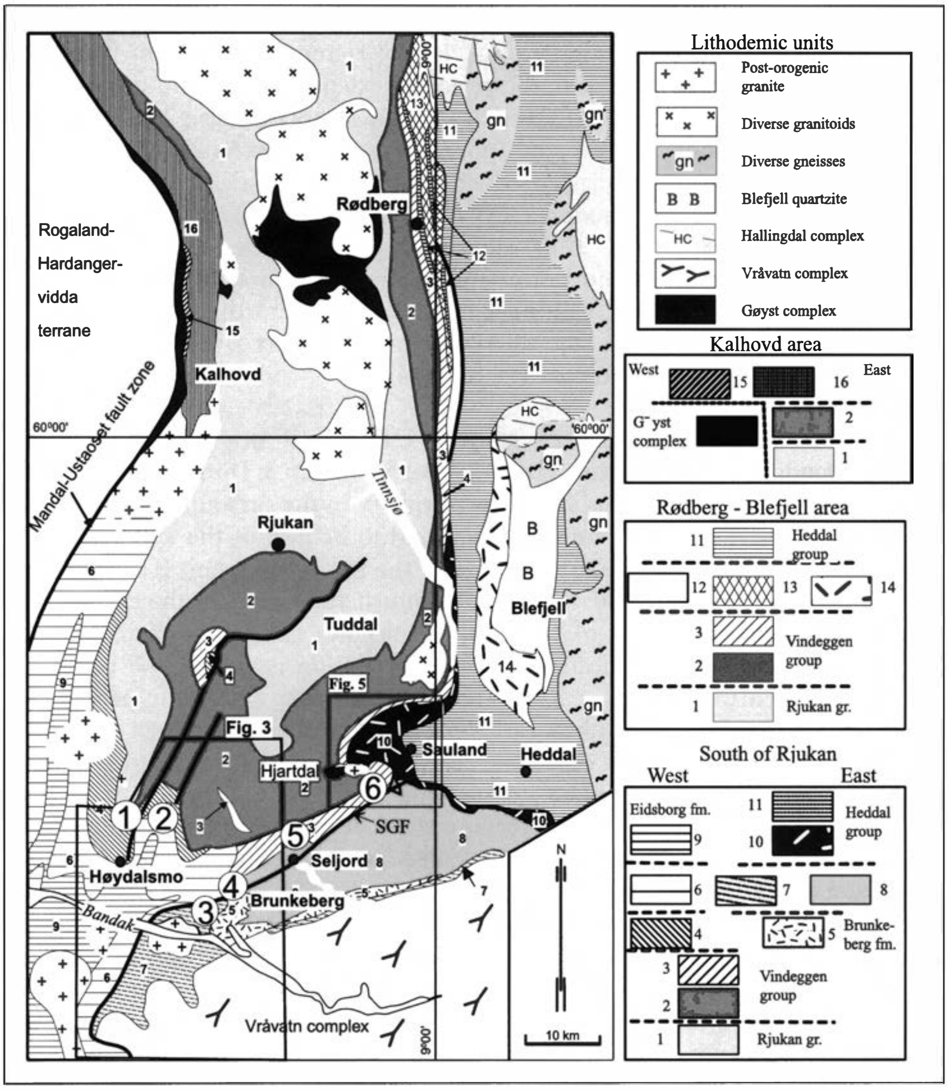

Fig. 2. Simplified geological map of the Rjukan rift basin in central Telemark (compiled and modified from Sigmond et al. 1997; Sigmond 1998; Nordgulen 1999). The lithostratigraphic nomenclature proposed in this paper and by Bingen et al. (submitted) is applied. The areas covered by Figs. 3 and 5 are framed. Circled numbers 1 – 6 refer to the columns in Table 1. Numbering of the lithostratigraphic units starts from the main study area south of the town of Rjukan and continues via the Rødberg-Blefjell area in the east to the Kalhovd area in the northwest: (1) Rjukan group. (2) Vindeggen group, the Upper Brattefjell formation excluded (3) Upper Brattefjell formation. (4) Oftefjell group. (5) Brunkeberg formation. (6) Høydalsmo group. (7) Transtaulhøgdi supracrustals. (8) Lifjell group. (9) Eidsborg formation. (10) and (11) Skogsåa porphyry and undifferentiated metasediments of the Heddal group, respectively. (12) and (13) felsic and mafic volcanics of the Nore group, respectively. (14) Sørkjevatn formation. (15) and (16) felsic volcanics and metasediments (Kalhovd formation) of the Kalhovd area, respectively. SGF = Slåkådalen-Grunningsdalen fault. Thick lines on the map and dashed lines in the legend refer to a fault and an unconformity, respectively.

Review and proposed adjustment of the lithostratigraphy of the Telemark supracrustals

Evolution of the lithostratigraphic nomenclature

The first observations of the "Telemark formationen" were by Keilhau (1823) and by Dahll (1860), who correctly identified some of the conglomerates and quartzites in the area (both referred to in Werenskiold 1910). Törnebohm (1889) may have been the first to identify the rock in Brunkeberg as a porphyroid. He also visited Heksfjellet and made observations of the Heksfjellet conglomerate and the boundary zone between the quartzite and (Heddal) "gneiss schists" at Himingen, and presented a rough stratigraphic scheme for the whole Telemark area. The most useful early work was done by Werenskiold (1910, 1912), who accurately noted the conglomerates in Brunkeberg, Seljord, and Heksfjellet among others, and whose 1910 map depicts nicely the main geological features of the Rjukan – Brunkeberg area. He correctly put the Svartdal (Seljord) quartzite above the Rjukan porphyroids (Table 1). The former was said to be overlain by the (Heddal) "quartz porphyries" and these by the Lifjell (type Seljord) quartzite. Bugge (1931) produced the first map of the Bandak area and introduced the names Bandak formation and Seljord quartzite, of which the latter was said to overlie the former (Table 1). He subdivided the Bandak formation into the lower greenstone-porphyry group, which also included the Brunkeberg porphyry, itself separated by a conglomerate from the upper schist group. Wyckoff (1934) discovered an angular unconformity between Werenskiold's porphyroids and Svartdal quartzite in the Gausta area and gave a detailed description of both units.

The most comprehensive stratigraphic work on the Telemark supracrustals was done by Dons (1959, 1960a, b, 1962, 1972), who in 1959 proposed the traditional tripartite subdivision of these formations with the Rjukan, Seljord, and Bandak groups, themselves subdivided into several formations and separated by angular unconformities (Table 1). The most important departures from Bugge's (1931) classification were the correlation of the Brunkeberg porphyry with the Tuddal formation of the Rjukan group and the incorporation of the rest of

Bugge's Bandak formation into the Bandak group together with the relocation of the latter above the Seljord group. The Svinsaga, Ofte, Røynstaul, Morgedal, Dalaå, and Gjuve formations corresponded to Bugge's greenstone-porphyry group (minus the Brunkeberg porphyry), and the Eidsborg formation corresponded to Bugge's schist formation. An age of ca. 1500 Ma for the oldest group (Rjukan) was suggested already in 1968, but no precise ages were given (Dons 1968). The distribution of the different units is accurately depicted on several maps (Dons 1961; Neumann & Dons 1961; Dons & Jorde 1978; Nielsen & Dons 1991; Dons 1994), but descriptions of the lithologies are only cursory.

Dons' stratigraphic scheme was slightly modified by Dahlgren et al. (1990b), who moved the Vemork formation from the Rjukan group to the Seljord group, and proposed the name Heddal group for Werenskiold's (1910) "quartz porphyry belt" (Table 1). The Heddal group was said to lie above the Seljord group in the east whereas its relationship to the Bandak group was not known. Subsequently, Dahlgren (1993) suggested that the Heddal group was deposited before the Bandak group. Dahlgren & Heaman (1991) provided U-Pb zircon ages of ca. 1500 Ma and 1160 Ma for the Tuddal and Bandak volcanic rocks, respectively.

The present lithostratigraphic nomenclature of the Telemark supracrustals is based mostly on the classical work by Dons (1960a, b). Unfortunately, none of the units have been established formally in the sense of the present Norwegian recommendations (Nystuen 1986, 1989) and only brief descriptions are available. The following summary is based on Dons (1960a) and short explanations to the most recent maps (Nielsen & Dons 1991; Dons 1994) complemented by our field observations. Dons' traditional nomenclature is used as much as possible, but we could not avoid introducing several new names, which are explained in this section (Table 1).

Adjustment of the Rjukan group

Previous usage. – The type area of the Rjukan group is around Rjukan (Fig. 2). The Rjukan group was deposited on a basement of strongly deformed and migmatized paragneisses and dioritic intrusions of unknown age, the Gøyst complex, exposed some 50 km north of Rjukan (Sigmond et al. 1997) and near the Mandal-Ustaoset shear zone in the Odda map sheet (Sigmond 1998) (Fig. 2). At the base of the Rjukan group, the Tuddal formation comprises acid lavas, ignimbrites, tuffs and minor volcanogenic sediments. Its type area is east of Mt. Gausta, where Wyckoff (1934) separated five different acid lava units. From here, the Tuddal formation continues as a coherent body to the southwest as far as Hjartdal (northeast corner in Fig. 3).

The age of the Tuddal volcanism is c. 1510-1500 Ma (Dahlgren et al. 1990b; Sigmond 1998), which corresponds to the period of extensive Pinwarian magmatism in North America (e.g. Rivers & Corrigan 2000). West of Rjukan, the Tuddal formation is overlain by the Vemork formation, which is composed of basaltic lavas and clastic sedimentary rocks, and was included by Dahlgren et al. (1990b) into the lower part of the Seljord group. The Vemork formation rims the Seljord group in the west and continues from Rjukan to north of Ljosdalsvatnet (Fig. 4), where the topmost part is made of foliated sandstone (Dons 1994).

Proposed changes. – In Dons' original stratigraphic scheme (Dons 1960a; Neumann & Dons 1961; Nilsen & Dons 1991) the porphyry in the surroundings of Brunkeberg was considered to be part of the Tuddal group. The 1155 Ma age of the Brunkeberg unit (Laajoki et al. 2000; this study) is much younger than the c. 1500 Ma age of the Tuddal volcanics (Dahlgren et al. 1990b), indicating that the correlation is invalid. We therefore revise the scheme by introducing a new unit named the Brunkeberg formation. The supracrustal rocks southeast of Brunkeberg, mapped as the Vemork formation by Nilsen and Dons (1991), must also be relatively young, as they overlie the Brunkeberg formation. They are collectively called the Transtaulhøgdi supracrustals (Fig. 3). The "basement gneisses" and other gneisses and granitoids (Cramez 1969; Martins 1969; Nielsen & Dons 1991) to the south are included in the Vråvatn complex.

Adjustment of the Seljord group

Previous usage. – The traditional Seljord group is almost entirely a metasedimentary unit dominated by quartzites, which have locally been deformed and eroded prior to the deposition of the Bandak group. In the Gausta area, the sediments are said to be separated from the Rjukan group by a high-angle unconformity (Wyckoff 1934; Dons 1960a) or a disconformity (Menuge & Brewer 1996). In this northern area, the Seljord group has been subdivided into six formations (Table 1). The basal Gausta formation is composed of conglomerates, containing up to boulder-size clasts of Tuddal-type acid volcanics, and grading upwards through arkosite into quartzite. The Gausta formation is overlain successively by the schists of the Bondal formation and the Lauvhovd formation, the quartzites of the Skottsfjell formation, the schists of the Vindsjå formation and the red quartzites and conglomerates of the Brattefjell formation. The Seljord group south and west of Hjartdal has only been mapped as undifferentiated Seljord quartzite (Neumann & Dons 1961; Dons 1994).

Subdivision proposed in this study. – The thick conglomerate deposited on the Brunkeberg porphyry in the Seljord-Brunkeberg area was considered to be a possible

Werenskiold 1910	**Bugge 1931**	**Dons 1960a,b**	**Dahlgren et al. 1990b, Dahlgren 1993**
Lifjeld and Blefjell quartzite	Seljord quartzite		
"Quartz porphyry belt" (Heddal area)	BANDAK FM. Schist group Greenstone porphyry gr.	BANDAK GR. Eidsborg fm. Gjuve fm. Dalaå fm. Morgedal fm. Røynstaul fm. Ofte fm. Svinsaga fm.	BANDAK GR. HEDDAL GR.
Svartdal quartzite		SELJORD GR. Brattefjell fm. Vindsjå fm. Skottsfjell fm. Lauvhovd fm. Bondal fm. Gausta fm.	SELJORD Gr. Dons' Seljord gr. + Vemork fm.
"Porphyroid field" (in Rjukan area)		RJUKAN GR. Vemork fm. Tuddal fm.	RJUKAN Gr. Tuddal fm.

1. Kultankriklan outlier	**2. Oftefjell - Brunkeberg**	**3. Transtaulhøgdi**	**4. Brunkeberg -**	**5. Seljord**	**6. Heksfjellet**
Røynstaul fm.	Eidsborg fm. ? *unconformity* HØYDALSMO GR. Gjuve fm. Dalaå fm **1150 ± 4 Ma.** Morgedal fm. Røynstaul fm.				HEDDAL GR. Metasediments Skogsåa porphyry **1145 ± 4 Ma**
	OFTEFJELL GR. -unsubdivided Ljosdalsvatnet fm. **1155 ± 3 Ma** Svinsaga fm.	TRANSTAULHØGDI SUPRACRUSTALS - orthoquartzite	LIFJELL GROUP - bulk orthoquartzite Vallar bru fm.		Heksfjellet congl.
		Brunkeberg fm. **1155 ± 2 Ma**			
VINDEGGEN GR (From Gausta fm. to Brattefjell fm.)		UNEXPOSED	VINDEGGEN GR. (from Gausta fm. to Brattefjell fm.)		
RJUKAN GR. c. 1500 Ma (Dahlgren et al. 1990b)					

Table 1. Upper part: Different previous stratigraphic classifications presented for the Telemark supracrustals. Dons' original formation names are adjusted to conform to present usage (Nielsen & Dons 1991; Dons 1994). Lower part: The lithostratigraphic classification proposed in this study with ages of the units dated. Numbers 1 – 6 before locality names refer to the map in Fig. 2. The age results in bold are from this study. Hatched lines mark unconformities.

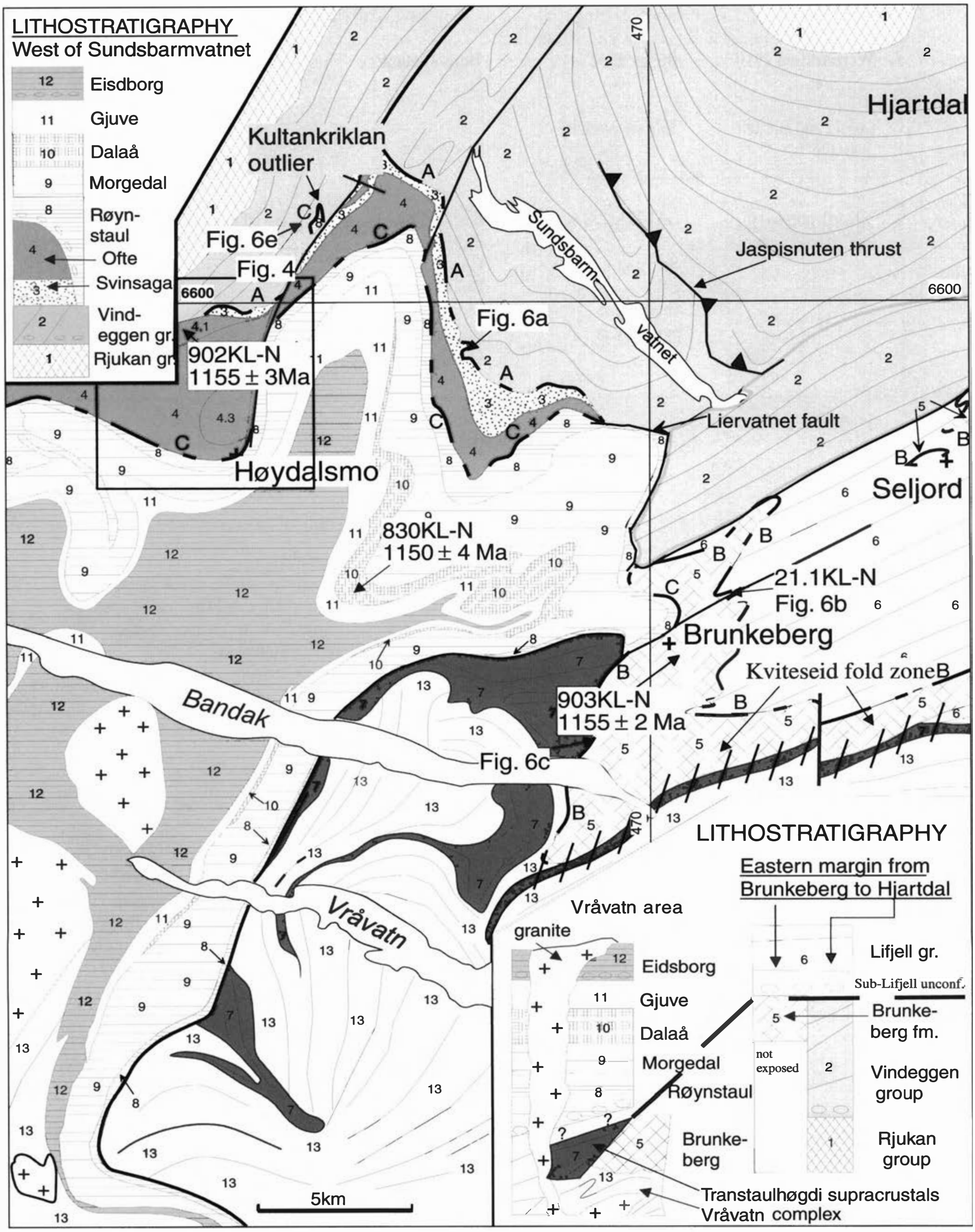

Fig. 3. Geological map of the Bandak - Seljord area (geology compiled and modified after Neumann & Dons 1961; Nilsen & Dons 1991; Dons 1994). For the lithostratigraphic nomenclature see the text. Localities and ages of the dated samples and locations of photographs in Figs. 6a-e are shown. The area of Fig. 4 is framed. Thick lines mark possible fault or thrust (with teeth). Unit numbers 4.1 and 4.3 north of Høydalsmo refer to the Ljosdalsvatnet porphyry and Ofte porphyry 3, respectively. Thin lines within the Vindeggen and Lifjell groups and thicker lines within the Transtaulhøgdi supracrustals and the Vråvatnet complex indicate bedding and folded gneissic banding, respectively. The latter are approximated from Nilsen and Dons (1991). Unconformities are marked by dashed lines and capital letters: A = Sub-Svinsaga, B = Sub-Lifjell, C = Sub-Røynstaul. Small ellipsoids in the legends refer to conglomerates above the unconformities. Thick lines indicate inferred faults.

correlative of the Gausta formation (Dons 1960a). However, the geochronological evidence discussed below shows that the conglomerate must be younger than 1155 Ma, hence younger than the Gausta formation. For reasons outlined below, we propose, to eliminate the designation Seljord group, replacing it with two new terms: (1) the Vindeggen group for the older part of the Seljord group lying unconformably on the Rjukan group and underlying the Svinsaga formation; and (2) the Lifjell group for that part of the traditional Seljord group that overlies both the Vindeggen group and the Brunkeberg formation, as is indicated by the Heksfjellet conglomerate (Laajoki 2002) and the Vallar bru formation (Laajoki 1998).

Adjustment of the Bandak group

Previous usage. – The traditional Bandak group occurs only in the southwest, north and south of Lake Bandak where it unconformably overlies the Seljord (Vindeggen) group (Dons 1960a, 1994; Nilsen & Dons 1991) and west of the Mandal-Ustaoset zone (Sigmond 1975, 1978). Both the base and top of the group are marked by major quartzite formations that sandwich five formations composed of volcanogenic-sedimentary rocks (Table 1, Dons 1960a, b).

The following description of the traditional Bandak group is based mainly on the legends of the Bandak and Åmotsdal 1:50 000 map sheets (Nilsen & Dons 1991; Dons 1994) and recent fieldwork (Laajoki 1998, 2000). The lowermost quartzitic unit, the Svinsaga formation, shows a deep erosional contact with folded Seljord (Vindeggen) group quartzites and has a basal unit of in situ and talus/debris flow breccias and conglomerates containing quartzite clasts derived solely from the underlying Seljord (Vindeggen) group. The bulk of the formation is feldspathic with pebbly units. The Ofte formation is a mixed unit starting with an acid volcanic unit, which is overlain by diverse units of quartzite, volcanic conglomerate, mafic volcanic-subvolcanic rocks and acid volcanics (see the next section). The second major sedimentary unit, the Røynstaul formation, starts with diverse conglomerates, which are overlain by feldspathic-muscovitic sandstone. The overlying Morgedal formation consists dominantly of mafic lavas with minor acid volcanics and 2 – 3 thin sedimentary interunits. Reddish quartz-feldspar porphyries constitute the Dalaå formation. It is overlain by the Gjuve formation which consists of basic volcanic rocks with local thin members of quartzite, limestone and acid volcanites. At the top of the Bandak group, the thick Eidsborg formation is made up mainly of feldspathic and sericitic quartzites with polymictic conglomerate units at the base and further up in the stratigraphy.

Proposed subdivision. – In this paper we propose a new subdivision of the traditional Bandak group (Table 1): (1) the Oftefjell group (lowermost), which comprises the Svinsaga and Ofte formations, (2) the Høydalsmo group, which contains Dons' Bandak formations from Røynstaul to Gjuve, and (3) the nonvolcanic Eidsborg formation (topmost) of rather monotonous quartzite. Three acid volcanite units of the Ofte formation are named Ljosdalsvatnet porphyry (the lowermost one, dated in this study), Ofte porphyry 2, and Ofte porphyry 3 (uppermost) (coded 4a, 4d, and 4e, respectively, in Fig. 4). The lowermost Bandak unit, which overlies successively the Brunkeberg formation, the Transtaulhøgdi supracrustals and the Vråvatn complex southwest of Brunkeberg (Fig. 3), is correlated with the Røynstaul formation; cf. Neumann & Dons (1961) vs. Nilsen & Dons (1991) and Dons (1994).

Nore group, Sørkjevatn formation, and Blefjell quartzite

The acid and basic volcanic rocks and associated sandstones east of the Vindeggen (Seljord) quartzite in Rødberg (Fig. 2) were previously correlated with the Bandak group (Sigmond 1998; Nordgulen 1999), but Bingen et al. (subm.) include them into a separate group named the Nore group. A rhyodacite of the Myrset formation dated by SIMS gives an average zircon age of 1169 ± 9 Ma (op.cit.). The rock unit west of the Blefjell quartzite mapped by Dons and Jorde (1978) as metarhyolite and metatuff is now known as the Sørkjevatn formation, whose metarhyolite gives an average SIMS zircon age 1159 ± 8 Ma (Bingen et al. subm.). The Blefjell quartzite was correlated by Werenskiold (1910) with the Lifjell quartzite and was said to overlie the "quartz porphyry belt" (the Heddal group of this study), but in this study its stratigraphic position is kept open.

The Heddal group

Dahlgren et al. (1990b) proposed the name Heddal group for the siliceous volcaniclastic sediments, rhyolitic ignimbrites, tuffs and minor marbles that occur east of the traditional Seljord group in the surroundings of Heddal (Fig. 2). They state that the Heddal group overlies the Seljord group, but were uncertain whether it was deposited as a continuation of the Seljord group or whether it represents a different event. Later on, Dahlgren (1993) suggested that the Heddal group had been deposited prior to the Bandak group.

In this study, the term Heddal group is used in the sense of Dahlgren et al. (1990b). The dated porphyry at the basal part of the group is called the Skogsåa porphyry (Fig. 5). The bulk sandstones and conglomerates overlying the Skogsåa porphyry are correlated with the metasediments of the northern part of the Heddal group (Fig. 2), which Bingen et al. (subm.) regard as continental intermontane sediment fill deposited after 1112 ± 20 Ma.

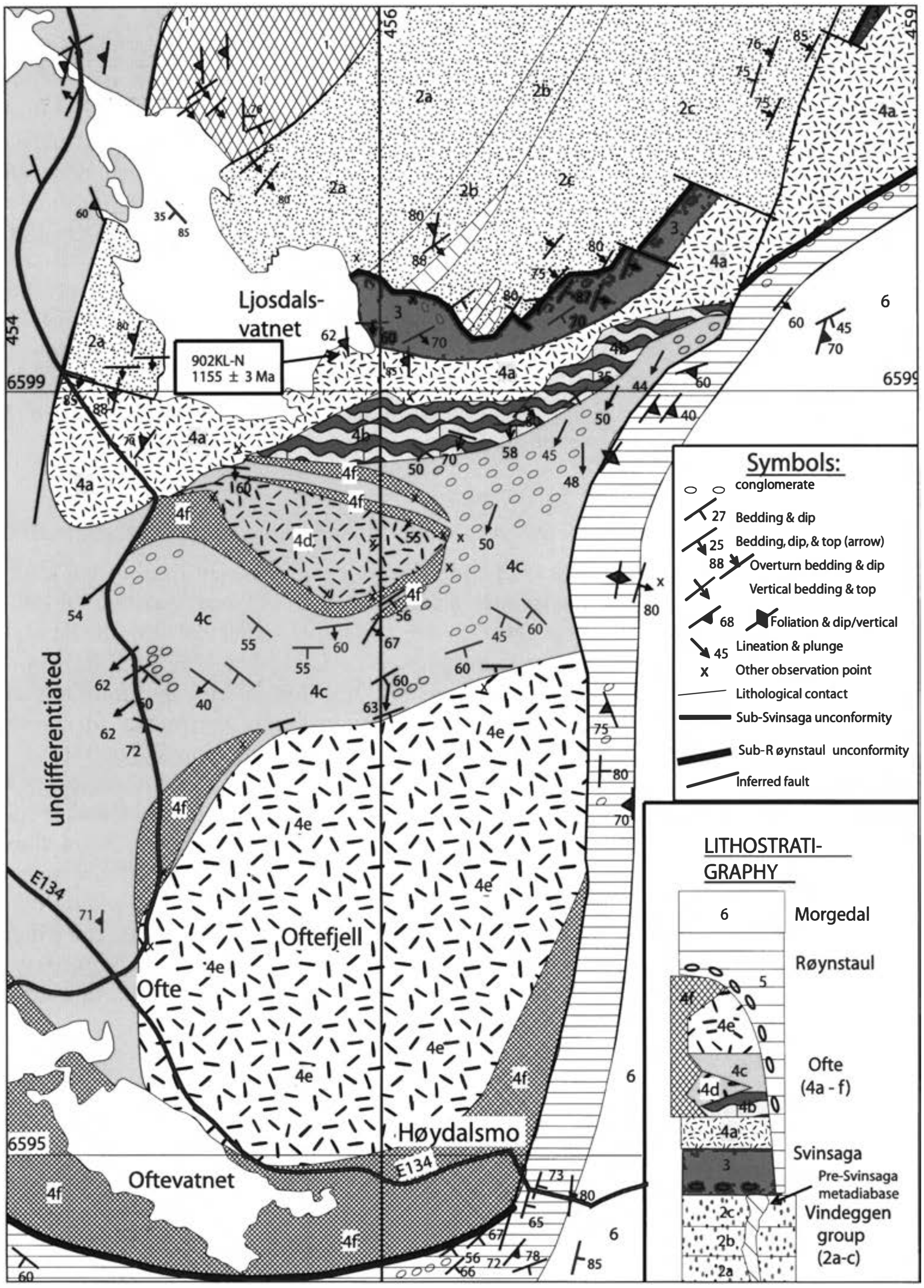

Fig. 4. Geological map of the Oftefjell-Ljosdalsvatnet area. The Vindeggen group is subdivided into: (2a) Gausta formation, (2b) mudstone, (2c) siltstone and quartzite and the Ofte formation into: (4a) Ljosdalsvatnet porphyry, (4b) unnamed quartzite, (4c) unnamed volcanic conglomerate and quartzite, (4d) Ofte porphyry 2, (4e) Ofte porphyry 3, (4f) Undifferentiated volcanic-subvolcanic metabasite. Note the angular unconformity between the Vindeggen group and the Svinsaga formation east of Ljosdalsvatnet and three acid volcanite units within the Ofte formation. The locality and age of the dated Ljosdalsvatnet porphyry sample 902KL-N are shown. Coordinates are given in UTM.

Kalhovd formation

The northwestern margin of the Telemark supracrustal comprises a 5 km wide N-S trending belt of conglomerate, sandstones, and quartz schists (Fig. 2). They lie nonconformably on the Gøyst gneiss complex (Sigmond 1998) and are included in the Kalhovd formation (Bingen et al. subm.). The youngest analysed detrital zircon grain in a sandstone from Kalhovd has an age of 1054 ± 22 Ma (op. cit), which significantly post-dates the age of the Skogsåa porphyry. Sedimentation of the Kalhovd formation could, therefore, only have been coeval with the bulk metasedimentary part of the Heddal group.

Basic intrusive rocks

The Telemark supracrustals are intruded by many metagabbroic sills and dykes, especially in the lower part of the Vindeggen group in the north. They form at least two age groups. The older one predates the Svinsaga formation (Fig. 4). The younger group includes the Hesjåbutind gabbro, which intrudes the Vindeggen group in the Gausta area and has a U-Pb zircon and baddeleyite age of 1145 +3/-2 Ma (Dahlgren et al. 1990a). Younger metagabbro intrusions are also fairly common in the upper part of the Lifjell group and the lower part of the Heddal group (Fig. 5).

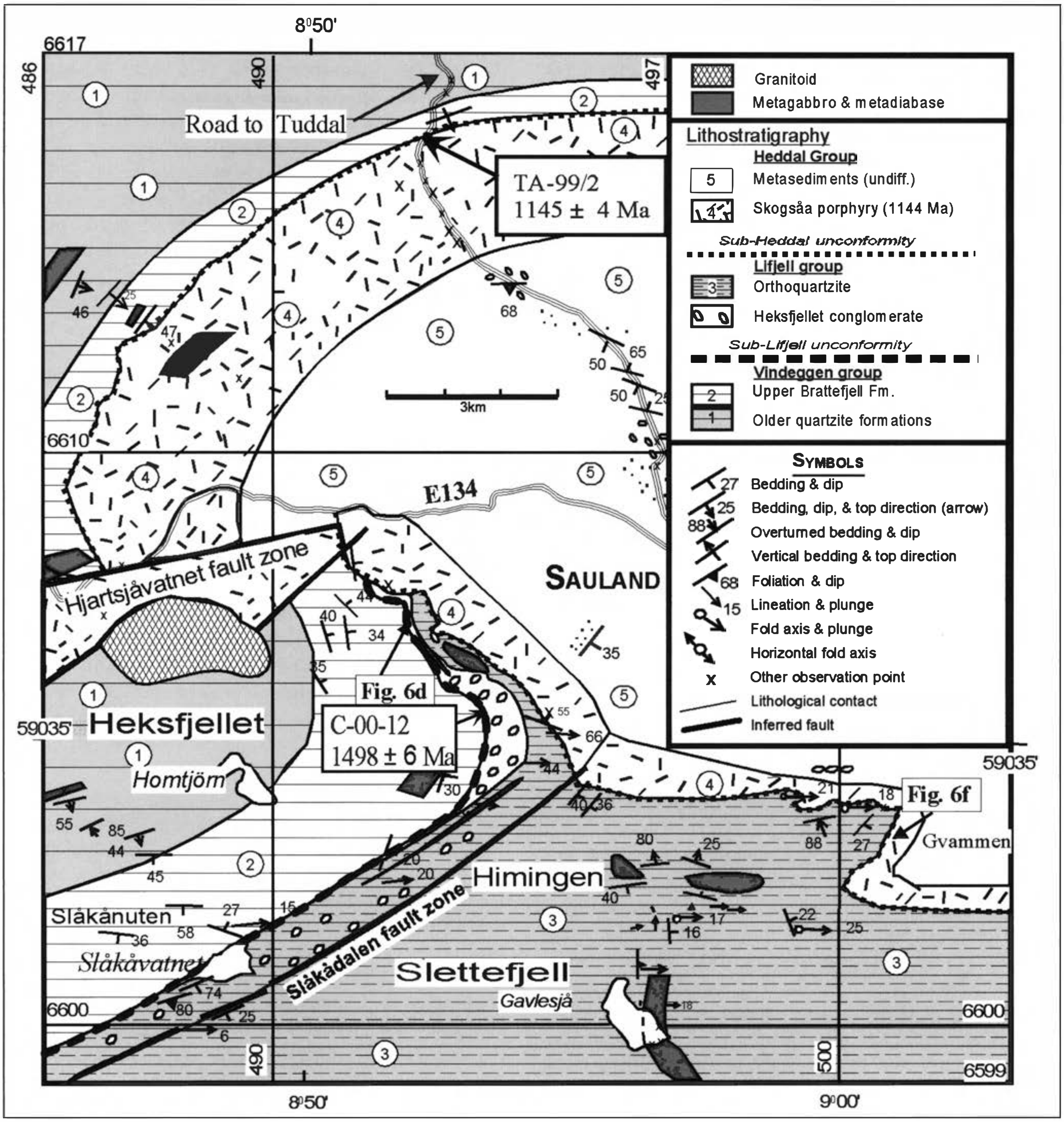

Fig. 5. Simplified geological map of the Sauland area. The locations of the samples dated and Figs. 6d and 6f are indicated. For more detailed geology see Laajoki (2002). Coordinates are given in UTM.

Contact relationships of the main stratigraphic units in the Bandak-Sauland area

As angular unconformities played a significant role in the original classification of the Telemark supracrustals (Dons 1960a), special attention was paid during fieldwork to contact relationships between major lithostratigraphic units. At least four major unconformities were verified in the study area. These are informally called: (1) the sub-Svinsaga unconformity, (2) the sub-Lifjell unconformity, (3) the sub-Røynstaul unconformity, and (4) the sub-Heddal unconformity (Table 1). These and other significant contacts will be described from the oldest to the youngest. It should be noted that all of these contacts have been folded and even tectonized in many places.

Sub-Svinsaga unconformity

The angular unconformity between the Vindeggen and Oftefjell groups is demonstrated convincingly where the

Svinsaga formation and its outliers were deposited unconformably on the folded Vindeggen group quartzite in the northern part of the Bandak area (Figs. 3 & 6a). This relationship is clear on the Åmotsdal map sheet by Dons (1994). Recent re-mapping of the unconformity confirms these observations. The unconformity is marked either by in situ breccia or breccia conglomerate lying on diverse formations of the folded Vindeggen group (Laajoki 2000). The angular relationship between the Vindeggen group and the Svinsaga formation is best visible southwest of Sundsbarmvatnet (Figs. 3 and 6a) and east of Ljosdalsvatnet (Fig. 4). Thin section studies show that the uppermost part of the Vindeggen group, the Brattefjell formation, went through silica diagenesis before it was exposed to erosion. This indicates that the group was buried at least to a depth of 2 – 3 km before its pre-Svinsaga exhumation (cf. Bjørlykke & Egeberg 1993).

Sub-Lifjell unconformity

The Lifjell group unconformably overlies the Brunkeberg formation in the Brunkeberg-Seljord area and the Vindeggen group at Heksfjellet.

Sub-Lifjell unconformity on top of the Brunkeberg formation. – This unconformity is gradual in the sense that the Brunkeberg porphyry, which shows a clear volcanic texture with plagioclase and minor microcline phenocrysts in fine-grained acid groundmass, is overlain without any clear boundary by a zone of volcanic detritus only some 1 – 3 m thick (Figs. 3 and 6b). It is exposed at several locations around the Brunkeberg formation. The detritus zone, containing solitary quartzite pebbles in its upper part, is overlain abruptly by a clast-supported, quartzite-clast dominated pebble-cobble conglomerate (Fig. 6b). Dons (1960a, p. 19) described this transitional zone and mentioned that "the true conglomerate" forms the basal part of his Seljord group, but did not define exactly where the unconformity between his Rjukan and Seljord groups lies. In this study, the lowermost part of the detritus zone is considered to be palaeoregolith on top of the Brunkeberg formation, and as such it marks an unconformity representing the erosional break between the Brunkeberg volcanism and the beginning of the deposition of the Lifjell group (Figs. 3 and 6b). It should be noted that this unconformity could not be defined as a clear surface. In terms of the geological time gap, it may correspond to a disconformity, but as this term is generally connected to a break between two sedimentary sequences (Jackson 1997), we prefer to call this part of the sub-Lifjell unconformity as an erosional unconformity. The overlying conglomeratic part is included into the Vallar bru formation (Laajoki 1998).

The contact between the Brunkeberg formation and the Transtaulhøgdi supracrustals is exposed in a small outcrop north of Lake Bandak (Fig. 3). It is similar to the one described above in that the Brungeberg formation is overlain by a palaeoregolith. This rocks is, however, more metamorphosed and intensely deformed being an epidote-bearing muscovite schist with abundant microcline porphyroblasts. The abundant muscovite indicates that the weathering here was more intense than in the Brunkeberg area. The 2 – 3 m thick muscovite schist is overlain by a folded, thin (a few tens of metres thick at most), granoblastic orthoquartzite bed dipping shallowly to the west (Fig. 6c). Neumann and Dons (1961) mapped it as the Røynstaul formation, whereas Nielsen and Dons (1991) considered it as the basal unit of the Vemork formation of their Rjukan group. However, the orthoquartzitic lithology and stratigraphic position directly upon the Brunkeberg palaeoregolith indicates that this orthoquartzite unit most likely represents the Lifjell group and consequently, the contact in question represents the southwesternmost extension of the sub-Lifjell erosional unconformity. A similar thin orthoquartzite unit (mostly too thin to be shown in Fig. 3) occurs at the southern margin of the Telemark supracrustals within the Kviteseid fold zone, which forms the tectonic-metamorphic boundary between the Vråvatn complex and the Telemark supracrustals in Fig. 3. Farther to the east, it is associated with volcanic detritus and quartzite clast conglomerates of the Vallar bru type lying upon the isoclinally folded Brunkeberg formation at Eidet (Laajoki 1998) and along the southern margin of Lifjell (Dons & Jorde 1978).

Sub-Lifjell unconformity on top of the Vindeggen group. – The contact between the Vindeggen and Lifjell groups is exposed in several outcrops at the eastern part of Heksfjellet (Fig. 5). Here an in situ weathering breccia is developed upon the uppermost orthoquartzites of the Brattefjell formation of the Vindeggen group (Fig. 6d). The breccia is overlain by the Heksfjellet conglomerate containing both quartzite clasts from the underlying Vindeggen group and porphyry clasts, of which at least the one dated (sample C-00-12) seems to be from the Rjukan group. The unconformity can be followed to the north, but there it is joined and eroded by the sub-Heddal unconformity (see below). West of Heksfjellet the unconformity is not exposed, but follows the Slåkådalen valley, which is a likely fault zone covered by recent sediments. Farther to the west, in Grunningsdalen and north of Seljord-Brunkeberg area, the unconformity cannot be detected as the Vindeggen group has tectonic contacts (GSF in Fig. 2) with the Brunkeberg formation and the lower parts of the Lifjell group.

As this eastern part of the sub-Lifjell unconformity lies upon the Vindeggen group, it may represent a longer period of erosion and/or non-deposition than the part of the sub-Lifjell unconformity above the Brunkeberg formation (Table 1).

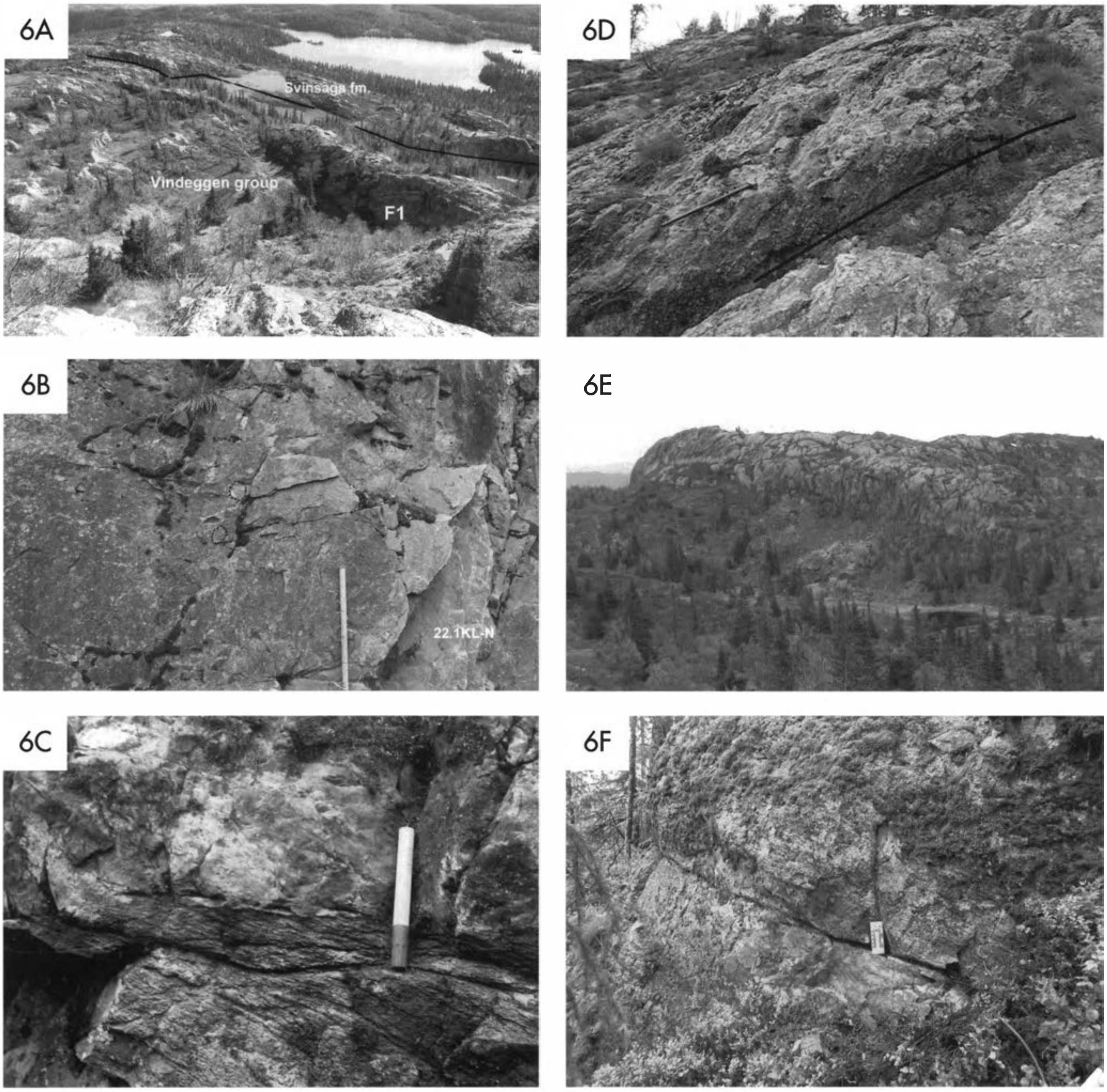

Fig. 6. Photographs of the unconformities within the Telemark supracrustals in the Bandak-Sauland area. For locations see Figs. 3 and 5.
(A) Sub-Svinsaga angular unconformity (black line) at Huvundvarden. Folded Vindeggen quartzite occupies the lower part of the photograph. F1 marks a pre-Svinsaga anticline of the Vindeggen group. Seen from the northeast. Photo 2155.
(B) Transitional contact between the volcanic detritus crust of the Brunkeberg formation (to the right of the 50 cm long stick) and a Vallar bru conglomerate (on the left). Solitary quartzite pebbles in the transitional volcanic detritus zone are circled (in the center). Location of the dated sample 22.1KL-N is indicated. Hesteskodiket. Station 22KL-N, UTM 47310/6589550. Photo 8127.
(C) Basal Transtaulhøgdi orthoquartzite lying on the palaeoregolithic muscovite schist mantling the Brunkeberg formation. Station 4547KL-N. UTM 468063/6595959. Photo 9558.
(D) Heksfjellet conglomerate separated by an in situ breccia from the underlying Brattefjell orthoquartzite of the Vindeggen group. The black line indicates the approximate site of the sub-Lifjell unconformity. Heksfjellet. Station 3065KL-N, UTM 491744/6607705. Photo 4712.
(E) The sub-Røynstaul unconformity (follows the soil line) under an outlier of the Røynstaul formation north of Lake Kultankriklan. Seen from the southwest. The foreground is underlain by vertical to steeply dipping Vindeggen group quartzites and associated metadiabase. Photo 4712.
(F) Sub-Heddal unconformity (under the scale) between the Lifjell group quartzite (below) and Heddal porphyry. Seen from the southwest. Gvammen, about 2 km east of Himingen. Station 2136KL-N, UTM 500926/6603551. Photo 3705.

Sub-Røynstaul unconformity

The conglomerates and sandstones of the Røynstaul formation overlie unconformably the Vindeggen group and the Ofte and Brunkeberg formations.

Sub-Røynstaul angular unconformity on top of the Vindeggen group. – The type locality of this unconformity is near Lake Kultankriklan, where small outliers of the Røynstaul formation lie discordantly upon the vertically dipping Vindeggen group quartzites and associated metadiabases (Figs. 3 & 6e). Its relation to the Vindeggen group is identical to that of the sub-Svinsaga unconformity, but the overlying rocks clearly represent the distinctive basal conglomerates of the Røynstaul formation (Laajoki in prep.). This part of the unconformity indicates a marked period of weathering and tilting. It is used to subdivide the traditional Bandak group into the Oftefjell and Høydalsmo groups (Table 1).

Sub-Røynstaul unconformity on top of the Ofte formation. – Northeast of Ljosdalsvatnet, the Røynstaul formation lies on the lowermost, dated acid porphyry of the Ofte formation (Fig. 4). This contact is erosional, but sheared. East of Oftefjell, the contact is not exposed, but the Røynstaul formation strikes north, highly oblique to the structural grain and bedding trends of the quartzite units of the Ofte formation (Fig. 4). The Røynstaul rocks are intensely sheared, which indicates that this part of the Ofte/Røynstaul contact might be a fault or shear zone as is indicated in Fig. 4, or it represents a tectonized sub-Røynstaul unconformity. South of Lake Oftevatnet the Ofte/Røynstaul contact is seemingly conformable or slightly erosional.

Sub-Røynstaul unconformity on top of the Brunkeberg formation. – Dons (1960a, p. 20) states that the Brunkeberg formation (his Tuddal formation) is overlain by a basal Bandak quartzite with an angular unconformity. This relationship has not been found in this study, but in several other well-exposed places it can be seen that the contact between the Brunkeberg and Røynstaul formations is transitional and of the same type as the sub-Lifjell erosional unconformity above the Brunkeberg formation described above. These two unconformities are so similar that they were first considered to be the same. However, the basal part of the Røynstaul formation, is less conglomeratic and much richer in muscovite than the basal parts of the Lifjell group. The muscovite-rich transitional part above the porphyry locally shows small-scale cross bedding defined by hematite-rich foreset laminae, which have not been seen in the basal Lifjell group. This unconformity is considered to represent an erosional unconformity.

Svinsaga formation/Røynstaul formation contact in the Liervatnet area. – The Svinsaga and Røynstaul formation rocks may occur side by side (the Ofte formation is missing) in the surroundings of Lake Liervatnet and south of it. However, the bedrock is highly deformed and poorly exposed, and it has not been possible to establish their primary stratigraphic relationships. The contact is marked by a fault in Fig. 3.

Transtaulhøgdi supracrustals / Røynstaul formation and Vråvatn gneiss / Røynstaul formation contacts. – The contact of the Røynstaul formation with the Transtaulhøgdi supracrustals and the Vråvatn complex has not been studied systematically, but structural observations on both sides of the contact indicate a narrow tectonic zone that runs from Brunkeberg to Bandak and Vråvatn and farther to the SSE (Fig. 4). This is supported by the map by Nilsen and Dons (1991), which shows quite different structural grains on both sides of this boundary.

Sub-Heddal unconformity

In the Sauland area (Fig. 5), the Heddal group was deposited progressively on older rocks when moving from south to north. In the south it overlies the topmost parts of the Lifjell group (Fig. 6f), whereas farther to the north it overlies the Brattefjell formation of the Vindeggen group. This significant unconformity is described more closely in an accompanying paper (Laajoki 2002).

U-Pb geochronology of the acid volcanics in the Bandak-Sauland area

Samples

The Ljosdalsvatnet porphyry sample **902 KL-N** was collected on the eastern shore of Ljosdalsvatnet (Fig. 4), close to the ventilation door to a hydroelectricity tunnel (for UTM coordinates of the samples see Table 2). The porphyry overlies the Svinsaga formation in the north, but the contact itself is not exposed. The angular unconformity between the Svinsaga formation and the Vindeggen group is visible at several localities in the Ljosdalsvatnet area (Fig. 4).

Sample 903 **KL-N**, collected from a road cut some 500 m south of Brunkeberg, represents typical Brunkeberg formation porphyry (Fig. 3). The sample is a homogeneous rock containing a few microcline blastoxenocrysts and quartz-filled vesicles in a recrystallized quartz- and microcline-rich groundmass with muscovite, biotite, epidote, opaques, some carbonate, apatite, and zircon. Opaques and muscovite define faint primary flow banding and (muscovite) a faint foliation. Sample 22.1KL-N was collected from the classical E134 road cut (Dons 1960a, Stop 11) at Hesteskodiket. This locality convincingly demonstrates the transitional nature of the sub-Lifjell unconformity described above (Fig. 6b). The rock is a weakly deformed porphyry with plagioclase and minor microcline phenocrysts and quartz-plagioclase-microcline aggregates in recrystallized felsic groundmass with some chlorite, muscovite, and opaques.

The Dalaå porphyry sample **830 KL-N** was collected from a new road cut (Fig. 3). It represents a well-preserved porphyry with up to 5 mm long feldspar and less abundant microcline phenocrysts and vesicles filled mainly by quartz in a fine-grained, well-preserved felsic groundmass.

The Skogsåa porphyry sample **TA-99/2** was collected approximately 1 km south of the topmost Lifjell group quartzite (Fig. 5). The rock is blastoporphyric with solitary quartz, plagioclase and microcline phenocrysts in fine-grained recrystallized felsic quartz- and microcline-rich groundmass. Accessory minerals include muscovite, epidote and opaques. The rock shows good flow banding in nearby outcrops.

The porphyry clast (**C-00-12**) represents deformed acid volcanic cobbles in the polymictic basal Heksfjellet conglomerate of the Lifjell group at the eastern flank of Heksfjellet (Fig. 5).

Analytical procedure

Zircon was extracted from the samples by crushing, pulverizing, separation by density using a Wilfley table and heavy liquids, and by magnetic properties on a Frantz separator. The crystals used for analysis were handpicked in alcohol using a binocular microscope and in some cases polished and examined with cathodoluminescence, before subjecting them to abrasion (Krogh 1982). They were then washed in dilute HNO3, rinsed in water and acetone and dissolved in teflon bombs with a mixed $^{205}Pb/^{235}U$ spike. Chemical separation of Pb and U was carried out in anion exchange columns for all, but the grains of less than 3 μg. Pb and U were loaded together on outgassed, zone-refined Re-filaments with Si-gel and H_3PO_4. The Pb and U isotopic ratios were measured with a MAT262 mass spectrometer, either with Faraday cups in static mode, or for the smaller samples and all the $^{207}Pb/^{204}Pb$ ratios, dynamically using an ion-counting SEM. The Pb and U data were corrected for 0.1%/amu fractionation, but ion-counting SEM measurements were additionally corrected for a non-linear bias determined by regular measurements of the NBS 982 Pb standard. Blank corrections were 2 pg Pb or less and 0.1 pg U. The residual common Pb was subtracted using compositions estimated with the Stacey and Kramers' (1975) model. The uncertainties on the ratios are given as 2σ values and were estimated by quadratic propagation of the main sources of error, including reproducibility terms of ±0.05%/amu for static, and ±0.1%/amu for SEM measurements. Two fractions of sample 903 KL-N were split prior to the chemical separation and measured separately to check the reproducibility of the method, yielding satisfactory results (Table 2). The decay constants are those of Jaffey et al. (1971). The data have been plotted and calculated using the program ISOPLOT (Ludwig 1999).

Zircon characteristics

The zircon populations in all these samples have a number of common characteristics. They all tend to contain many crystals which are commonly euhedral and have prominently developed {100} and {101} crystal faces (high A and T indices of Pupin 1980). Inclusions of other minerals and of melt are ubiquitous. Also common are xenocrystic zircons, as cores surrounded by euhedral rims and as individual grains. The selection of zircon fractions for analysis was done, therefore, with two goals in mind: (1) to minimize discordance, if possible by using gem-quality material; and (2) to avoid xenocrystic material by selecting crystals or parts of crystals devoid of core components. Unfortunately, it was not always easy to pick grains that fulfilled both requirements in an optimal way. The various fractions consisted either of whole euhedral grains, or of tips broken away from visible cores, free tips without apparent cores, and fragments of long-prismatic zircons inferred to be core-free based on the presence of longitudinal cracks or longitudinal melt-channels (e.g. Bussy & Cadoppi 1996).

U-Pb results

The zircon data are presented in Table 2 and plotted in Fig. 7. Most analyses plot within a few percent of the Concordia curve, but in several cases there is a distinct dispersion of the $^{207}Pb/^{206}Pb$ ages. This pattern reflects mainly the presence of older inherited zircon in at least part of the analysed grains, combined, in some cases, with the effects of secondary Pb loss.

Samples 903 KL-N and 22.1 KL-N, Brunkeberg porphyry. – Initial sets of analyses of sample 903 KL-N were carried out both on fractions of gem-quality whole crystals and on broken tips. The whole crystals, one fraction of which was split to check the reproducibility, yield overlapping analyses (5-7) with an average $^{207}Pb/^{206}Pb$ age of 1155.5 Ma, whereas the tips (1-2) and one fraction of fragments (3) yield older $^{207}Pb/^{206}Pb$ ages. Evidently some core components were present in some of the tips, and it is possible that these crystals may have fractured because of internal tensions acting at the core-rim boundary. To increase our confidence that the 1155.5 Ma age was not biased by inheritance, a set of crystals was sectioned in half and examined by cathodoluminescence. Two grains devoid of cores, one an equant crystal showing well developed oscillatory zoning (8) and the other an essentially homogeneous prism with only a faint longitudinal zonation (7, Fig. 7) were extracted

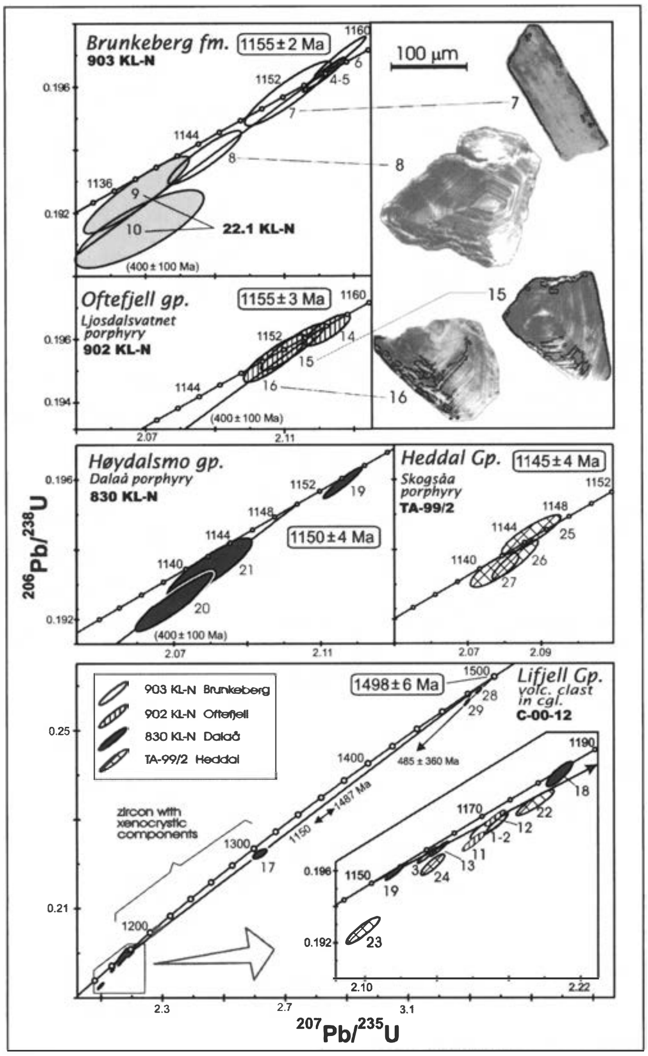

Fig. 7. Concordia diagram with the U-Pb results for zircon in volcanic units of the Telemark area. Ellipses indicate the 2σ uncertainty. The upper right corner displays cathodoluminescence photographs of selected zircons from the Brunkeberg and Ljosdalsvatnet porphyries.

from the grain-mount, abraded and analyzed. Unfortunately, the large flat surface created during polishing impeded a proper air abrasion, and the two analyses still show the effects of some Palaeozoic Pb loss with a the lower intercept of about 490 Ma for a line calculated through data points 4-8. By constraining the lower intercept at 400 ± 100 Ma to obviate the lack of spread, we yield an upper intercept of 1155 ± 2 Ma with a MSWD of 1.7. This age is interpreted to represent the time of crystallization of the Brunkeberg unit.

Because the age of 1155 Ma was radically different from that expected based on the proposed correlation of this unit with the ca. 1500 Ma Tuddal formation, it became a concern that the sampled outcrop may perhaps not be related to the unit exposed at the actual contact with the Vallar bru conglomerate. To verify this possibility, some zircons were extracted from a chip of porphyry taken at that location (sample 22.1KL-N). Three crystal tips containing large wormy (melt) inclusions and no visible zircon core were strongly abraded and the resulting pieces analyzed as a single grain and a small fraction. Although the two analyses (9 and 10) are not very precise, they amply confirm that the Brunkeberg unit below the sub-Lifjell erosional unconformity cannot be correlated with the Tuddal formation.

Sample 902 KL-N, Ljosdalsvatnet porphyry, Oftefjell group. – Initial attempts to avoid inheritance by using specific selections of long prismatic or tabular crystal fragments or of tips did not succeed as analyses 11-13 are scattered and discordant, indicating the presence of an older component (Fig. 7). By contrast, the analysis of a single prismatic crystal (14) plots concordantly and overlaps data points 15 and 16. The latter were obtained from two single grains that had a well-defined concentric zonation and no obvious core when viewed with cathodoluminescence. The interpretation of these data is not quite straightforward. The average $^{207}Pb/^{206}Pb$ age of the two CL-grains (15-16) is slightly lower than that of analysis 14, hence the latter could still be affected by some inheritance. On the other hand, because the sectioned and polished CL-grains could not be properly abraded, it is possible that the latter analyses are slightly biased downward by the effects of some Pb loss. A discordia line projected from 400 ±100 Ma through all three data points has an MSWD of 1.6 and an upper intercept age of 1155 ± 3 Ma, which is considered the best estimate of the crystallization age of the porphyry.

Sample 830 KL-N, Dalaå porphyry, Høydalsmo group. – Problems of inheritance also affected the age determination of this sample, but cathodoluminescence did not help differentiate xenocrystic and newly formed crystals. Fraction 17, exhibiting the largest inherited component of all the fractions described in this paper, was recovered from rusty fragments of zircon prisms that contained many wormy melt inclusions and, thus, deemed to have no cores. The old apparent age of this analysis demonstrates, however, that entire grains with such inclusions belong to the older zircon generation. Some inheritance was also present in a fraction of euhedral tips (18) with an apparent age at 1186 Ma. Another selection of tips (19) yields a nearly concordant analysis with a $^{207}Pb/^{206}Pb$ age of 1156 Ma. The youngest $^{207}Pb/^{206}Pb$ ages were obtained from two analyses of prism fragments, chosen among grains having prominent longitudinal inclusions. A common regression of the three youngest analyses (19-21) projects towards a very high and geologically rather unlikely lower intercept age of 700 Ma; when the line is forced through 400 ±100 Ma, as was done above, the MSWD increases to 4.8. Hence, it appears likely that fraction 19 is still slightly biased by some inheritance. Projecting a discordia line from 400 ± 100 Ma through only the two lowermost points we yield an intercept at 1150 ± 4 Ma, which overlaps the mean $^{207}Pb/^{206}Pb$ age of 1146 ± 3 Ma of the two points. Some Pb loss appears plausible given the relatively poor quality of the analysed zircons, which had to be recovered from grains with many inclusions and fractures in order to circumvent inheritance. Thus, the upper intercept age of 1150 ± 4 Ma is considered to be the most reliable date for magmatic crystallization of this unit.

Sample TA 99/2, Skogsåa porphyry, Heddal group. – Three of the analyses done on zircons from this sample contained some inheritance (22-24). Three other analyses (25-27) are grouped near Concordia. In this case, the attempt to force a regression line through 400 ± 100 Ma increases the MSWD to 2.8 from 1.9 obtained for the weighted average of the $^{207}Pb/^{206}Pb$ ages (but both indicate the same age). The mean age of 1145 ± 4 Ma dates magmatic crystallization of the porphyry.

Sample C-00-12, volcanic clast in Heksfjellet conglomerate, Lifjell group. – Two fractions were analysed for this sample. The two data points (28-29) are 1 to 2% discordant and define a line projecting to an upper intercept age of 1498 ± 6 Ma with a Palaeozoic lower intercept age. The 1498 Ma age shows that the clast was likely derived from volcanic units related to the Rjukan group to the north.

Sources of the xenocrystic zircons

All the zircon analyses affected by some degree of inheritance are plotted in the bottom diagram of Fig. 7; together with the two analyses for the clast sample C-00-12 (see above). A large component of older Pb is present in analysis 17; a line projected from 1150 Ma through this point has an intercept at about 1487 Ma indicating a likely provenance from Rjukan group-type sources. Several of the other analyses with xenocrystic components plot on or below this. The latter could reflect either a superimposed Pb loss or the presence of xenocrystic components predating 1500 Ma, for example the 1800 Ma group that is so prominent among the detrital zircons of the quartzite units investigated by de Haas et al. (1999). One exception is analysis 18, which overlaps Concordia and displays a $^{207}Pb/^{206}Pb$ age of about 1186 Ma pointing to a younger source, perhaps the 1190 -1205 Ma gneisses and granites present in the region (Dahlgren & Heaman 1991; Heaman & Smalley 1994). As the age of the inheritance was not the main focus of the present study, no efforts were made to analyze these data further.

Discussion

The new geological and geochronological observations introduce significant changes to the lithostratigraphy and modify our understanding of the sedimentary-volcanic stratigraphy of the southern Telemark supracrustals. The proposed new lithostratigraphic scheme with crucial age results is given in Table 1.

Subdivision of the Seljord group

The ages of the Ljosdalsvatnet and Brunkeberg porphyries overlap within error. Since the two units both overlie and underlie, respectively, the conventional Seljord group, the latter must consist of two separate successions. This bipartite subdivision is confirmed by the in situ breccias and conglomerates above the sub-Lifjell unconformity described from Heksfjellet (Laajoki 2002). The two successions are:

(1) The older part was deposited and folded before deposition of the Svinsaga formation and extrusion of the 1155 Ma old Ljosdalsvatnet porphyry. Consequently, deposition occurred sometime after ca. 1500 Ma (the age of the underlying Rjukan group, Dahlgren et al. 1990b) and before 1155 Ma. Preliminary mapping indicates that this sedimentary group includes all six formations from the Gausta to the Brattefjell formation of Dons' (1960a) classification in the Rjukan area and as such would represent the typical Seljord group (Table 1). However, these formations, cannot be identified in the area around the town of Seljord and thus retaining Seljord as the name of this group would be inappropriate and confusing. As the type areas of most of these formations occur in the surroundings of Mount Vindeggen, the name Vindeggen group is suggested for this lower and northern part of the traditional Seljord group. Lithologically this group is variable, containing basal conglomerates and arkosites, diverse lithic or pebbly quartzite, siltstone and mudstone units. Typical quartzite lithologies include mud-capped, cross-bedded quartzite sets (e.g. Figs. 17-19 in Singh 1969) and rippled or mud-cracked quartzites (Dons 1963). The uppermost part of the Brattefjell formation consists of rippled - parallel laminated orthoquartzite with occasional low-angle cross-beds. Deposition of the group took place mainly in a fluvial-shallow sea-intertidal environment.

(2) The younger part of the traditional Seljord group overlies the Brunkeberg formation and the Brattefjell formation of the Seljord (Vindeggen) group in the Brunkeberg-Seljord and Heksfjellet areas, respectively, but is in turn unconformably overlain by the Heddal group in the latter area. Therefore, the ages of 1155 ± 2 Ma of the Brunkeberg porphyry and that of 1145 ± 4 Ma of the Skogsåa porphyry bracket its sedimentation into a narrow time span of ca. 10 Ma (Table 1). In the Brunkeberg-Seljord area, this succession starts with the volcanic detritus zone and conglomerates of the Vallar bru formation, followed by rather monotonous quartzite, which corresponds to Bugge's (1931) type Seljord quartzite. The underlying volcanic rocks are missing in the Heksfjellet area and the sequence lies directly on the Vindeggen group. It comprises the southern part of the

Table 2. U-Pb zircon data, Telemark supracrustals, Norway

	Zircon characteristics[1]	Weight [µg][2]	U [ppm][2]	Th/U[3]	Pbc [pg][4]	$^{206}Pb/^{204}Pb$[5]	$^{207}Pb/^{235}U$[6]	2 σ [abs][6]	$^{206}Pb/^{238}U$[6]	2 σ [abs][6]	rho	$^{207}Pb/^{206}Pb$ [Ma][6]	2 s [abs]	Disc. [%][7]
	903 KL-N: Brunkeberg formation, porphyry, (470772/6588373)*													
1	eu tips	79	119	0,37	7,4	15790	2,1689	0,0081	0,19844	0,00055	0,88	1178,9	3,7	1,1
2	------- *duplicate*	79	119	0,38	6,5	17985	2,1740	0,0048	0,19868	0,00042	0,94	1181,2	1,5	1,2
3	lp fr	76	105	0,40	10,6	9355	2,1348	0,0045	0,19686	0,00037	0,96	1163,4	1,2	0,5
4	eu sp [28]	128	133	0,42	7,2	29192	2,1217	0,0051	0,19638	0,00044	0,97	1156,0	1,2	0,0
5	------- *duplicate*	128	133	0,42	6,3	32951	2,1222	0,0046	0,19644	0,00040	0,95	1155,9	1,3	0,0
6	eu sp [20]	97	126	0,42	24,9	6044	2,1263	0,0061	0,19693	0,00053	0,97	1154,7	1,3	-0,4
7	eu lp CL-hom [1]	3	72	0,40	0,7	3594	2,1112	0,0102	0,19578	0,00083	0,91	1152,3	4,0	0,0
8	eu CL-oz [1]	9	97	0,42	2,2	4740	2,0872	0,0086	0,19376	0,00069	0,91	1150,1	3,4	0,8
	22.1 KL-N: Brunkeberg formation, porphyry, (470772/6588373)*													
9	eu tips in [7]	<1	>175	0,35	0,6	3299	2,0675	0,0124	0,19258	0,00100	0,91	1143,4	4,9	0,8
10	eu tip [1]	3	49	0,38	1,5	1184	2,0683	0,0152	0,19149	0,00101	0,80	1155,4	8,8	2,4
	902 KL-N: Oftefjell group, Ljosdalsvatnet porphyry, (455963/6599191)*													
11	lp flat fr in [29]	62	165	0,41	33,3	3812	2,1608	0,0053	0,19762	0,00043	0,93	1179,6	1,7	1,6
12	lp fr in	42	104	0,42	6,4	8593	2,1727	0,0044	0,19891	0,00036	0,94	1177,6	1,4	0,8
13	eu tips in	57	125	0,37	4,6	18964	2,1413	0,0042	0,19721	0,00034	0,96	1165,9	1,1	0,5
14	lp fr in [1]	18	132	0,39	18,7	1574	2,1222	0,0054	0,19628	0,00041	0,80	1157,5	3,0	0,2
15	eu CL-oz [1]	6	149	0,39	1,4	7961	2,1124	0,0076	0,19575	0,00061	0,91	1153,6	3,0	0,1
16	eu CL-oz [1]	11	108	0,41	1,8	8258	2,1073	0,0073	0,19539	0,00061	0,87	1152,4	3,4	0,2
	830 KL-N: Høydalsmo group, Dalaå porphyry, (460640/ 6591124)*													
17	lp fr in [4]	<1	>113	0,44	2,0	792	2,6170	0,0186	0,22225	0,00090	0,68	1324,7	10,2	2,6
18	eu tips in [6]	19	96	0,39	5,1	4510	2,2086	0,0059	0,20137	0,00056	0,85	1185,7	2,9	0,3
19	eu tips in [13]	23	171	0,39	2,9	16656	2,1160	0,0044	0,19590	0,00037	0,95	1155,5	1,3	0,2
20	lp fr [1]	<1	>240	0,52	0,7	4027	2,0703	0,0089	0,19252	0,00070	0,92	1146,7	3,3	1,1
21	lp fr [6]	2	273	0,38	3,6	1837	2,0797	0,0094	0,19346	0,00070	0,88	1146,1	4,4	0,6
	TA-99/2: Heddal group, Skogsåa porphyry, (4926/66146)*													
22	eu tips (in)	14	131	0,42	2,7	8605	2,1950	0,0087	0,19978	0,00058	0,91	1189,2	3,5	1,4
23	lp fr in [18]	15	159	0,47	6,8	4243	2,0989	0,0076	0,19265	0,00060	0,90	1172,6	3,1	3,4
24	eu sp-eq (in)	17	114	0,47	4,9	4909	2,1378	0,0054	0,19633	0,00048	0,87	1171,5	2,5	1,5
25	eu tips (in)[12]	10	106	0,42	3,8	3450	2,0873	0,0066	0,19442	0,00045	0,89	1143,4	3,0	-0,2
26	eu lp fr [10]	14	144	0,45	4,1	5969	2,0829	0,0051	0,19370	0,00045	0,91	1146,6	2,0	0,5
27	eu tips in [19]	23	138	0,40	18,2	2136	2,0773	0,0053	0,19340	0,00040	0,79	1144,3	3,1	0,4
	C-00-12: Heddal group, felsic volcanic clast in Heksfjellet conglomerate, (493956/6604352)*													
28	eu lp in [28]	26	94	0,43	5,6	7069	3,3308	0,0076	0,25883	0,00057	0,91	1494,7	1,8	0,8
29	eu lp in [14]	22	132	0,45	6,0	7706	3,2924	0,0084	0,25628	0,00063	0,94	1491,5	1,7	1,6

[1] *zircons, all abraded; eu = euhedral; lp = long-prismatic; sp = short-prismatic; eq = equant; in = inclusions of other minerals; fr = fragment; CL = cathodoluminescence; hom = homogeneous; oz = oscillatory zoned; square brackets indicate the number of grains for fractions of less than 30 grains. Duplicate analyses were split after equilibration in 3.1 N HCl and treated as separate samples through chemistry and mass spectrometry.*

[2] *weight and concentrations of grains known to about +/- 10%, except for samples below 3mg where uncertainty is about 50%*

[3] *Th/U model ratio inferred from 208/206 ratio and age of sample*

[4] *Pbc = total common Pb in sample (initial +blank)*

[5] *raw data corrected for fractionation and blank*

[6] *corrected for fractionation, spike, blank and initial common Pb (estimated from Stacey & Kramers (1975) model); error calculated by propagating the main sources of uncertainty*

[7] *degree of discordance (in percent).*

* *UTM coordinates of sample locations (refer to the 1: 50 000 topographic map sheets of Statens Kartverk)*

traditional Seljord group from Brunkeberg via Seljord to Heksfjellet area and had not been subdivided on previous maps (Dons 1960a, 1994; Neumann & Dons 1961). Although for historical reasons it would seem logical to retain the name Seljord group for this younger part, this would be confusing because this name and the term Seljord quartzite have long been used to refer to the older part. Furthermore, this usage would conflict with Norwegian stratigraphic rules and recommendations (Nystuen 1986, 1989). As this unit corresponds approximately to Werenskiold's (1910) Lifjell (Lifjeld) quartzite, the name Lifjell group is proposed. The lithology of this group is rather simple: the conglomeratic Vallar bru formation and the Heksfjellet conglomerate are overlain by the bulk Lifjell orthoquartzite. The latter is dominated by monotonous orthoquartzite with wave ripples, parallel lamination, and low-angle cross bedding indicating beach depositional setting.

Recent SIMS studies on detrital zircons from the lower parts of each of these two new groups yield quite different age distributions lending further support to this subdivision. Detrital zircon U-Pb ages from the basal part of the Vindeggen group north of Hjartdal show a maximum at ca. 1500 Ma (Andersen & Laajoki subm.), whereas this age group is poorly represented in the zircon population of conglomeratic units of the Vallar bru formation, which has a frequency maximum at ca. 1800 Ma and also contains pre-1800 Ma zircons (sample GA526 in de Haas et al. 1999). Interestingly, no 1155 Ma zircons were detected in the Vallar bru sediments despite the fact that the conglomerate lies only a few metres above its Brunkeberg porphyry basement.

Subdivision of the Bandak group and intraregional correlations

The sub-Røynstaul unconformity subdivides the traditional Bandak group into two major parts. The lower part includes Dons' (1960a) Svinsaga and Ofte formations, developed at around 1155 Ma as indicated by the age of the Ljosdalsvatnet porphyry. The Ofte formation consists, in fact, of so many different and contrasting lithological units (4a-f in Fig. 4), that is should be subdivided into several formations. The name Oftefjell group is proposed for this lower part of the traditional Bandak group, as many of its units are exposed around the Oftefjell mountain.

The middle part of the Bandak group comprises four formations (from Røynstaul to Gjuve, Table 1). The 1150 Ma age of the Dalaå porphyry indicates the time of volcanism of this group, for which the name Høydalsmo group is proposed, as these assemblages are well exposed south and east of this village.

The Eidsborg formation on top of the traditional Bandak group is kept separate from the Høydalsmo group, as it starts with a thick polymictic conglomerate overlain by monotonous quartzites indicating, together with the lack of volcanic rocks, a significant change in depositional conditions after the mainly volcanic Gjuve formation. A detrital zircon study carried out by de Haas et al. (1999) on a sample of the basal Eidsborg formation found five detrital grains with ages around 1500 Ma and 1800 Ma, consistent with the general range of sources observed in the Vallar bru samples discussed above, but they also detected one grain with a $^{207}Pb/^{206}Pb$ age of 1118 ± 38 Ma. Although this age is indistinguishable within error from the 1150 Ma age of the Dalaå porphyry, it is possible that the Eidsborg formation might be a younger deposit, perhaps coeval to the ca.1054 ± 22 Ma old Kalhovd formation (Bingen et al. subm.) further north (Fig. 2)

An open question is how all the units above the sub-Svinsaga unconformity are related to each other. The coeval ages and similar lithological characteristics of the Brunkeberg and Ljosdalsvatnet porphyries indicate that they could be parts of the same entity, but each of them is overlain by a unit of drastically different character, the Lifjell group and the rest of the Oftefjell group, respectively. The former is predominantly monotonous beach orthoquartzite, whereas the latter is a mixture of diverse volcanic rocks and volcanic epiclastic rocks. On the other hand, the Transtaulhøgdi supracrustals, which also overlie the Brunkeberg formation, resemble in some respects (it is a mixed sedimentary-volcanic sequence) the Ofte formation, suggesting that they represent a more metamorphosed lateral equivalent of the Ofte formation. As the thin orthoquartzite at the base of the Transtaulhøgdi supracrustals likely belongs to the Lifjell group, the Lifjell group could represent a marine facies that was deposited east of the volcanic Brunkeberg-Transtaulhøgdi-Oftefjell system. Conversely, one might then also postulate a correlation between the Lifjell group and the quartzite unit above the Ljosdalsvatnet porphyry (4b in Fig. 4) in the Oftefjell group. If correct, it would indicate that the Lifjell group underwent folding before deposition of the Røynstaul formation, and this would mean that in the short time period between 1155 and 1145 Ma complex tectonism created both tensional regimes to permit the extensive accumulations of quartz-rich sediments and compression to explain the folding, all accompanied by intermittent, bimodal volcanism.

The relationship between the Bandak and Heddal groups has presented another point of debate (Dahlgren et al. 1990b). Dahlgren (1993) tentatively suggested that the Heddal group might predate Bandak. Our new results demonstrate that the Heddal group is significantly younger than the Oftefjell group, and may also be a little younger than the Høydalsmo group as the zircon age of the Dalaå porphyry (1150 ± 4 Ma) appears to be older than that of the Skogsåa porphyry (1145 ± 4 Ma).

However, because the ages overlap within uncertainties, it cannot be excluded that the two porphyries are coeval.

General considerations

The stratigraphic observations and U-Pb results described in this paper show that the sedimentary-volcanic evolution of the Brunkeberg formation, Oftefjell, Lifjell, Høydalsmo, and Heddal groups took place in several major stages including 1 – 2 deformation phases, but within a relatively short time span at c. 1155 – 1140 Ma. It falls within a period of some 50 million years, that was characterized by both extension and compression, by local high-grade metamorphism and by widespread intrusions of mafic dykes and alkalic and anorthositic complexes in a region stretching across the western Baltic Shield and Laurentia. This orogenic phase pre-dated the main Sveconorwegian compressional events and has been considered to indicate an anomalous thermal regime that lead to widespread mantle melting (Heaman & Smalley 1994). Hanmer et al. (2000) interpret these events in terms of upper mantle melting and crustal extension related to post-collisional (Elzevirian collision) collapse of the subcontinental lithosphere.

Conclusions

1. At least one angular unconformity and three other major unconformities occur within the Telemark supracrustals in the southern part of the Rjukan palaeorift.
2. The Brunkeberg and the Ljosdalsvatnet porphyries yield identical U-Pb zircon ages of 1155 ± 2 and 1155 ± 3 Ma, respectively, the Dalaå porphyry 1150 ± 4 Ma, and the Skogsåa porphyry at the base of the Heddal group 1145 ± 4 Ma. Because of the 1155 Ma age, the Brunkeberg formation and the overlying Transtaulhøgdi supracrustals cannot be correlated with the Rjukan group, as previously assumed.
3. As conglomerates and quartzites previously assigned to the Seljord group unconformably overlie the Brunkeberg porphyry, they cannot be related to other parts of the Seljord group that predate the Ljosdalsvatnet porphyry. The traditional Seljord group is therefore subdivided into two parts: the Vindeggen group, whose depositional age is only broadly constrained between 1500 Ma and 1155 Ma, and the Lifjell group, which was deposited between about 1155 Ma and 1145 Ma ago. This new subdivision is confirmed by the Heksfjellet in situ breccias and conglomerates upon the topmost Vindeggen quartzite.
4. The presence of 1500 Ma old porphyry clasts in the Heksfjellet conglomerate indicates that the Rjukan group was exposed to weathering and erosion in the initial stages of deposition of the Lifjell group.
5. The sub-Røynstaul unconformity subdivides the traditional Bandak group into the Oftefjell and Høydalsmo groups. Their ages of volcanism and associated sedimentation are approximated by the 1155 Ma and 1150 Ma ages of the Ljosdalsvatnet and Dalaå porphyries, respectively.
6. The 1145 ± 4 Ma age of the Skogsåa porphyry indicates that the lower part of the Heddal group is younger than the Oftefjell group.

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