Geology of the Setesdalen area, South Norway: Implications for the Sveconorwegian evolution of South Norway

SVEND PEDERSEN & JENS KONNERUP-MADSEN

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Crust forming processes in the Setesdalen area in the central part of southern Norway are dominated by the development of pre-Sveconorwegian supracrustal rocks (immature clastic sediments and bimodal volcanics) with an assumed depositional age of 1150–1100 Ma and by the emplacement of scattered infracrustal granitoids. The supracrustal rocks were deposited on a partly older than 1300 Ma gneissic basement including rocks which may have suffered one or more pre-Sveconorwegian orogeneses. During the Sveconorwegian orogeny, with the main upper greenschist to middle amphibolite facies high-temperature metamorphism and deformational phases in the period 1060–970 Ma, igneous activity comprising K-rich rocks high in elements such as P, Ti, La, Sr, Zr, and LREE and Ba was dominant. Significantly younger than this activity is the development of many REE pegmatites which are so characteristic for the region. The Precambrian geological activity terminated (at about 830 Ma?) with the development of E-W trending tholeiitic dolerites.

Key words: Geochronology, granites, metagabbros, Norway, Precambrian, REE pegmatites, Sveconorwegian orogeny

Svend Pedersen & Jens Konnerup-Madsen, Geologisk Institut, Copenhagen University, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. 22 June 1999.

Southern Norway and Sweden make up the Sveconorwegian Province of the Baltic Shield and consist of rocks formed during the Sveconorwegian orogeny and pre-existing rocks which were tectonically reworked and metamorphosed during this tectonothermal event.

The Sveconorwegian orogeny – the Scandinavian counterpart to the Grenvillian – has determined the structural pattern observed west of the Sveconorwegian Front (Fig. 1) and plausibly developed at the margin of a larger continent (Laurentia and Baltica) as a result of oblique collision(s) with another unknown continent (Romer & Smeds 1996). The present level of exposure in southern Norway has been considered to represent the deep roots of a Cordilleran type convergent plate margin and a subsequent collision zone which is often indicated to have formed in the period 1100–900 Ma. The Vest Agder-Rogaland area (Fig. 1) is by many authors described as being situated in the core zone of the orogen (e.g. Falkum & Petersen 1980, Falkum 1985, Bingen & van Bremen 1998) with extensive polyphase deformation, metamorphism and magmatism.

The Sveconorwegian Province in southwestern Scandinavia includes several Proterozoic crustal segments separated by thrust and shear zones (Fig. 1A), some of which show evidence of sinistral strike-slip movements (Hageskov 1997). West of Oslo Fjord the dominant thrust zone, the Kristiansand-Bagn shear zone (the Bamble and Kongsberg shear zones, Fig. 1) (Hageskov 1980) divides southwestern Norway into two main crustal segments, the Kongsberg-Bamble and the Telemark-Vest Agder-Rogaland segments. The Mandal-Ustaoset lineament (Sigmond 1985) has more recently also been considered to be a significant thrust (e.g. Starmer 1993) and to divide the Telemark-Vest Agder-Rogaland segment into a Telemark sector and a Vest Agder-Rogaland sector (Fig. 1); the geological history of the individual segments and sectors probably differs.

The crustal evolution between Oslo Fjord and the Mylonite zone is dominated by Gothian (1710-1570

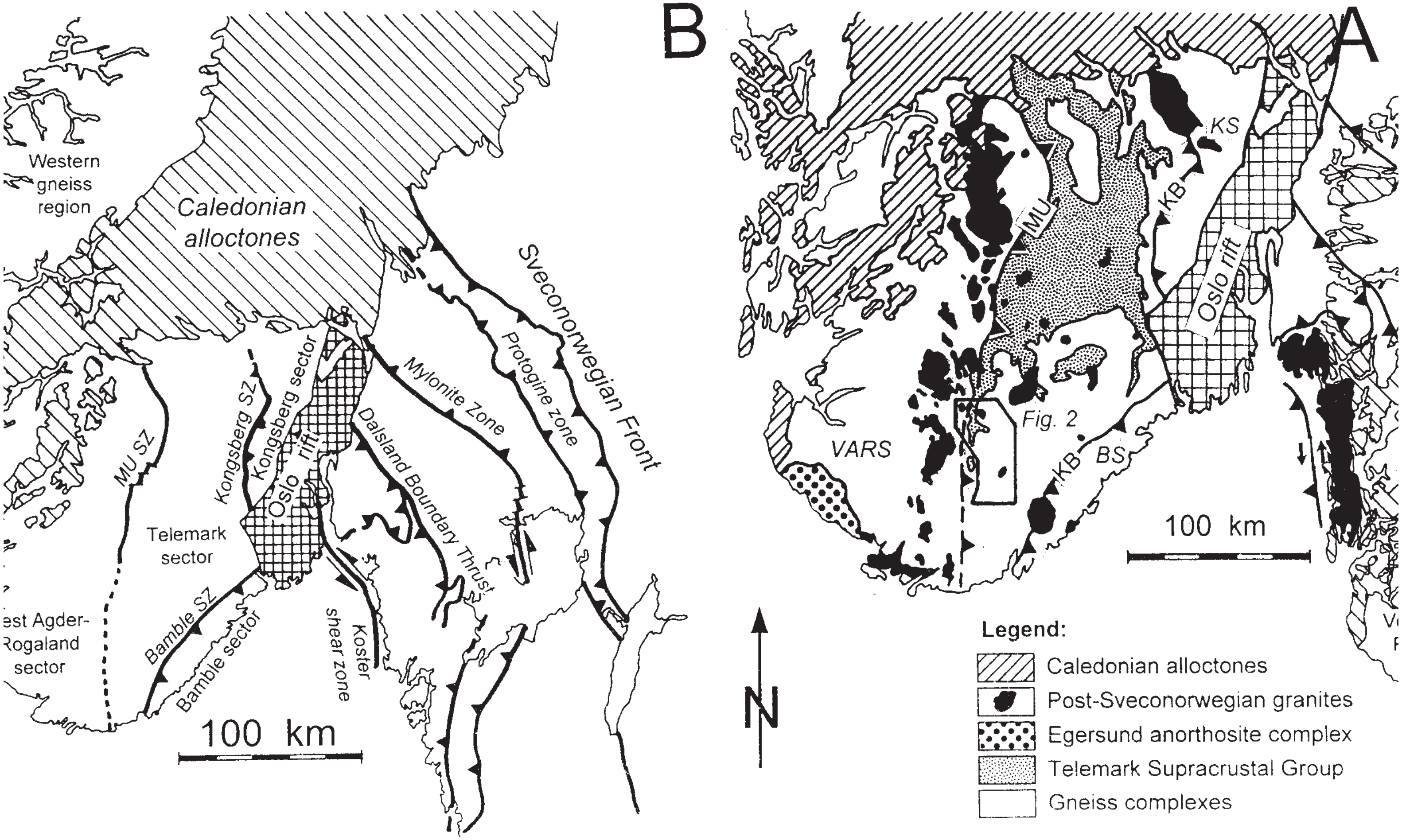


Fig. 1. The left map (A) shows the major structural divisions of the basement in South Norway and Southwest Sweden, the Western Gneiss Region, and the extent of Caledonian and younger cover. Abbreviations: SZ: shear zone; MU SZ: the Mandal Ustaoset shear zone. The right map (B) is a simplified geological map of South Norway showing the location of the Setesdalen area.

Ma) orogenic processes (Gaál & Gorbatschev 1987, Graversen & Pedersen 1999) and widespread post-Gothian intracratonic magmatism during several temporally and spatially distinct episodes in the period 1530–1130 Ma (Åhäll & Connelly 1998) before the Sveconorwegian (1100–900 Ma) overprinting. The Kongsberg and Bamble sectors were also affected by the Gothian orogeny, the widespread influence of which has not been convincingly demonstrated in areas west of the Kristiansand-Bagn shear zone, where Sveconorwegian crust-forming processes appear to be the determining event.

Sveconorwegian magmatic activity is far less important east than west of the Kristiansand-Bagn shear zone where magmatic activity contemporaneous with and later than the Sveconorwegian orogenic evolution is widespread, particularly west of the Mandal-Ustaoset lineament (Fig. 1B). Emplacement of most of the late- to post-Sveconorwegian granites appears to have occurred along several N-S to NNE-SSW lineaments which might represent zones of crustal weakness reflecting the orientation of the Sveconorwegian collision (Fig. 1). Judged from age determinations of younger intrusions and pegmatites not influenced by Sveconorwegian deformations (e.g. Falkum 1998), a lower limit to the Sveconorwegian orogeny of around 980–970 Ma is favoured by the authors.

The metamorphic rock complex in southern Norway is generally divided into two main lithological suites, a granitic gneiss suite and a banded gneiss suite, comprising several mappable units (Falkum 1998). The former suite includes several types of granitic gneiss units including granitic orthogneisses and augen gneisses with a plutonic precursor. The banded gneiss suite comprises a series of generally banded gneisses with alternating mafic and felsic layers and amphibolite facies mineral assemblages. Parts of the banded gneiss suite are of an indisputable supracrustal origin and represent metamorphosed clastic sediments and basaltic tuffs. Rb-Sr whole rock age determinations and U-Pb zircon dating of the gneisses mostly give ages around 1130–1030 Ma (e.g, Knudsen et al. 1997, Bingen & van Bremen 1998) believed to reflect Sveconorwegian metamorphism, but ages of 1190–1130 Ma on metaplutonic rocks with A-type geochemical signatures indicate pre-Sveconorwegian crustal additions (e.g. Bingen & Bremen 1998). Even older ages have been obtained (e.g. Birkeland et al. 1997) and suggest local (?) Gothian and pre-Gothian igneous activity as well. However, the actual amount of pre-Sveconorwegian rocks in the Vest Agder-Rogaland sector is still largely unknown. In the Bamble sector, Sveconorwegian (granulite facies) metamorphism is indicated to have ended around 1095 Ma (Kullerud & Dahlgren 1993), whereas in the Vest Agder-Rogaland sector the last Sveconorwegian deformation and metamorphism occurred around 990-980 Ma (Falkum 1998). The differences in age between these sectors are substantiated by similar differences in cooling and uplift histories (e.g. Bingen et al. 1998) and suggest that the Sveconorwegian orogeny was not one continuous orogeny but different orogenies, one ending at around 1100 Ma and the other around 980 Ma.

Rocks of pre-Sveconorwegian, unequivocal supracrustal origin are especially known from the Telemark region, where large areas are covered by volcanic rocks and clastic sediments belonging to the so-called Telemark supracrustals (Dons 1960, Sigmond et al. 1997) and have only been affected by low to medium grade metamorphism in its central part. The Telemark supracrustals are divided into four groups: the Rjukan (oldest), Seljord, Heddal and Bandak (youngest) groups (Dahlgren 1996). The age of the Telemark supracrustals is somewhat uncertain but recent studies suggest ages and deposition of the volcanic dominated Rjukan and Bandak groups of about 1500 Ma and 1120 Ma, respectively (Dahlgren 1996). Dating of detrital zircons from a metasandstone-arkose in the top of the Bandak group suggests deposition ages as young as 1045±22 Ma (Bingen et al. 1999). The age of deposition of the intermittent, essentially clastic sedimentary Seljord group is not known but parts of it are constrained by an age of 1145 Ma obtained on a gabbroic sill emplaced in the sediments (Dahlgren et al. 1990) and being in agreement with U/Pb ages of detrital zircons of about 1350 Ma (Bingen et al. 1999).

Basement relations for the Telemark supracrustals are not well established, but it is commonly inferred that (parts of) the gneisses exposed in the Vest Agder-Rogaland sector and in the southern part of the Telemark sector are plausible basement candidates.

Geology of the Setesdalen area

The Setesdalen area is situated in the southern part of the Telemark sector, south of the principal area of the Telemark supracrustals and just east of the Mandal-Ustaoset lineament/shear zone as defined by Sigmond (1985) (Fig. 2). The 1:250,000 geological map MANDAL (Falkum 1982) covers part of the area, and additional geological information may be obtained from the 1:50,000 preliminary map EVJE (Pedersen 1985). In addition, various aspects of the geology of parts of the area have been presented by Andersen (1931), Barth (1947), Bjørlykke (1934, 1937, 1947), Teisseyre (1970), Pedersen (1975, 1981), Pedersen & Konnerup-Madsen (1994) and Hansen et al. (1998).

Based on these previous studies and more recent detailed field and geochemical studies, the present knowledge of the geological evolution of the Setesdalen area may be summarised chronologically under the headings (Fig. 3):

(1) *Formation of the Setesdalen metamorphic basement complex* consisting of pre-Sveconorwegian basement gneisses which host a series of calc-al-

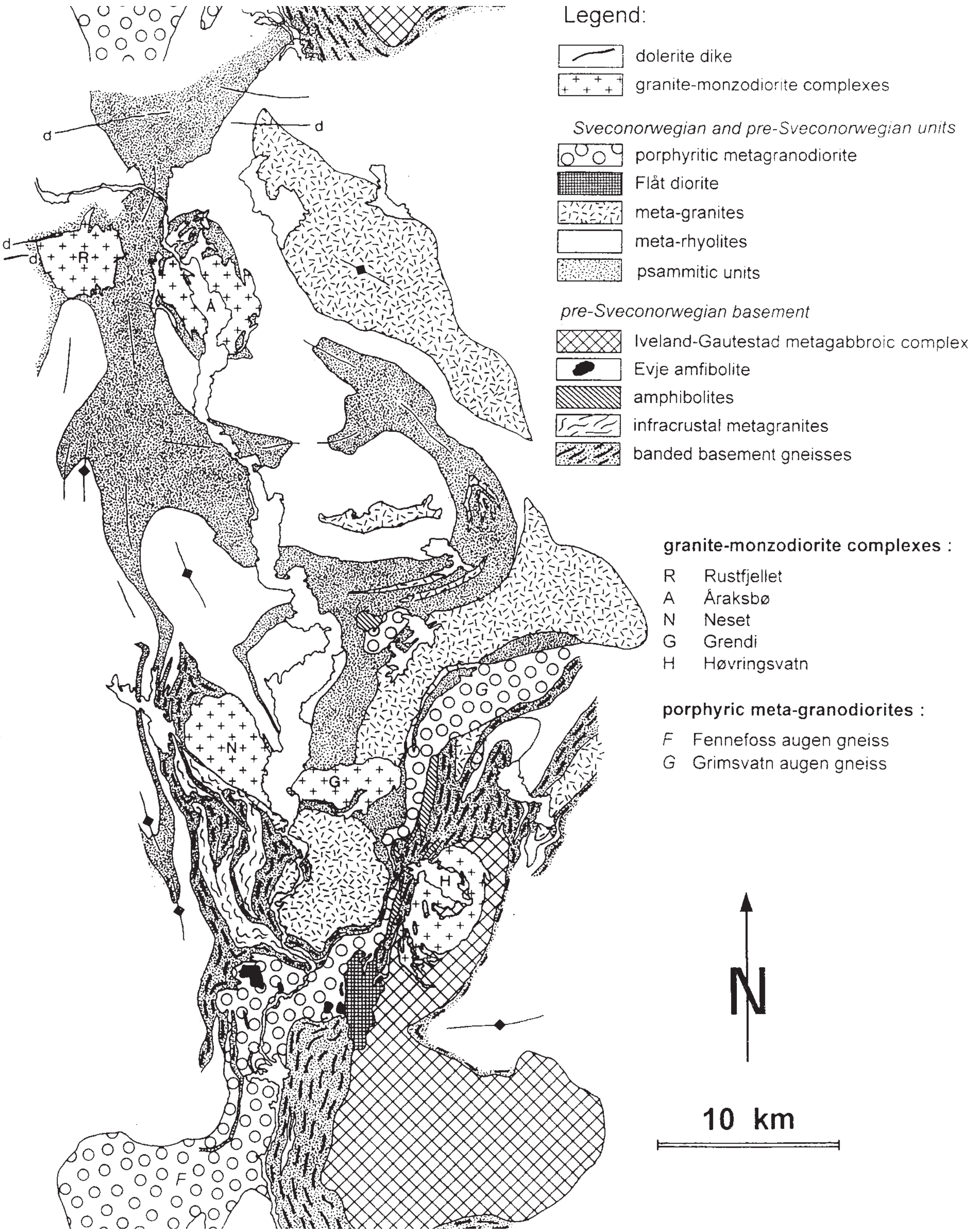


Fig. 2. Geological map of the Setesdalen area.

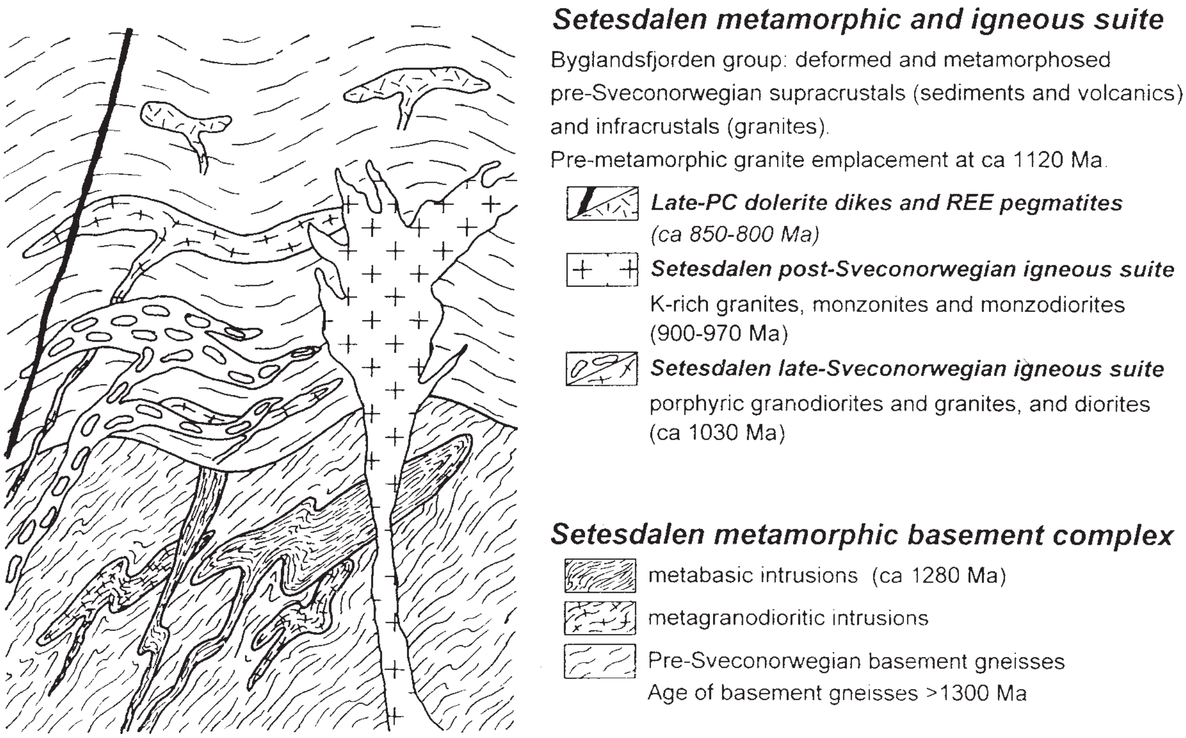


Fig. 3. Schematic lithological and chronological column for the rock types in the Setesdalen area.

kaline granodiorites and granites, as well as basic igneous rocks with a continental margin arc signature (e.g. the Iveland-Gautestad metagabbro). Subsequently this basement complex was metamorphosed under upper amphibolite facies conditions during a pre-Sveconorwegian tectonothermal event.

(2) *Formation of pre-Sveconorwegian supracrustal and infracrustal rocks* (the Byglandsfjorden group), comprising deposition of immature clastic sediments and igneous activity related to bimodal anorogenic volcanic and plutonic complexes as well as the emplacement of minor bodies of gabbros and diorites.

(3) *Sveconorwegian regional amphibolite facies metamorphism*, possibly with associated synorogenic emplacement of calc-alkaline granites and ferrodiorites (e.g., the Flåt Complex).

(4) *Late- to post-Sveconorwegian emplacement of a highly potassic granitoid suite* of bimodal (granite-monzodiorite) igneous complexes.

(5) *Formation of the Iveland-Evje REE pegmatite field*, and e*mplacement of post-Sveconorwegian E-W trending tholeiitic dykes*.

In this paper, a summary of the geological evolution of the Setesdalen area will be presented, with the main emphasis placed on the character of magmatic activity as time markers in the area. The geological map of the Setesdalen area is shown in Figure 2, and a generalised lithological-chronological diagram in Figure 3.

The Setesdalen metamorphic basement complex

Remnants of the metamorphic basement complex have mainly been identified in the southern part of Setesdalen, around and south of Evje village. Banded gneisses dominate and consist of alternating cm-dm thick felsic and mafic bands. The individual bands comprise mainly amphibolites, granodioritic biotite-hornblende gneisses, alkalifeldspar-garnet gneisses, and cummingtonite-rich gneisses, but occasionally patches of mafic two-pyroxene, garnet-bearing gneisses occur. These mineral assemblages indicate the attainment of upper amphibolite to lower granulite facies conditions.

The minimum age of metamorphism is indicated from dating on igneous rocks crosscutting folds in this series of banded gneisses. The oldest age obtained has been on a metagranodiorite of calc-alkaline affinity, the Sletthei augen gneiss, which yields a Rb-Sr whole rock age of 1350 ± 80 Ma (Pedersen 1981) (MSWD: 3.58); a Sr_{IR} of 0.701±0.003 precludes significant involvement of older crustal components. Rocks similar in composition and age to the Sletthei augen gneiss occur scattered in the Vest Agder-Rogaland,

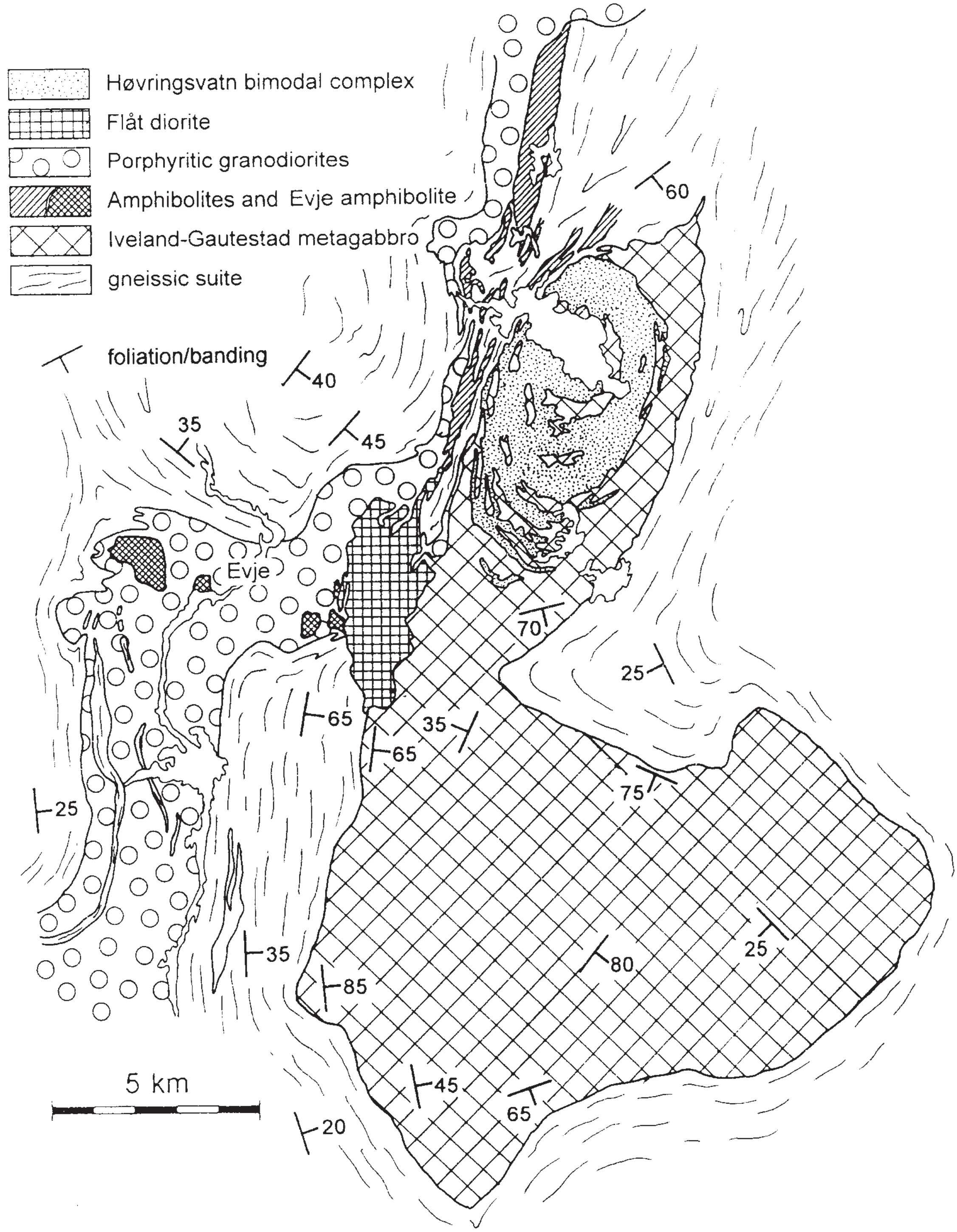


Fig. 4. Geological map of the area around Evje and Iveland in the southern part of the Setesdalen showing the relationships between the Iveland-Gautestad metagabbro and other metabasic bodies and basement gneisses.

Kongsberg, and Bamble sectors (Falkum, 1985; Sigmond, 1978). Their actual proportion of the pre-Sveconorwegian rocks within the Agder Complex is still not fully elucidated, but they form an important type.

Another indication is provided by the Iveland-Gautestad metagabbroic complex described below which is the most important indication of pre-Sveconorwegian igneous activity prior to the formation of the Byglandsfjorden group.

The Iveland-Gautestad metagabbroic complex

The main occurrence of basic rocks in Setesdalen is the Iveland-Gautestad metagabbroic complex (see Fig. 2) which was originally termed the Iveland-Evje amphibolite by Barth (1947). The amphibolite is a large body covering 160 km^2 and stretching 30 km in the N-S direction and up to 15 km in the E-W direction. It was originally described by Barth (1947) as a thoroughly reworked, metamorphosed and metasomatised norite now present as various types of hornblende gabbros, diorites and amphibolites, and with only minor noritic patches being preserved. The strongest argument for the originally noritic character was the occurrence of several nickel deposits. Recent studies have shown it to be composed of several distinctly different bodies, the composite and layered Iveland-Gautestad metagabbroic complex, and the somewhat younger Evje amphibolite (previously termed evjeite by Barth (1947)) and Mykleås ferrodiorite, which is now regarded as part of the Flåt complex (see below) (M. Pedersen 1993) (Fig. 4).

The Iveland-Gautestad intrusion is a composite body which consists of igneous rocks ranging in composition from ultramafic to felsic, and which has been partly metamorphosed under static conditions. The dominant rock types are gabbronorites, occasionally olivine-bearing, grading into diorites and quartz diorites. Tonalitic and leucotonalitic (trondhjemitic) rock types occur in subordinate amounts. Field observations and gravimetry (Smithson 1963) indicate the shape of the intrusion to be that of a folded flat bowl, the thickness of which is in the order of 1-2 km at maximum, and that the present level of erosion is close to the roof of the intrusion. The intrusion was emplaced discordantly into highly deformed and isoclinally folded, predominantly mafic, middle to upper amphibolite facies banded gneisses (locally granulite facies). Subsequent to its plausibly syn-kinematic emplacement the Iveland-Gautestad body was deformed together with the enclosing banded gneisses. The contact is sharp although the presence of mafic layers in the gneiss may obscure the contact relations. Streaks and wedges of gneissic material are sandwiched between gabbroic layers in the contact zone.

In the northern part of the intrusion Rønholt (1990) was able to distinguish between an ultramafic unit (hornblendite and pyroxene-hornblendite lenses or boudins), a massive gabbronoritic unit, and a layered series of predominantly diorites, all of which are cut by dykes or plugs of gabbronoritic, tonalitic and gabbroic compositions. The ultramafic bodies clearly belong to the same stratigraphic level within the intrusion. Further south and more central in the intrusion, larger bodies of hornblende pyroxenites and peridotites occur with up to 50% olivine in addition to smaller scattered occurrences of lenses, schlieren or bands of hornblende pyroxenite within the gabbronoritic unit (Bertelsen 1984). Occasionally rounded bodies of harzburgitic pyroxene-hornblende peridotite with olivine (Fo86), orthopyroxene, spinel and hornblende occur within the hornblende pyroxenite. The ultramafic series is considered to represent various types of peridotitic and in particular pyroxenitic cumulates.

A weakly foliated, coarse-grained to pegmatitic unit (essentially a hornblende diorite) was mapped out in the central part of the intrusion by Bertelsen (1984) and suggested to represent a largely continuous pegmatite-rich layer occasionally crosscutting the layered gabbroic series at a low angle.

Within the intrusion a number of small and uneconomic Fe-Ni-Cu sulphide showings are known. Mineralization occurs in irregular zones up to 25 meters wide with intervening zones lacking mineralization; all gradations from finely disseminated ore, through ore forming a network to cm-dm-sized rounded blebs, aggregates and bands of sulphides are seen. The mineralization displays textural, mineralogical and chemical characteristics similar to those of orthomagmatic deposits of segregative origin associated with mafic-ultramafic compositions and to those described for similar types of mineralization from the Bamble area (Brickwood 1986).

In the eastern part of Lake Høvringsvatn and in an area towards the southeast, coarse-grained amphibolite is found as xenoliths in the fine-grained metabasites of the Iveland-Gautestad body. The xenoliths have suffered stronger deformations than the gneissic host rocks and complicated fold patterns including sheath folds can be seen. Calc-silicate like lenses are seen in the metabasic xenoliths.

Representative analyses of the main rock types in the Iveland-Gautestad intrusion are given in the Appendix.

The observed trends in variation diagrams (Fig. 5) are typical for low- to medium-K_2O, tholeiitic to calc-alkaline basaltic rock suites.

The ultramafic unit is high in MgO, Ni and Cr, and low in major elements such as K_2O, P_2O_5 and TiO_2 indicating an early stage of fractionation of Mg-rich phases such as olivine and pyroxenes. High Ni and Cr contents support this.

Attempts to determine the tectono-magmatic environment using the mantle normalised hygromagmatophile element diagram of Wood et al. (1979) lead to trends strongly resembling those typical of low-po-

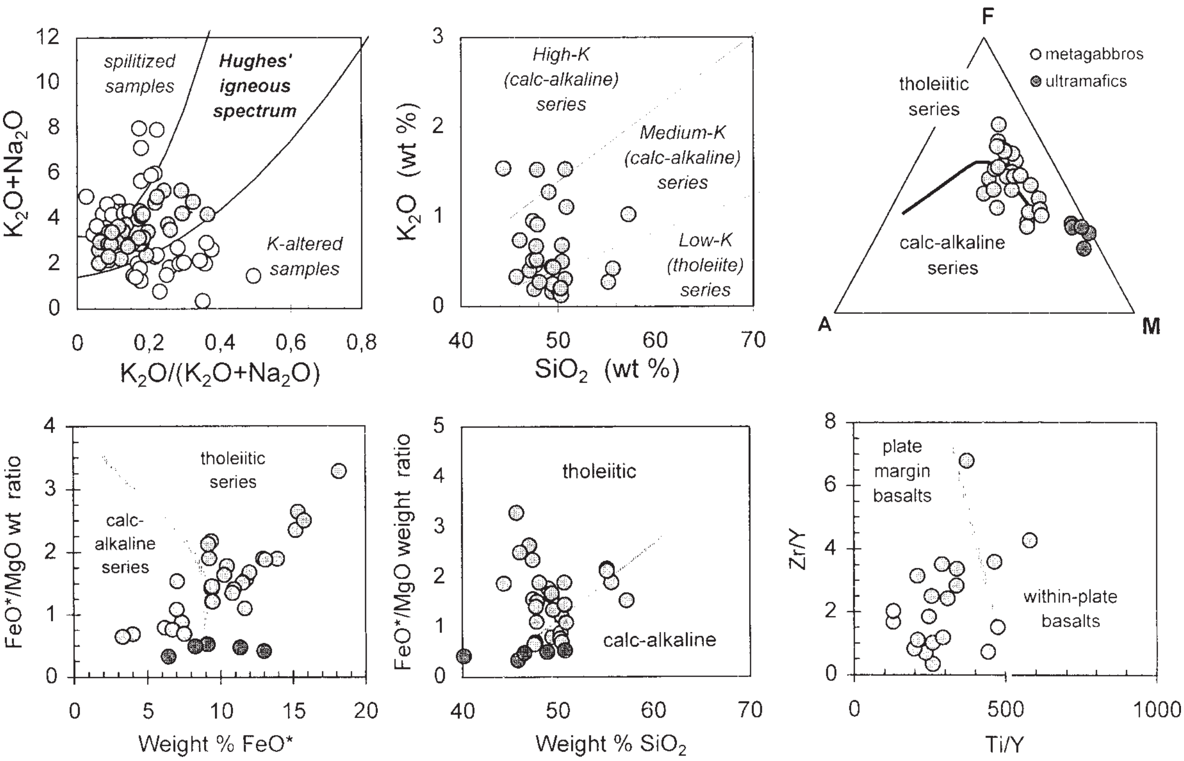


Fig. 5. Selected chemical relations illustrating some basic chemical characteristics of the Iveland-Gautestad metagabbroic complex. The upper left diagram presents the Hughes (1973) screening off of altered samples; only samples within the Hughes' igneous spectrum have been plotted in the other diagrams. Other discimination lines in the diagrams are taken from Miyashiro (1974), Pearce & Gale (1977) and Irvine and Barager (1971).

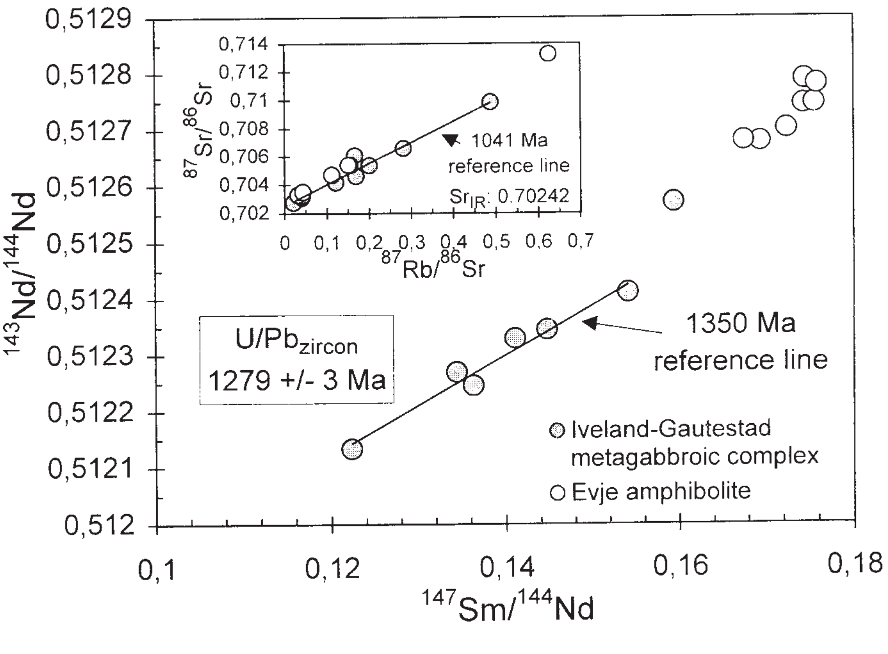


Fig. 6. Sm-Nd and Rb-Sr isotopic characteristics for the Iveland-Gautestad metagabbro and the Evje amphibolite as discussed in the text.

tassium tholeiites from destructive plate margins and the trends in the TiO_2-K_2O-P_2O_5, Ti-Zr-Sr and Ti-Zr-Y diagrams further give a continental margin signature.

Isotope signature and age of the Iveland-Gautestad metagabbro

U/Pb dating on euhedral and unzoned zircons separated from a sample of coarse-grained (pegmatitic) diorite from the southern part of the complex gave an age of 1279±3 Ma, considered to be the emplacement and cooling age of the complex. A lower intercept age of 228 Ma indicates isotope disturbance at a later time.

In addition, eight samples were analysed for Rb/Sr and Sm/Nd isotopes and the results are summarized in Figure 6. The Sm/Nd data do not constrain an age. A 1350 Ma reference line has been added to Figure 6 and represents the best fit to six of the eight samples analysed; however, the scatter in data points indicate that the data do not represent an isochron but more likely reflect assimilation of older crustal material by the basic melt which is plausibly from a depleted mantle source. The Rb/Sr isotopes on the same samples appear to define an 1040 Ma isochron (Figure 6). Accepting the age of 1279 Ma as the emplacement age, the age obtained from the Rb/Sr data may represent a metamorphic (Sveconorwegian) event.

Other occurrences of basic bodies

In addition to the Iveland-Gautestad metagabbroic complex, a number of smaller basic bodies have been discovered and show that basic magmatism was more extensive than earlier recognised. Most of these bodies are rather small but may collectively cover several square km. The smaller bodies are usually fine- to medium-grained and homogeneous. They show clear intrusive features and in places exhibit igneous layering and contain ultramafic units.

The pre-Sveconorwegian Byglandsfjorden supracrustal and infracrustal units

The metabasic units of the metamorphic basement complex are discordantly overlain by rocks of what tentatively has been termed the Byglandsfjorden group. Detailed mapping has shown that a major part of what was previously described as heterogeneous gneisses belonging to the Agder Complex are actually distinguishable pre-Sveconorwegian metasupracrustal units. In the Setesdalen area these include a series of interlayered metavolcanic rocks and metasediments, and a sequence of metamorphosed immature sediments. Together with the volcanics, granitic intrusions are found.

The Byglandsfjorden group

The Byglandsfjorden group is dominated by supracrustal rocks of both volcanic and sedimentary origin. The early volcanism is clearly bimodal and includes metarhyolitic lavas, pyroclastic rocks or volcanic sediments and metabasic tuffs and/or lavas, as well as plutonic (granitic) equivalents, which together constitute the Bygland formation. The metavolcanic sequence contains interlayered metasediments varying in composition from arkoses to quartzites and conglomerates. The amount of metasedimentary layers increases towards the stratigraphic top of the volcanic sequence; on top of the volcanic sequence a metasedimentary unit is seen. Likewise, metavolcanics are found interlayered with the metasedimentary unit near the base of the sedimentary sequence indicating that there is a transitional evolution from the volcanic Bygland formation to the overlying sedimentary units of the Jordalsvatn formation. In the northern part of Setesdalen, the Jordalsvatn formation corresponds to the lowermost part of the Bandak group.

The Bygland formation. The volcanic-dominated Bygland formation consists of an often banded sequence of pink, fine- to medium-grained metarhyolites forming up to m-thick units interlayered with up to dm-thick amphibolites and biotite schists. Between individual layers grey to white, coarse-grained rocks representing different kinds of psammites are seen. Leucocratic veining often parallels the foliation of the metarhyolites but locally discordances are seen.

Within the Bygland formation, metagranites believed to represent intrusive (sub-volcanic ?) analogues to the extrusives occur. One such example is the Syrtveit gneiss (metagranite) described earlier by Pedersen (1981). The Syrtveit gneiss has been dated by the Rb-Sr whole-rock method (11 samples) to 1120 ± 31 Ma with a Sr_{IR} of 0.706 ± .002. This age is considered to reflect the time of emplacement and cooling of the granitic precursor of the Syrtveit gneiss. The Syrtveit gneiss is a foliated and lineated, reddish to greyish, leucocratic, medium- to coarse-grained gneiss of granitic to granodioritic composition, with linear and planar structures defined by mm-thin aggregates of biotite and hornblende. Antiperthite has been observed in several samples. Accessories are titanite, apatite, zircon, allanite and opaque minerals.

Both the acid metavolcanic and metaplutonic rocks are characterised by rather high SiO_2 contents and high FeO^{Total}/MgO ratios (>8) considered characteristic of North American anorogenic granites, e.g. Anderson (1983).

The Jordalsvatn formation. The metasediments of the

Jordalsvatn formation consist mainly of immature coarse arkosic metasediments but more mature (quartzitic) units and conglomeratic units also occur. Some of the units are sufficiently characteristic to be mappable, such as a green spotted quartzite (where the green spots consist of an intergrowth of amphibole, biotite and epidote), orthoquartzites interlayered with amphibolites, a metaarkose and a metaconglomerate.

The psammites are grey, fine-grained, often compositionally laminated (mm-cm scale) and foliated with the foliation parallel to the lamination. Less frequent are biotite schists and ultramafic rocks now present as talc-rich lenses/boudins. Metabasic rocks with a mineral assemblage containing cordierite, anthophyllite, sillimanite and garnet are observed locally. Clasts of quartzite, metagranite and different types of gneisses can be recognised in the metaconglomerates and indicate the presence nearby of an eroded gneissic basement during deposition of the Jordalsvatn formation.

The Jordalsvatn formation in places has clearly discordant contact relationships to the Bygland formation, but mostly it is concordant with a gradation as described above.

In the southern part of the Setesdalen, orthoquartzite units are seen interlayered with amphibolites and metarhyolites and in direct contact with metarhyolite from the Bygland formation. Further to the north, the orthoquartzite changes laterally into more impure feldspathic gneisses, and thins out and is gradually replaced by amphibolites and biotite-schists. The orthoquartzite unit apparently dies out toward the south. This whole sequence seems to be discordantly cut by the granitic gneiss of the Syrtveit type.

Thick layers of mafic rocks (amphibolite and biotite schists) locally occur between the Jordalsvatn and Bygland formations

Representative chemical analyses of the Syrtveit granitic gneiss, metarhyolites and psammites are given in the Appendix.

Sveconorwegian magmatic activity in the Setesdalen area

Following deposition of the Byglandsfjorden group and emplacement of infracrustal granitic rocks, the Setesdalen area was subjected to an event of highly diffentiated and mostly potassic to ultrapotassic magmatism from about 1030 Ma to possibly around 900 Ma. Together this igneous activity constitutes the Setesdalen Igneous Province which falls into two distinctly different periods.

The earliest magmas were emplaced around 1030 Ma as large elongated composite complexes consisting of granodiorite and granite ('feldspar porphyritic' augen gneisses) and different types of diorites (the Evje amphibolite) and ferrodiorites (the Flåt diorites). The later magmas, belonging to the younger part of the province, were emplaced around 970-900 Ma (preferentially in the older end of the interval) as small plutons and accompanying dykes, in dyke systems and as minor bodies. Magma compositions of these are bimodal with one component being granitic and the other ranging from monzodiorite over monzonite to syenite. Four (perhaps five) such bimodal complexes have been identified (see Fig. 2). The associated dykes often exhibit pronounced foliated/lineated fabrics.

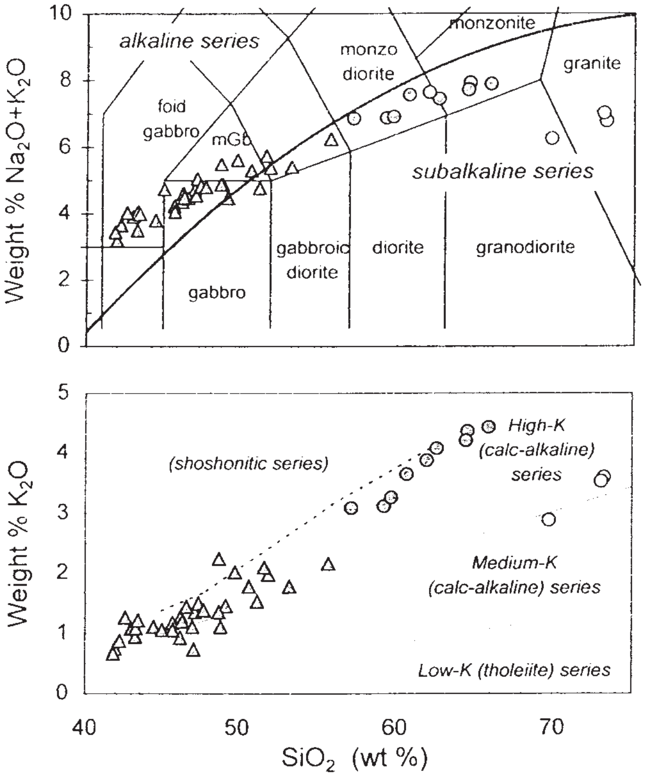
The early Sveconorwegian igneous activity

Representatives of the early Sveconorwegian igneous activity in Setesdalen are a deformed granodiorite (the Fennefoss augen gneiss) and granite (Grimsvatn augen gneiss) and a dioritic phase dominated by highly evolved rocks some of which are described as ferrodiorites (i.e. the Flåt diorite comprising the Mykleås diorite and the so-called ore diorite). The Fennefoss augen gneiss is an approximately 45 km long folded body stretching in a NNE-SSW direction, and the current mapping has demonstrated that it actually consists of two bodies, the Fennefoss augen gneiss and the Grimsvatn augen gneiss (Fig. 2). The Fennefoss augen gneiss is briefly described by Pedersen (1981).

The presence of crenulate to cuspate contacts indicate that the time between emplacement of the 'Fennefoss granodiorite' and the Mykleås diorite was short; the occurrence of hybrids in the contact zone between the two complexes indicates that the granodioritic rocks were not fully consolidated at the time of emplacement of the diorites. This observation is supported by zircon datings of both rock types. U/Pb dating on separated zircons from the Mykleås diorite and the Fennefoss augen gneiss give ages of 1034 (±2) and 1031 (±2) Ma, respectively. The age obtained on the Fennefoss augen gneiss is in close agreement with the previously obtained U/Pb zircon age of 1035 Ma (Bingen 1998) and the 1026 (± 26) Ma Rb-Sr whole-rock age of Pedersen (1981).

The Flåt dioritic rocks. The Mykleås diorite body consists of different types of diorites. The main type is a plagioclase-phyric rock with abundant phenocrysts. The ore diorite, which is more equigranular but does not differ in mineralogy or chemistry from the Mykleås diorite, hosts the ore body of the Flåt nickel mine (Bjørlykke, 1947), at one time the largest nickel mine in Europe. The mining was stopped in 1944. The ore is very heterogeneous and ranges from ore diorite with disseminated sulphides to nearly 100 % sulphide ore. The ore minerals are mainly pyrite, pyrrhotite, pentlandite and chalcopyrite.

Representative chemical relations of the igneous complexes of the early Sveconorwegian activity are shown in Figure 7. The calc-alkaline, high-K charac-



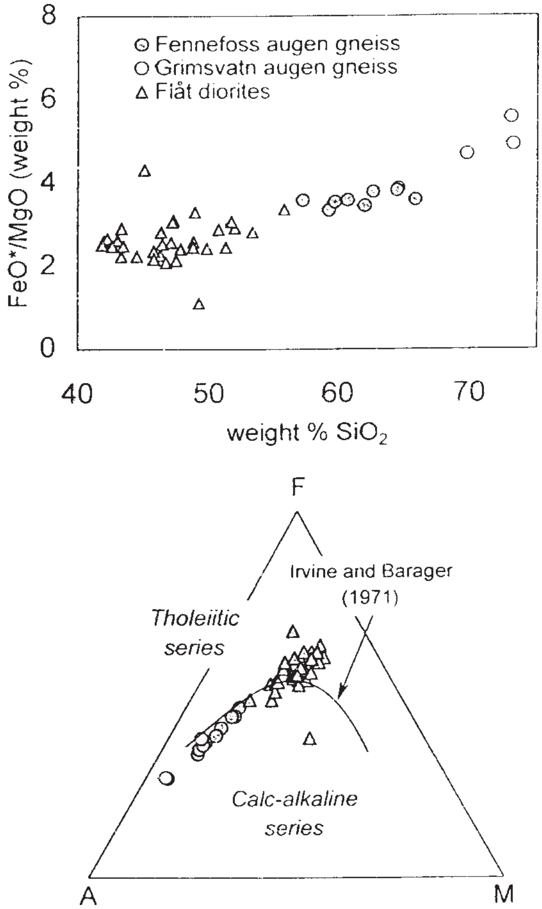


Fig. 7. Selected chemical relations illustrating some basic chemical characteristics of the Fennefoss and Grimsvatn augen gneisses (see Fig. 4) and the Flåt diorites. See text for further discussion.

ters of this early Sveconorwegian activity is clearly seen.

The Evje amphibolite. The Evje amphibolite, named after the village Evje (Fig. 4), was originally described as a gabbro with primary hornblende and called evjeite by Barth (1947). Field evidence shows the Evje amphibolite to be a composite body that mostly occurs as xenoliths within the Fennefoss augen gneiss. Some of these xenoliths themselves contain xenoliths of rocks from the Byglandsfjorden group.

The typical Evje amphibolite is a black fine-grained dioritic rock with thin, a few mm thick veins of pure hornblende. It typically contains plagioclase, hornblende and opaque phases as the main minerals, but occasionally minor amounts of garnet and biotite are present and probably reflect the results of assimilation of older gneisses. At a few localities corona textures after pyroxene can be observed in some of the basic rocks which may belong to the Evje amphibolite.

The Evje amphibolite is clearly distinguished chemically from the Iveland-Gautestad complex by higher contents of Y, Zr and Nb and slightly lower Rb, Sr and Cr. Chemically, it strongly resembles enriched MORB or oceanic island tholeiites; discrimination diagrams of TiO_2-K_2O-P_2O_5, Ti-Zr-Sr and Ti-Zr-Y also give an oceanic signature for the Evje amphibolite (Pedersen 1993).

The late- to post-Sveconorwegian igneous Setesdalen activity

The magmatic character of the plutons emplaced during the younger part of the Setesdalen igneous activity is established from studies of four intrusive complexes, their accompanying dyke systems and single, irregular dykes. Intrusive rocks comparable – and in many cases identical – to those found in the complexes can be observed as smaller dykes and plugs elsewhere in the Setesdalen area indicating that further similar intrusive complexes may occur at depth. Smaller monzonitic dykes have also been observed outside Setesdalen.

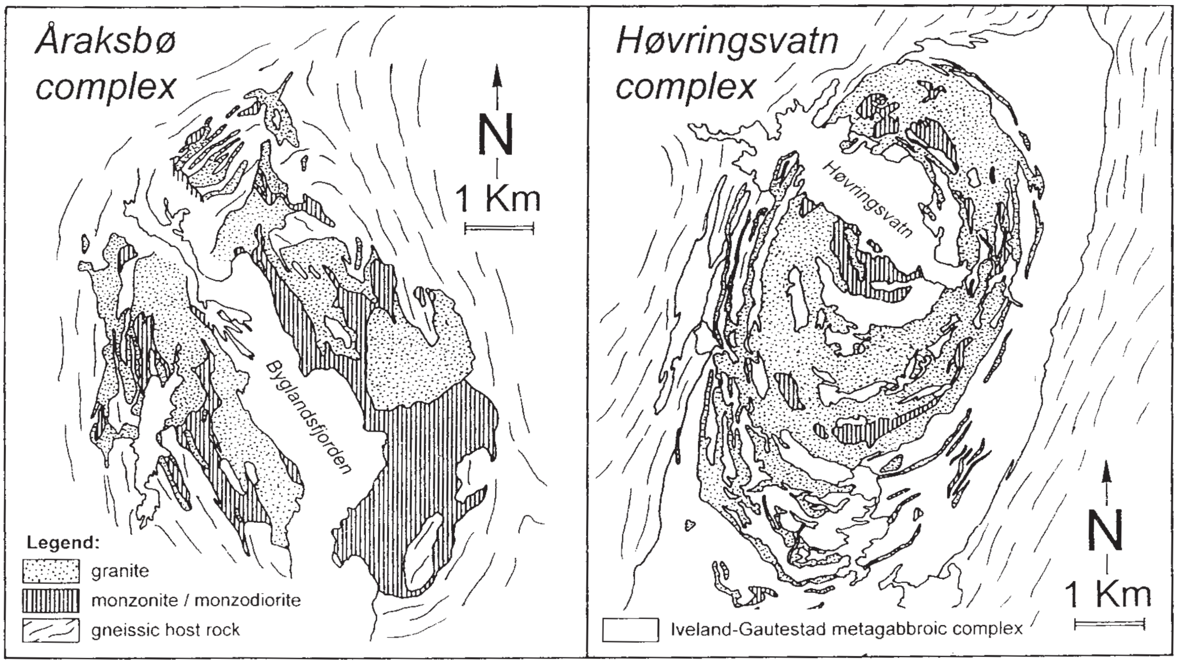


Fig. 8. Geological maps of the Åraksbø and Høvringsvatn bimodal granite-monzonite complexes.

The complexes are up to 35 km^2 large and usually have an elongated or ellipsoidal form. They exhibit different characteristics regarding magmatic evolution but all contain a characteristic monzonitic-monzodioritic phase and a granitic phase which is occasionally porphyric. Associated minor bodies, mostly of monzonitic composition, but also of granitic and mixed bimodal compositions are characteristic. In the smaller bodies and dykes, cuspate and crenulate contacts typical of coexisting basic and felsic melts are often observed and indicate the coexistence of monzodioritic and granitic melts in the evolution of these complexes. In the smaller monzonitic dykes a pronounced fabric is usually observed as well as special structures of deformation. These minor intrusions are treated by Skjernaa & Pedersen (this volume).

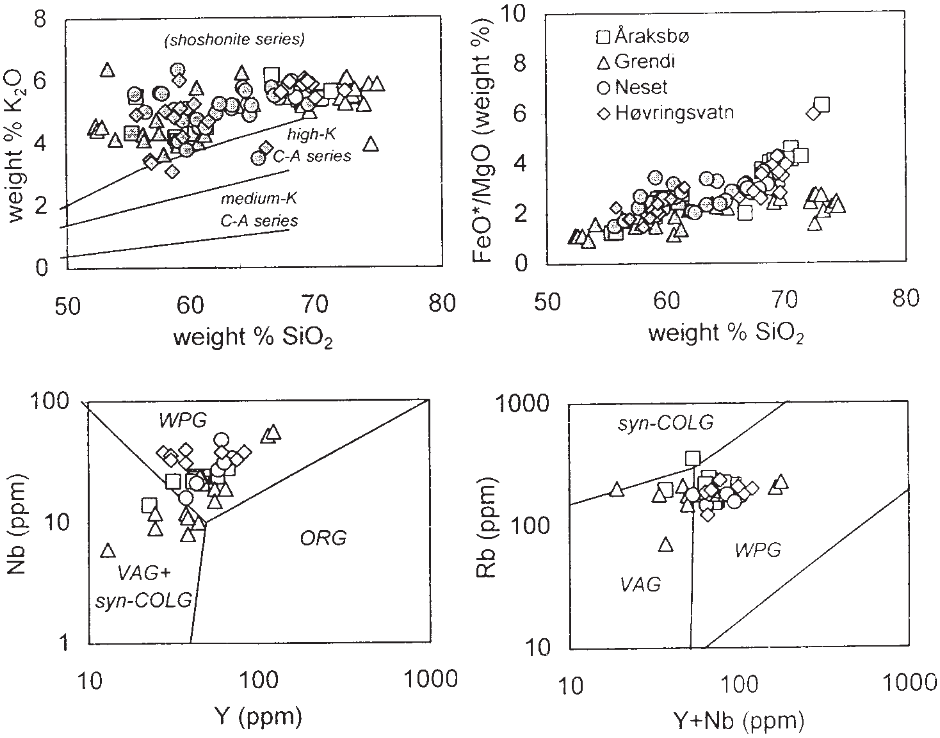
The complexes of the Setesdalen Igneous Province occur aligned in a NNW-SSE direction, even though the individual ellipsoid complexes may have a different elongation. The mapping of the individual complexes has revealed the emplacement of different magmatic pulses of monzonitic and granitic compositions. In one of the complexes (the Neset complex) magmatic layering is a pronounced feature. All complexes except one may have been slightly deformed. In the following the complexes will be briefly treated. Geological maps illustrating the form of observed structures are shown in Figure 8 for two of the complexes, the northernmost Åraksbø complex and the Høvringsvatn complex emplaced in the northernmost part of the Iveland-Gautestad metagabbroic complex.

Representative chemical relations of the four igneous complexes of the late- to post-Sveconorwegian activity are shown in Figure 9. A high-K to shoshonitic character for both monzonites and granites and a within-plate granite setting is clearly seen.

The Neset intrusion. The Neset intrusion (N in Fig. 2) is elliptical with a NW-SE orientation of the longest axis; it developed as a ring intrusion. The intrusion seems to be cut by the Grendi Complex (see below). Near the northern contact small scale igneous layering with alternating monzonitic and granitic layers is found. The monzonitic layers are of a dark grey medium-grained equigranular type and are a few cm thick. Often the transition to granite is abrupt, but in other cases a small transition zone with phenocryst-bearing monzonite is developed. Some massive sheets of a coarse-grained granite crosscut the fine layering.The granite which alternates with the monzonite is of a red medium-grained type.

Some hundred meters south of the northern contact the type of layering changes and the layers become several meters, up to around 10 meters, thick. All layers start with a dark medium-grained equigranular monzonite and, towards the centre of the intrusion, K-feldspar phenocrysts (and in some cases phenocrysts consisting of antiperthitic plagioclase) become increasingly abundant until a red granitic rock with only few dark minerals takes over. In many of the layers the evolution stops before ‘the granitic end member’. Crosscutting the layering are medium- to coarse-

Fig. 9. Selected chemical relations illustrating some basic chemical characteristics and the possible tectonic setting of the four bimodal granite-monzonite complexes described in the text. Empty symbols represent granites; filled symbols monzonites and monzodiorites. See text for further discussion.



grained granitic bodies ('dykes') and thin monzonitic dykes, most probably cone sheets.

Most of the rocks in the intrusion have a contact-parallel fabric. A large number of thin granitic veins cut the fabric especially in the monzonitic and the phenocryst-bearing parts.

In the western part of the intrusion the layered series form only part of the exposed rocks. The ring structure here is defined by the presence of cone sheets and individual rock types which fit into the ring structure as screens. Further to the west the ring structures are still defined by thin monzonitic cone sheets but it is significant that different rocks of true granitic compositions also form ring structures. Outside the intrusion small bodies and/or dykes of monzonite and granite are present often as irregular dyke-shaped bodies.

A Rb-Sr whole rock age (based on 6 samples) for the emplacement of the monzonites in the complex of 969 ± 18 Ma (MSWD: 1.59) has been obtained (Pedersen & Konnerup-Madsen 1994) with a Sr_{IR} of 0,70381 (± 0.00006).

The Høvringsvatn complex. The Høvringsvatn complex (in Fig. 2 and Fig. 8) is an elliptical ring complex consisting of a monzonitic and a granitic component. A unique feature of the complex is the development of well-defined cone sheet systems as well as a bell jar system indicating its emplacement at a high level in the crust (Anderson 1936). The complex is elongated approximately north-south. The present level of erosion is close to the roof as indicated by the many xenoliths and roof pendants.

The monzonites are of a dark grey, medium-grained type, and a light grey type which often forms hybrids in contact with granite. Both rock types are homogeneous and generally without any preferred orientation of the minerals. The granite in the central part is medium- to coarse-grained and contains phenocrysts of alkali feldspar. The phenocrysts usually become larger towards the centre of the intrusion and are absent close to contact. In addition, a fine-grained aphyric granite type is present in the south-eastern part of the complex and in places within the coarser type. The granite usually has a weakly developed fabric of parallel arranged biotite or flattened aggregates of biotite and hornblende. This fabric becomes more and more pronounced towards the marginal parts of the intrusion, and in the outer cone sheet system (see below) a streaky rock is seen.

Cone sheets are present in three major systems. The inner cone sheet system consists of different types of fine grained monzonite similar to those seen as dykes and minor bodies in other places within the intrusion. The intermediate and outer cone sheet systems consist of several individual sheets of both granitic and monzonitic composition. In places, between 10–20 or even more individual sheets lying close to each other can be counted. Also sheets of compositions intermediate between granite and monzonite are found. The monzonitic sheets are mostly of a spotted type (biotite or biotite + amphibole aggregates form the spots) with sheets, veins and marginal veins of granitic aplite material.

The cone sheet systems are the dominant ring forming structures. However, other dyke systems include a horizontal system interpreted as a bell jar feature, and a radial system with only a few dykes developed. In addition to these well-defined dyke systems, a large number of irregular dykes and smaller bodies of monzonitic composition occur throughout the intrusion.

Within the complex, a large number of pegmatites are found especially in the south-eastern part. The pegmatites belong to the Iveland-Evje pegmatite field (see below).

Rb-Sr whole-rock ages of 945 ± 53 Ma (Sr_{IR} : 0,7041 ± 0.0007) ; MSWD: 0.88) and 900 ± 53 Ma (Sr_{IR} : 0,7041 ± 0.0002; MSWD: 0.78), respectively, for the emplacement of the granites and monzonitic dykes in the complex have been obtained (Pedersen 1981, Pedersen & Konnerup-Madsen 1994).

The Grendi complex. The Grendi complex (G; Fig. 2), about 15 km^2 in size and elongated in an east-west direction, has been interpreted as a giant south dipping sheet. The Grendi complex is younger than the Neset Complex.

A dark grey medium-grained monzonite is the dominant rock although variations are seen. The dominant monzonite shows gradual transitions to more felsic rock types which sometimes grade into coarse-grained granitic rocks.

The complex consists of a lower part of medium grained monzonite and an upper part dominated by alternating fine-grained granitic and monzonitic rocks. Also within the lower series some south dipping sheets of fine-grained granitic and monzonitic compositions are observed which intruded lit-par-lit into the monzonites. A foliation in all sheets parallelling the contacts is thought to be primary and formed during consolidation.

In the western part an evolution from the dark grey medium-grained monzonite through a light alkali feldspar-porphyric monzonite to a light porphyric granite is observed. To the east a similar evolution is not present. In addition, outside the intrusion abundant small monzonitic and granitic dykes are seen. The term monzonite includes rocks ranging from quartz monzonite to monzodiorite, quartz monzodiorite and syenite.

Rb-Sr whole-rock ages for the emplacement of the medium/coarse-grained granites and the fine-grained granites in the complex of 973 ± 74 Ma (Sr_{IR}: 0.7037 ± 0.0003; MSWD: 2.37) and 1004 ± 200 Ma (Sr_{IR}: 0.7036 ± 0.0006; MSWD: 0.69), respectively, have been obtained (Rasmussen 1993). Field relationships similarly suggest that only the coarser-grained granites form part of the complex whereas the fine-grained granites may be representatives of melts generated during the Sveconorwegian orogeny.

The Åraksbø complex. The Åraksbø complex (A in Fig. 2 and Fig. 8) is divided into two parts by Lake Byglandsfjorden (Fig. 8) and covers an area of 35 km^2. It contains abundant xenoliths of psammites of the Jordalsvatn formation. To the north the complex comprises a dark grey quartz monzonite and red granitic rocks which are generally porphyric. This composite part of the complex includes several intrusive pulses of granite and monzonite with irregular contact relations, and between the monzonite and the granite a transition zone of several hundred meters with hybrid rocks is observed.

The monzonitic rocks comprise several types. The main type is a homogeneous dark grey, medium grained rock without phenocrysts but locally a light, finer-grained massive type is seen. The hybrid zone between the two principal rock types varies greatly in appearance, from a complex (mechanical) mixture where it is possible to identify features from both end members to monzonitic rocks which nevertheless contain varying amounts of often rounded alkali feldspar phenocrysts/xenocrysts. These hybrid rocks cover considerable areas of the intrusion and also occur as dykes.

Towards the southeast, a body of fine-grained monzonite crosscuts the composite part of the complex resulting in intricate structures especially between the porphyric granite and the fine-grained younger monzonite. The complex here is clearly deformed apparently exhibiting fold axes parallel to the regional axes in the supracrustal host rocks.

Two fundamental intrusive features can be noted: some major NNW-SSE trending dykes up to 50–100 m wide of porphyric granite which can be followed for several hundreds of meters, and different types of monzonitic dykes some of which apparently form cone sheets. These dykes can only be followed over short distances. Other dykes exhibit a pronounced radial pattern. The dykes comprise both medium-grained dark monzonite and a fine-grained spotted monzonite similar to that seen in the other complexes. The cone sheet systems are cut by subhorizontal dykes of monzonites with deformation structures similar to the structures from the subhorizontal dykes described by Skjernaa & Pedersen (this volume).

A Rb-Sr whole rock age for the emplacement of the porphyritic granites and the monzonites in the complex of 971 ± 16 Ma (MSWD: 2.54) with a Sr_{IR} value of 0.7036 (± 0.0002) has been obtained (Pedersen & Konnerup-Madsen 1994).

The Rustfjellet granite. Northwest of the Åraksbø complex, another complex, the Rustfjellet granite (R; Fig. 2), which may be comparable to the Åraksbø complex, has been observed. Around the complex, monzonitic dykes are observed but the intrusion has not been investigated in any detail and will not be treated further in this paper.

The Iveland-Evje REE pegmatite field

The Setesdalen area is well known for the Iveland-Evje REE pegmatites which have been described in detail by Andersen (1931), Barth (1931) and Bjørlykke (1934, 1937). In addition to their REE- and U/Th-bearing minerals, the pegmatites have been quarried primarily for quartz, micas and feldspars.

The pegmatites occur in an approximately 5 km wide and about 30 km long N-S trending belt extending southward from the Høvringsvatn complex. Most pegmatites are hosted by the Iveland-Gautestad metagabbroic complex and appear to have been emplaced along pre-existing zones of weakness determined by the previous structural history of the Iveland-Gautestad metagabbroic complex and the emplacement of the Høvringsvatn complex. Both steep N-S and E-W striking as well as sub-horizontal orientations are seen and occasionally mushroom-shaped pegmatite bodies are developed (Fougt 1993) due to a high level of emplacement (Brisbin 1986). Most of the pegmatites consist of an outer wall zone composed of a coarse-grained graphic intergrowth of quartz and alkali feldspar, several intermediate zones with heterogeneous textural developments, and an inner quartz core with blocks of alkalifeldspar and euhedral meter-sized alkalifeldspar crystals.

The mineralogy and the peraluminous bulk composition of the Iveland-Evje pegmatites is typical of the mixed-type REE pegmatites (Cerný 1991), for which an origin by partial melting of lower crustal lithologies is often favoured. No regional distribution of pegmatite minerals is seen.

In earlier descriptions it has been inferred that the pegmatitic activity marked the terminal stages of the late- to post-Sveconorwegian igneous activity in Setesdalen and was closely related to the Høvringsvatn complex. However, a Rb-Sr mineral age of 845 ± 12 Ma (Sr_{IR}: 0,70628 ± 0,00013; MSWD: 1,46; 9 samples) does not support such a relationship (Pedersen, unpublished data; Stockmarr 1994). In addition, a preliminary age obtained by step-wise leaching of garnets from another of the pegmatites indicated an age of about 800 Ma (R. Frei, pers. comm. 1998).

Besides the Iveland-Evje pegmatite field, important pegmatite areas are also found in the gneissic complex outside the Iveland-Gautestad metagabbro body.

Dolerite dykes

Emplacement of a minor swarm of generally only meter-thick basaltic dykes trending E-W occurred in the northernmost part of the area (Fig. 2) and represents the last sign of genuine magmatic activity in the Setesdalen region. These dykes are tholeiitic and thus similar in composition to those described from the Rogaland area in SW-Norway (Venhuis & Barton, 1986) where an age of about 835 Ma has been suggested (Maijer & Verschure 1998). However, an age of 616 ± 3 Ma was obtained by Bingen et al. (1998). A chemical analysis of one of these dykes is included in the Appendix.

Structural considerations: the possible significance of the Mandal-Ustaoset lineament

The importance of the Mandal-Ustaoset lineament for the geological evolution of the Setesdalen area has not been touched upon in this paper. However, detailed geological mapping of various regions previously thought to cover parts of the suggested shear zone, and preliminary structural analyses do not support its presence at the present level of erosion. Thus, the direct influence of a shear zone on the geological evolution of southern Norway – as indicated by e.g. Sigmond (1985) and Sigmond et al. (1997) – will be restricted to periods before the deposition of the Byglandsfjorden group supracrustals, that is before about 1120 Ma. However, its existence as a deep-going zone of crustal weakness may have been influential for emplacement of the later magmas and pegmatitic melts.

Concluding remarks and summary

The geological studies summarized in this paper clearly indicate a long and complex mid- to late-Proterozoic crustal evolution in the Setesdalen area, with both an important Sveconorwegian history as well as clear indications of older orogenies and intermittant tectonically quiet periods. Based on our present knowledge the authors suggest the following framework for the evolution of the Setesdalen area and possibly for a more general model for the evolution of southern Norway:

1. *Formation of a pre-Sveconorwegian basement*. This consists of heterogeneous gneiss intruded by the younger calc-alkaline granitoids (1350–1300 Ma) and by the Iveland-Gautestad gabbroic complex (1279) Ma). The geochemical characteristics of both of these suites of rocks suggest a continental margin setting and the possible initiation of a stage of subduction around 1350–1300 Ma followed by regional metamorphism.
2. *Uplift, erosion and peneplanization, and anorogenic conditions*. During this period, rifting occurred allowing bimodal volcanism and later deposition of clastic sediments (the Byglandsfjorden group). The ages indicated for associated infracrustal granites constrain this event to 1150–1100 Ma. Diorites, e.g. the Evje amphibolite, and gab-

bros may possibly have been emplaced at this stage too.

3. Subsequently, the area was again subjected to *granite emplacement, regional deformation and metamorphism*. Based on studies elsewhere in SW Norway, where more distinctly calc-alkaline granitic melts occur (Bingen & van Bremen 1998), Setesdalen is at a larger distance from the suggested site of subduction, implying a probable east-dipping position off the present west coast of South Norway. Ages of about 1031 Ma for the deformed Fennefoss augen gneiss, the Rb-Sr age of metamorphic resetting of about 1040 Ma for the Iveland-Gautestad metagabbroic complex, and ages obtained further west in south Norway indicate an age of 1060-1040 Ma for the initiation of the Sveconorwegian orogeny.
4. *The end of the Sveconorwegian orogeny* is marked by emplacement of a series of K-rich igneous, bimodal complexes with a clear within-plate signature in Setesdalen. The ages for their emplacement around 980–975 Ma, their largely undeformed nature, and their high crustal level define an intermittent stage of the post-Sveconorwegian uplift and peneplanization of the area.
5. *Post-Sveconorwegian events*. Finally, emplacement of the Iveland-Evje REE pegmatites and E-W trending tholeiitic dykes occurred around 835–800 Ma and possibly as late as around 620 Ma, respectively; they represent a tensional stage possibly reflecting one or more attempted early break-up of the continent. The presence of basic melts may have been influential in generating higher heat flows at this stage (Hansen et al. 1996) and provoking the formation of the crustally derived REE-rich pegmatitic melts.
6. Following this final igneous activity in Setesdalen, continued uplift and peneplanization occurred (e.g. Hansen et al. 1996).

Dansk Sammendrag

Den geologiske udvikling i Setesdalen i Sydnorge repræsenterer mindst 500 millioner års udvikling, fra tidligere end ca. 1300 Må til ca. 800 Må før nu, der belyser væsentlige aspekter af den Proterozoiske udvikling i Sydskandinavien.

De skorpedannende processer i Setesdalen domineres af præ-Svekonorvegiske suprakrustaler (umodne klastiske sedimenter og bimodale vulkanitter) med en formodet aflejringsalder på 1150–1100 Må, samt af emplaceringen af spredte infrakrustale granitter og granodioritter. De suprakrustale bjergarter aflejredes på et allerede tidligere deformeret og metamorfoseret nederoderet grundfjeld, der er ihvertfald delvis ældre end 1300 Må.

Under den senere Svekonorvegiske orogenese, med øvre grønskifer til mellem amfibolit facies høj-temperatur metamorfose og hoveddeformationsfaserne i perioden 1060-970 Må, prægedes den magmatiske aktivitet af K-rige bjergarter med høje indhold af P, Ti, La, Sr, Zr, de lette sjældne jordsartselementer, og Ba. Emplacering af de sjældne jordartselementholdige pegmatitter som området er kendt for, er yngre og ikke genetisk tilknyttet denne magmatiske aktivitet. Setesdalens magmatiske aktivitet sluttede omkring 830 Må før nu med dannelsen af Ø-V strygende tholeiitiske doleritgange.

Resultaterne viser, at det Sydnorske grundfjeldsområde også vest for Oslo feltet har en lang og vigtig præ-Svekonorvegisk historie.

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References

Åhäll, K.-I. & Connelly, J. 1998: Intermittent 1.53-1.13 Ga magmatism in western Baltica; age constraints and correlations with a postulated supercontinent. Precambrian Research 92, 1–20.

Andersen, O. 1931: Feltspat II. Norges Geologiske Undersøkelse 128b, 107pp.

Anderson, E.M. 1936: The dynamics of the formation of cone-sheets, ring-dykes and cauldron subsidence. Proceedings of the Royal Society of Edingburgh 56, 128–157.

Anderson, J.L. 1983: Proterozoic anorogenic granite plutonism of North America. Geological Society of America Memoir 161, 133–154.

Barth, T.F.W. 1931: Feltspat III. Norges Geologiske Undersøkelse 128b, 107pp.

Barth, T.F.W. 1947: The nickeliferous Iveland-Evje amphibolite and its relation. Norges Geologiske Undersøkelse 168a, 71 pp.

Bertelsen, S. 1984: A geological description of the basic rocks in the southern part of the Iveland-Gautestad complex (south Norway). Unpublished M.Sc. Thesis, University of Copenhagen, 231 pp. (in Danish).

Bingen B. 1998: Geochemistry of Sveconorwegian augen gneisses from SW Norway at the amphibolite-granulite facies transition. Norsk Geologisk Tidsskrift 69, 177–189.

Bingen, B. & van Bremen, O. 1998: Tectonic regimes and terrane boundaries in the high-grade Sveconorwegian belt of SW Norway, inferred from U-Pb zircon geochronology and geochemical signature of augen gneiss

suites. Journal of the Geological Society, London, 155, 143–154.
Bingen, B., Boven, A., Punzalan, L., Wijbrans, J.R. & Demaiffe, D. 1998: Hornblende $^{40}Ar/^{39}Ar$ geochronology across terrane boundaries in the Sveconorwegian Province of S. Norway. Precambrian Research 90, 159–185.
Bingen, B., Birkeland, A., Nordgulen, Ø., Sigmond, E. & Whitehouse, M. 1999: Detrital zircon ages from sediments in Hardangervidda, Telemark and Kongsberg, S Norway, and implications for Proterozoic crustal boulding in the Sveconorwegian Province. EUG 10, Abstract Volume, 126.
Bingen, B.: Demaiffe, D. & van-Breemen, O. 1998: The 616 Ma old Egersund basaltic dike swarm, SW Norway, and late Neoproterozoic opening of the Iapetus Ocean. Journal of Geology 106, 565–574
Birkeland, A., Sigmond, E.M.O., Whitehouse, M.J. & Vestin, J. 1997: From Archean to Proterozoic on Hardangervidda, South Norway. Norges geologiske Undersøkelse Bulletin 433, 4–5.
Bjørlykke, H. 1934: The mineral paragenesis and classification of the granite pegmatites of Iveland, Setesdal, southern Norway. Norsk Geologisk Tidsskrift 14, 211–311.
Bjørlykke, H. 1937: The granite pegmatites of southern Norway. The American Mineralogist 22, 241–255.
Bjørlykke, H. 1947: Flaat nickel. Norges Geologiske Undersøkelse 168b, 39 pp.
Brickwood, J. D. 1986: The geology and mineralogy of some Fe-Cu-Ni sulphide deposits in the Bamble area, Norway. Norsk Geologisk Tidsskrift 66, 189–208.
Brisbin, W.C. 1986: Mechanisms of pegmatite intrusion. American Mineralogist 71, 644–651.
Cerný, P. 1991: Rare-element granitic pegmatites. Part II. Regional to global environments and petrogenesis. Geoscience Canada 18, 68–81.
Dahlgren, S.H. 1996: An introduction to the geology of the Telemark crustal block. A Guide to the SNF Excursion, 9pp.
Dahlgren, S.H., Heaman, L. & Krogh, T. 1990: Geological evolution and U-Pb geochronology of the Proterozoic central Telemark area, Norway. Geolognytt 17, Oslo University, 38–39.
Dons, J.A. 1960: The stratigraphy of supracrustal rocks, granitization and tectonics in the Precambrian Telemark area, southern Norway. International Geological Congress, XXI Session, Norden. Guidebook to Excursion A10, Norges geologiske Undersøkelse 212h, 30pp.
Falkum, T. 1982: Geologisk kart over Norge, berggrundskart Mandal 1:250,000 Norges Geologiske Undersøkelse.
Falkum, T. 1985: Geotectonic evolution of southern Scandinavia in light of a late-Precambrian plate collision. In Tobi, A.C. & Touret, J.L.R. (eds): The Deep Proterozoic Crust in the North Atlantic Provinces, NATO Advanced Science Institutes Series, Series C, 158, 309–322. Reidel, Dordrecht.
Falkum, T. 1998: The Sveconorwegian magmatic and tectonometamorphic evolution of the high grade Proterozoic Flekkefjord complex, south Norway. Norges geologiske undersøkelse, Bulletin 434, 5–33.
Falkum, T. & Petersen, J.S. 1980: The Sveconorwegian Orogenic Belt, a case of Late-Proterozoic plate-collision. Geol. Rundshau 69, 622–647.
Fougt, H. 1993: A geological study of the pegmatites in the area around Einerkilen-Ånestølkilen, south Norway (in Danish). M.Sc. Thesis, Copenhagen University, 88 pp.
Gaál, G. & Gorbatschev, R. 1987: An outline of the Precambrian evolution of the Baltic shield. Precambrian Research 35, 15–52.
Graversen, O. & Pedersen, S. 1999: Timing of Gothian structural evolution in SE Norway: A Rb-Sr whole-rock age study. Norsk Geologisk Tidsskrift 79, 47–56.
Hageskov, B. 1980: The Sveconorwegian structures of the Norwegian part of the Kongsberg-Bamble-Østfold segment. Geologiske Föreningen Stockholms Förhandlinger 102/2, pp. 150–155.
Hageskov, B. 1997: Geochemistry and tectonic significance of late Gothian mafic dikes in the Østfold-Marstrand belt of S.E. Norway and W. Sweden. Precambrian Research 82, 287–309.
Hansen, K., Pedersen, S., Fougt, H. & Stockmarr, P. 1996: Post-Sveconorwegian exhumation and cooling history of the Evje area, southern Setesdal, Central South Norway. Norges geologiske undersøkelse Bulletin 431, 49–58.
Hughes, C.J. 1973: Spilites, keratophyres and the igneous spectrum. Geological Magazine 109, 513–527.
Irvine, T.N. & Barager, W.R.A. 1971: A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences 8, 523–548.
Knudsen, T.-L., Andersen, T., Whitehouse, M.J. & Vestin, J. 1997: Detrital zircon ages from Southern Norway – implications for the Proterozoic evolution of the southwestern Baltic Shield. Contributions to Mineralogy and Petrology 130, 47–58.
Kullerud, L. & Dahlgren, S.H. 1993: Sm-Nd geochronology of Sveconorwegian granulite facies mineral assemblages in the Bamble shear belt, south Norway. Precambrian Research 64, 389–402.
Maijer, C. & Verschure, R.H. 1998: Petrology and isotope geology of the Hunnedalen monzonoritic dyke swarm, SW Norway: a possible late expression of Egersund anorthosite magmatism. Norges geologiske undersøkelse Bulletin 434, 83–107.
Miyashiro, A. 1974: Volcanic rock series in island arcs and active continental margins. American Journal of Science 274, 321–355.
Pearce, J.A. & Gale, G.H. 1977: Identification of ore-deposition environment from trace element geochemistry of associated igneous host rocks. Geological Society Special Publication 7, 14–24.
Pearce, J.A., Harris, N.B.W. & Tindle, A.G. 1984: Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology 25, 956–983.
Pedersen, M. 1993: A geological study of the Flåt complex, Aust-Agder, Norway. M.Sc. Thesis, Copenhagen University, 128pp. (in Danish).
Pedersen, S. 1975: Intrusive rocks of the northern Iveland-Evje area, Aust-Agder. Norges geologiske undersøkelse 322, 1–11.
Pedersen, S. 1981: Rb-Sr age determinations of Late Proterozoic granitoids from the Evje area, south Norway. Bulletin of the Geological Society of Denmark 29, 129–143.
Pedersen, S. 1985. Geologisk kart over Norge, berggrundskart Evje 1:50,000. Norges Geologiske Undersøkelse.

Pedersen, S. & Konnerup-Madsen, J. 1994: Geology of the Setesdal Region. Excursion Guide to the SNF Excursion, August 1994, Copenhagen University, 55 pp.
Rasmussen, T. 1993: Geochemistry and petrogenesis of the Grendi complex – a Late Proterozoic intrusion in the Setesdalen Province, South Norway. Unpublished M.Sc. Thesis (Copenmhagen University), 133 pp. (in Danish).
Romer, R.L. & Smeds, S.-A. 1996: U-Pb columbite ages of pegmatites from Sveconorwegian terranes in southwestern Sweden. Precambrian Research 76, 15–30.
Rønholt, K.P. 1990: A geochemical and mineralogical description of metagabbros from the Åvesland area, the Iveland-Gautestad complex, south Norway. M.Sc. Thesis, Copenhagen University, 137 pp. (in Danish).
Sigmond, E.M.O. 1975: Geologisk kart over Norge, berggrunnskart Sauda 1:250,000. Norges Geologiske Undersøkelse.
Sigmond, E.M.O. 1978: Beskrivelse til det berggrunnsgeologiske kartbladet Sauda 1:250,000. Norges Geologiske Undersøkelse, Skrifter 23, 94pp.
Sigmond, E.M.O. 1985: The Mandal-Ustaoset line, a newly discovered major fault zone in south Norway. In A.C. Tobi & J.L.R. Touret (eds): The Deep Proterozoic Crust in the North Atlantic Provinces, NATO Advanced Science Institutes Series, Series C 158, 323–331. Reidel, Dordrecht.
Skjernaa, L. & Pedersen, S., 1999. Late Sveconorwegian monzonitic dykes in the Setesdalen area of Central South Norway: Examples of structures in dykes and their indications of accumulated strain. Bulletin of the Geological Society of Denmark 46, ***??–??***.
Sigmond, E.M.O., Gjelle, S. & Solli, A 1997: The Rjukan Proterozoic rift basin, its basement and cover, volcanic and sedimentary infill, and associated intrusions. Norges geologiske undersøkelse. Bulletin 433, 6–7.
Smithson, S.B. 1963: Granite studies: I. A gravity investigation of two Precambrian granites in South Norway. Norges Geologiske Undersøkelse 214b, 53–140.
Starmer, I.C. 1993: The Sveconorwegian Orogeny in southern Norway, relative to deep crustal structures and events in the North Atlantic Proterozoic Supercontinent. Norsk Geologisk Tidsskrift 73, pp. 109–132.
Stockmarr, P. 1994: A description of the pegmatites near Åvesland, Evje, south Norway. M.Sc. Thesis, Copenhagen University, 133 pp. (in Danish).
Teisseyre, J.H. 1970: Geological investigations in the Byglandsfjorden-Gyvatn area. Norges Geologiske Undersøkelse 266, 206–229.
Venhuis, G.J. & Barton, M. 1986: Major element chemistry of Precambrian dolerite dykes of tholeiitic composition from Rogaland/Vest Agder, SW Norway. Norsk Geologisk Tidsskrift 66, 277–294.
Wood, D.A., Joron, J.L. & Treuil, M. 1979: A reappraisel of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings. Earth and Planetary Science Letters 45, 326–336.

x Representative chemical compositions of the main rock types from the Setesdal region, south Norway

	Basement gneisses		Iveland-Gautestad gabbroic complex						Byglandsfjord Group			
	108147	108170	KR44549	108184	KR44842	108137	34010	SP25190	99191	51483	19722	44386
	Bio-hbl gneiss	Opx-cpx gneiss	Ultramafic unit	Prx metadiorit	Banded metagabbro	Metatonalit	Slетthei augen gneiss	Evje amphibolite	Metasediment Reiårsvatn	Syrtveit graniic gneiss	Bygland Metarhyolite	Hovvatn Metarhyolite
SiO_2	61,82	65,61	45,81	50,73	55,67	64,30	72,75	46,43	77,81	72,41	74,54	75,47
TiO_2	0,51	0,82	0,15	1,30	0,90	1,12	0,38	2,77	1,08	0,38	0,19	0,12
Al_2O_3	17,63	14,86	11,66	15,22	15,37	12,94	13,38	16,48	8,91	12,95	12,75	13,05
Fe_2O_3	1,49	2,30	3,07	2,83	3,17	5,32	0,78	5,93	2,27	1,05	0,55	0,65
FeO	3,32	3,99	3,71	10,42	6,42	5,35	2,18	7,88	1,56	2,51	1,63	0,59
MnO	0,09	0,12	0,11	0,20	0,19	0,19	0,04	0,14	0,04	0,06	0,03	0,03
MgO	2,45	1,79	19,82	6,87	4,90	0,97	0,61	5,87	1,22	0,35	0,10	0,14
CaO	6,12	5,32	10,78	8,44	8,45	3,98	1,88	9,88	0,94	1,54	0,77	1,04
Na_2O	4,87	3,79	1,23	3,09	3,21	3,75	3,19	3,04	1,73	3,71	3,51	3,87
K_2O	0,52	0,30	0,23	0,30	0,42	0,40	3,97	0,33	3,31	4,05	5,40	4,56
P_2O_5	0,15	0,26	0,04	0,18	0,27	0,27	0,10	0,28	0,13	0,09	0,02	0,04
LOI	0,67	0,86	3,02	0,72	1,10	0,93	0,47	1,17	0,88	0,40	0,24	0,23
Total	99,62	100,01	99,63	100,31	100,07	99,52	99,74	100,20	99,86	99,51	99,73	99,78
Rb	3,2	3	4	2	20	7	97	2	119,0	152	166	275
Ba	229	172	58	133	84	320	929	145	512	668	643	766
Pb	4	4	6	3	9	5			-			
Sr	441	377	94	249	310	343	176	281	73,0	124	66	194
La	11	10	2	12	17	21	36		-		84	52
Ce	23	24	<2	32	17	46			62			
Nd	12	16	2	22	15	27			-			
Y	9	17	1	37	27	42		46	2			
Th	-		3	0	<1	0			-			
Zr	89	83	10	116	22	258	247	215	430	434	349	182
Nb	4,2	4	2	5	5	5		25	-			
Zn	62	88	51	145	89	161			46			
Cu	19	66	2	9	58	110		45	7			
Co	73	124	64	104	59	92		55	-			
Ni	16	7	424	49	36	12		88	8			
Sc	13	25	29	52	38	33			-			
V	99	89	75	326	224	28		295	81			
Cr	24	11	1395	235	93	25		92	41			
Ga	18	17	9	22	20	26			-			

	Sveconorwegian augen gneisses				Flåt diorites		Åraksbø complex				Neset complex	
	99157	22091	99156	44322	Av (n=5)	98391B	68572	68613	68594	68556	45873	
	Fennefoss augen gneiss	Fennefoss augen gneiss	Grimsdalsvatn augen gneiss	Åsland diorite	Mykleås diorite	Ore diorite	Porphyritic granite	Fine-grained granite	Coarse-grained monzonite	fine-grained monzonite dyke	Porphyritic monzonite	
2	60,53	65,90	73,24	49,67	46,66	46,68	69,11	71,42	59,85	59,28	66,65	SiO
2	1,53	0,95	0,35	2,50	3,55	2,50	0,55	0,41	1,45	1,54	0,79	TiO
)$_3$	14,49	13,98	13,32	15,47	14,29	16,62	14,17	13,48	14,95	14,59	14,64	Al$_2$C
)$_3$	3,37	2,30	0,62	4,22	6,08	8,29	1,07	0,96	2,22	2,89	1,818	Fe$_2$C
)	4,09	2,60	2,17	6,86	6,08	5,63	1,89	1,27	4,22	3,99	2,05	FeC
)	0,12		0,05	0,15	0,13	0,13	0,05	0,04	0,09	0,09	0,05	MnC
)	1,97	1,30	0,55	3,43	5,22	4,60	0,80	0,50	2,46	2,56	1,18	MgC
)	4,34	3,08	1,97	7,66	7,92	7,46	1,55	1,38	4,26	4,47	2,11	CaC
O	3,61	3,45	3,18	3,70	2,97	4,60	3,30	3,20	3,60	3,43	3,52	Na$_2$
)	3,38	4,43	3,59	1,80	1,52	0,57	5,32	5,63	4,09	4,01	5,76	K$_2$C
$_5$	0,80	0,40	0,08	1,65	2,34	0,88	0,20	0,13	0,73	0,69	0,28	P$_2$C
I	0,67	0,59	0,39	1,44	2,30	0,96	1,15	0,94	1,11	1,16	0,28	LO
al	98,87	98,99	99,43	98,55	99,06	98,90	99,16	99,36	99,03	98,70	99,128	Tota
	89	149	112	62	66	22	162	220	130	97	151	Rb
	2076	1790	922	1595	760	468	1610	1400	2730	3010	2088	Ba
							44	73	42	43	43	Pb
	696	513	138	1196	1085	1125	470	410	1536	1550	1023	Sr
	58	125	6	53	74	76	139	178	119	105	133	La
							266	326	230	210	267	Ce
							101	107	106	99	110	Nd
							49	42	34	30	42	Y
							32	44	16	12	19	Th
	773	448	232	639	323	891	461	398	307	417	474	Zr
							24	22	17	15	25	Nb
							54	46	107	102	63	Zn
							17	13	26	50	16	Cu
							67	85	59	50	57	Co
							7	4	21	22	12	Ni
							2	3	9	11	5	Sc
							29	19	109	116	49	V
							6	0	24	33	17	Cr
							20	19	19	18	22	Ga

	Høvringsvatn complex					
	4864 granite central stock	25008 granite cone-sheet	1181 coarse-grained monzonite	34068 coarse-grained monzonite	1098 monzonite dyke	99190 Reiårsvatn Dolerite dyke
SiO_2	67,40	69,15	54,48	60,41	59,23	50,63
TiO_2	0,63	0,48	1,11	1,30	1,23	2,12
Al_2O_3	14,51	14,64	11,18	15,53	14,54	16,64
Fe_2O_3	1,52	0,96	1,88	1,91	2,69	0,75
FeO	1,72	1,75	6,11	3,37	3,32	9,75
MnO	0,03	0,03	0,12	0,05	0,11	0,15
MgO	1,08	0,66	8,89	1,97	2,73	5,58
CaO	1,70	1,47	6,62	3,24	4,65	7,43
Na_2O	3,56	3,21	2,67	3,69	3,42	3,78
K_2O	5,62	5,86	3,90	5,26	6,02	1,23
P_2O_5	0,21	0,11	0,57	0,44	0,66	0,34
LOI	0,67	0,71	1,99	1,15	0,94	1,28
Total	98,63	99,03	99,52	98,32	99,54	99,67
Rb	123	202	140	133	151	44
Ba	3300	2650	2100	3700	3500	305
Pb						
Sr	976	615	884	1584	1673	442
La	125	265	140	150	165	
Ce						
Nd						
Y	28	84	22	25	42	19
Th						
Zr	355	500	295	800	660	161
Nb	38	38	33	40	40	19
Zn						103
Cu	7	17		14	15	38
Co	48	79	49	58	15	
Ni			265	23	32	62
Sc						
V	40	35	125	110	105	161
Cr	20	30	480	29	41	48
Ga						