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Protoliths of the gneisses and mafic rocks in the Hellevik - Flekke Area in Sunnfjord, Western Norway

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REPORT

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Title:
Protoliths of the gneisses and mafic rocks in the Hellevik - Flekke Area in Sunnfjord, Western Norway.

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Summary:

The Hellevik-Flekke area comprises Precambrian crystalline rocks that have experienced a complex history of deformational and metamorphic events through both Precambrian and Caledonian times. The area can be divided into four different lithological units. The Basal Gneisses, the Flekke Unit, the Gjølanger Unit and the Vardeheia Unit.

During the Caledonian Orogeny all units were deformed and metamorphosed under eclogite facies conditions, but relicts of undeformed and unmetamorphosed protholiths from the units can be identified.

To the south, granodioritic and monzonitic gneisses occur together with granites, pegmatites, and minor amphibolitic and eclogitic bands and lenses. This assembly of lithologies is similar to those of the Western Gneiss Complex in the middle part of the Sognefjord transect.

The Flekke Unit is interpreted to represent an allocthonous nappe containing a layered mafic-ultramafic complex. The gabbroic rocks of the complex are dated to 1522±55 Ma (Sm-Nd age). The Gjølanger Unit consists of grey and green orthogneisses of dioritic to granitic composition, with geochemical characteristics of rocks formed at an active continental margin. Rb-Sr isotopic data indicate a minimum age for the gneisses of 1500 Ma, with subsequent Sr-isotope disturbance. This unit is also interpreted to be an allochthonous nappe.

The Vardeheia Unit in the north experienced the strongest Caledonian deformation and is dominated by heterogeneous banded gneisses and mylonites with small lenses of amphibolites and eclogites.

Keywords: prekambrisk	kaledonsk	aldersdatering
Sm-Nd	Rb-Sr	gabbro
eklogitt	gneis	fagrapport

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1. Introduction

In connection with the NGU-project "Rutilprovinser i Norge" some selected areas at the south side of the Dalsfjord were mapped in June 1995. The purpose of the mapping was to attempt to determine the various protoliths to the lithologies, to outline the relationship between the lithologies in this area and to outline the geological history and compare it with the Sognefjord area to the south. Four geological maps were made, the Areklatten-Instetjørna area, the Selvika-Gjølanger area, the northern side of the Tyssekvamvatnet and the forest road to the south of Solheim, Flekke.

2. Rockdescription

2.1 Introduction

Plate 2 shows that four different lithological units can be distinguished in this area.

1) To the south, the Basal Gneisses are composed of grey and pink granodioritic and monzonitic gneisses, with additional granites, pegmatites, and minor amphibolitic and eclogitic bands and lenses.

2) The Gjølanger Unit is composed of homogeneous grey and green granodioritic gneisses and amphibolites, cut by mafic and ultramafic intrusions. Both the amphibolites and the mafic intrusions are variably metamorphosed to eclogites.

3) The Flekke Unit consists of meta-gabbroic and meta-anorthositic rocks, with minor ultrabasic rocks. The rocks are metamorphosed to coronitic gabbros and eclogites and are variably retrograded to amphibolites. This unit is assumed by Cuthbert (1985) to represent a layered mafic-ultramafic complex.

4) The Vardeheia Unit to the north is dominated by heterogeneous banded gneisses and mylonites with small pods of garnet amphibolites and eclogites. The most common lithology is a mica-plagioclase-quartz gneiss, other lithologies include mica-amphibole-epidote schists, granitic gneisses and augen gneisses. All the three lithological units above the Basal gneisses have non-tectonic contacts, and are regarded as one tectonostratigraphic unit, separated from the basal gneisses by mylonites (Cuthbert 1985).

In this work, I use the same rock names and lithological units as those of Cuthbert (1985). The work was concentrated on the main lithologies of the Gjølanger and the Flekke Units. The two common lithologies in the Gjølanger Unit are grey and green gneisses, which in the least deformed conditions, show primary magmatic textures. In the Flekke Unit, the protolith can be demonstrated to be an anorthositic-gabbroic rock.

The metamorphism and deformation of the rocks are inhomogeneous; for example on a scale of 1 m, the unmetamorphic and undeformed protolith can be transformed into an eclogite and/or a foliated rock. Thus rocks of the same protolith, may look very different in the field.

2.2 The Gjølanger Unit

2.2.1 Grey gneisses

The most pristine protoliths of the Gjølanger Unit vary between a grey, unfoliated medium-grained granular rock and a porphyritic variant (fig. 1); in cases where the rock is foliated, the former is a homogeneous, foliated gneiss and the latter, an augengneiss. The composition of the rocks is dioritic to granitic; Plagioclase is the dominant feldspar and occurs together with quartz, +/- microcline, biotite and epidote, with accessory titanite, chlorite, apatite, opaques and zircon. Cuthbert (1985) additionally described diopsidic clinopyroxene, hornblende, ilmenite and magnetite from these gneisses.

Associated with the grey gneisses are more course-grained charnockitic rocks that contain hypersthene and blue quartz. Field observations support a gradually transition from the protoliths of the grey gneisses to the coarse-grained charnockite. Cuthbert (1985) interpret these rocks as belonging to the same lithology.

2.2.2 Green gneisses

The rock is a foliated medium-grained rock, comprising quartz, a symplectitic mass of amphibole and plagioclase, small garnets, white mica, kyanite, rutile and opaque minerals. Lenses of eclogite with gradual transition to the green gneisses occur at several localities (for example loc. 9 plate 5 at the eastern side of the Tyssekvamvatn). The eclogites have the same foliated texture as the gneisses, and nearly identical mineralogy, but the eclogites have omphasite instead of the symplectitic masses of amphibole and plagioclase. In the more retrograded variants of the green gneisses amphibole is altered to biotite.

The boundary to the grey gneisses is gradual. Cuthbert (1985) described a decrease in the content of biotite and plagioclase and an increase in amphibole, omphasite, white mica and kyanite in the grey gneisses as they pass into green gneisses.

The foliation in this rock is cut by eclogitized mafic dykes and bodies of pyroxenites; a later, assumed Caledonian foliation cuts again these rocks. Where the green gneisses have been foliated by the assumed Caledonian deformation, they show their strongest foliation and schistosity, or a strong lineation with a «flaser gabbro» texture. This mixing between the post-dyke foliation in the green gneisses and the older foliation is well exposed at the read cuts at localities 10 and 11 on the forest road to the west of Flekke (Plate 6).

2.2.2 Metabasites

According to Cuthbert (1985), metabasites occur as dykes a few metres wide, as small lenses, and as large bodies up to hundreds of metres thick, concordant with the regional foliation in the gneisses. The transition between the metabasites (except for the dykes) and the gneisses seems to be gradational with compositionally and mineralogically diffuse margins.

Metabasic dykes are observed at three localities. At the road to Selvika from Gjølanger (locality 7 on Plate 4), dykes cut through the foliation of the grey gneisses (fig. 2). The metabasite is a fine-grained, partly foliated garnet-amphibolite to eclogitic rock consisting of garnet + plagioclase + amphibole-plagioclase symplectite or omphacite + garnet +/- rutile (Cuthbert 1985).

On the forest road to the west of Flekke 0,3 - 0,5 m metabasite dykes, cutting the foliation in the green gneisses (fig. 3), have been observed at two localities (on the western side of the road at locality 12 on Plate 6, and on the eastern side of the road ca. 200 to the south). The dykes are fine grained and composed of garnet, clinopyroxene, opaque minerals and rutile.

Lenses of fine-grained eclogitic rocks occur in the green and grey gneisses at several localities, for example locality 11 (Plate 6), and 150 m to west of locality 6 (Plate 4). The borders with the foliated gneisses are concordant (fig. 4), but it is difficult to determine if the lenses are the deformed equivalents to the described dykes, or if the metabasic lenses are older.

2.3 The Flekke Unit

2.3.1 Anorthosite and gabbro (and coronitic anorthosite and gabbro)

These granular, medium- to course-grained rocks, consist primaly of white to grey plagioclase, olivine, clinopyroxene, orthopyroxene, and minor opaques. Coronitic anorthosite and gabbro are the dominant rocks of the mafic protoliths of the Flekke Unit; garnet growth defines the corona textures of the mafic minerals. In the most pristine protolith, these textures are likely to be the result of sub-solidus recrystallization under granulite facies conditions Cuthbert (1985). The grain size of plagioclase and pyroxene is usually between 1 mm and 4 cm, but megacrystals of pyroxene (20-30 cm) were observed at Botnatjørna (UTM KP 953 000) on the forest road from the farm Holt.

The best localities of this rock, with the primary mineralogy, are at the forest track by Ystetjørna and on the small hills to the north. The rocks show magmatic layering at a scale of tens of cm (fig. 5), and good localities are, for example, localities 2, 3 and 5 of Plate 3. Cuthbert (1985) classifies the rocks as anorthositic and gabbroic troctolite. There are, however, variations in the composition of the mafic minerals and many of the rock varieties can be classified as olivine gabbronorites.

The gabbros and anorthosites are slightly to completely eclogitized via breakdown of plagioclase, growth of garnet and increasing jadeite content of pyroxene. Varying degrees of eclogitization can be attributed to pervasive amphibolitization of mafic protoliths prior to eclogitization, while the coronites were never amphibolitized (Cuthbert 1985). Locality 1 (plate 3) is one of the best eclogite localities where original magmatic layering is preserved.

2.3.2 Amphibolite

The gabbros and anorthosites are deformed and retrograded into amphibolites (fig. 6). The amphibolite is a foliated, medium-grained and banded rock, composed of the minerals amphibolite, plagioclase, zoisite, white mica, biotite, chlorite, garnet and opaque minerals. The amphibolites often contain lenses of eclogite.

3. Whole-rock Geochemistry

3.1 Introduction

Whole-rock major and trace element analyses of the rocks are shown in table 1. Rock classifications and magmatic trends are shown in figures 7 and 8. For interpretation of the geochemical characteristics of the rocks, I additionally used those of Cuthbert (1985).

3.2 The Gjølanger Unit

The analysed protoliths of the grey gneisses range from granitic to granodioritic composition, whereas the green gneisses range from granodiorite to diorite (fig. 7). In figure 8 the element concentrations show two overlapping groupings for the different lithologies. Cuthbert (1985) concluded from his work that the grey and green gneiss lithologies are directly related. The grey and green gneisses are subalkaline, the magmatic trend shows a calc-alkaline nature, and the trace element chemistry indicates a continental arc (Andean-type) type tectonic setting (figure 9).

Two of the grey granodiorites plot in profoundly different fields from the other rocks, especially with respect to TiO_2, MgO, (K_2O) and Zr, and are probably not comagmatic with the rest of the gneisses.

3.3 The Flekke Unit

The analysed samples plot in the gabbro field (fig. 7). Features like magmatic layering, for example, indicate that most of the rocks in the Flekke Unit are cumulates, thus making this unit look similar to the layered mafic-ultramafic complexes that are often anorogenic (Cuthbert 1985). Oxide-rich chloritized harzburgites and dunites (Plate 2) are considered to be late differentiates of the same magma from which the gabbros crystallised (Cuthbert 1985).

4. Age determination of gabbroic rocks in the Flekke unit

Two gabbroic rocks of olivine gabbronoritic composition from locality 5 (Plate 3) were chosen for Sm-Nd isotopic age determination. Both rocks (ØS-95-53 is coarse-grained and ØS-95-70 is medium-grained) are fresh, free of garnet and without any sign of prograde or retrograde metamorphism. The magmatic layering at this locality shows that the rocks are cumulates. Whole-rock major and trace element data of the rocks are presented in table 1. Mineral separates of the rocks were prepared by sawing into thin slices, crushing, and hand-picking under a binocular microscope. The cleaned separates were crushed and dissolved. Sm and Nd were separated by standard wet-chemical methods, and the samples were analysed using a Finnigan 262 mass spectrometer in static mode.

The $^{147}Sm/^{144}Nd$ ratio is usually assumed to have a precision of 0.5% (2σ, Mearns 1986). The precision of $^{143}Nd/^{144}Nd$ ratio (2σ) of the analysed data is between $4x10^6$ and $8x10^6$ for four samples and $21x10^6$ and $27x10^6$ for the two other samples (table 2). These are within the range of the long-term (~ 1 year) variation in the $^{143}Nd/^{144}Nd$ ratio of a standard which is ~ $40x10^6$ (2σ), (Johansson & Kullerud 1993). The isochron were calculated according to York (1969) with a decay constant of $6.54 \cdot 10^{-12}$, isotopic ratios have been normalised to $^{146}Nd/^{144}Nd = 0.7219$. The mineral and whole-rock analyses of the two olivine gabbronoritic rocks define an age of 1522±55 Ma with MSWD = 13 (fig. 11). The initial ratio is 0.510886±0.000065 (2σ) corresponding to Epsilon (CHUR) = 4.3.

5. Interpretation of field relationships and age determinations

The age obtained is interpreted as the intrusion age of the anorthosite and gabbro of the Flekke Unit. The large error in the isochron age is due to the small spread in the Sm/Nd ratio. To get a more precise age determination it is necessary to analyse garnet in a corona-textured gabbro. The garnet should be of the sub-solidus type, recrystallized in granulite facies during the cooling of the magma, and not during the later, Caledonian eclogite facies metamorphic phase. The analysed samples contained no garnet, but coronitic gabbros are closely associated with similar rocks at several localities (plate 5). The ε^{Nd} (CHUR) = 4.3 of the rocks is close to DePaolo`s (1981) mantle curve and reflects a magma from a juvenile depleted mantle.

In addition to the age determination of gabbroic rocks of the Flekke Unit (1522±55 Ma) in this work, three other lithologies in the Gjølanger area are dated, but the results are ambiguous. Cuthbert (1985) reports that zircons from garnetite veins in pyroxenite give U-Pb age of ca. 1500 Ma. The pyroxenites and the mafic dykes are interpreted to be intrusives in the grey and green gneisses of the Gjølanger Unit, and thus put a minimum age on the gneisses. The pyroxenites are chemically different from the gabbroic rocks of the Flekke Unit dated in this study, therefore the chemical relationship between them are not clear, although they are closely related in age. Cuthbert (1985) suggested that the mafic dykes in the Gjølanger Unit can be feeder dykes to the mafic complex in the Flekke unit, but the mafic dykes are not dated. Field evidences support that the gneisses and the associated charnockites are older than the pyroxenites (dated to be ca. 1500 Ma), but the gneisses gave an «Rb-Sr errorchron» age of 1255 ± 309 Ma, and Cuthbert (1985) interpreted this age as an open system incomplete resetting of the Sr-isotope system. The initial $^{87}Sr/^{86}Sr$ ratio for these rocks are 0,7040 ±0,0018, that give a positive ε^{Sr} (CHUR) of 18-20 for the assumed age (1500-1600 Ma). Those ratios may indicate that the gneisses had a crust-derived component when they were formed, but since the initial ratio is only very poorly defined, this can only be a tentative suggestion. On the small island Bårdsholmen (western side of Gjølangerfjord) lithologies similar to the grey gneisses of the Gjølanger Unit are present, and Gromet and Andersen (1994) dated the granulite facies granitoids to be ca. 1000 Ma (U-Pb age).

My tentative conclusions for this rock complex are that the grey and green gneisses of the Gjølanger Unit are the oldest rocks formed in an orogenic event prior to 1500 Ma (Gothian orogeny). These rocks were deformed prior to the ca. 1500 Ma anorogenic intrusions of pyroxenites and gabbroic rocks (Flekke Unit), and possibly the basic dykes. Sveconorwegian events included granulite facies metamorphism (ca. 1000 Ma), and resulted in disturbance in the Rb-Sr isotopes. Caledonian deformation and metamorphism caused strong deformation of the rocks and eclogite facies metamorphism, followed by retrograde metamorphism during exhumation.

4. Comparison between the Hellevik - Flekke area and the mafic rocks of the Lavik area.

Plate 7 is a geological map of the Lavik area at the outlet of the Sognefjord. Bailey (1989) identified five tectonostratigraphic units, 1) the Basement gneisses 2) the Lower Mafic Unit (mostly amphibolite schists), 3) the Middle Mafic Unit (Gråfjell gneisses), 4) the Upper Mafic Unit (Mølmesdal Gabbro) and 5) the Hyllestad schists. The Middle- and Upper Mafic Units are lithologically similar to the Gjølanger- and Flekke Units respectively.

According to Bailey (1989) the most common lithology of the Middle Mafic Unit is a medium- to coarse-grained tonalitic grey gneiss, other lithologies are syenogranitic to granodioritic gneisses, amphibolites and amphibolitic schists, and serpentinites and ultramafic schists. The Upper Mafic Unit comprises mainly coarse-grained gabbros which are deformed to amphibolites and amphibolitic schists in shear zones. At one locality coarse-grained granitic to monzonitic rocks occurs, and diabase dykes cut the course-grained gabbros. The gabbro consists of plagioclase, clinopyroxene, orthopyroxene and olivine. Garnet occurs at some localities as coronas on olivine and orthopyroxene, and ilmenite is the dominant opaque mineral. One ore has been mined from a gabbro body. The gabbroic rocks are gabbronorites, olivine gabbronorites and troctolites. Anorthosite is common and Bailey (1989) describes cumulate layering at one locality.

The Basement Gneisses and the Hyllestad Schists include high-pressure metamorphic mineral assemblages, while the Lower-, Middle- and Upper Mafic Units show evidence of pressures not higher than 5 to 10 kbar, and temperatures of 500 to 525°C; both the Hyllestad Schists and Mafic Units are considered to be allocthonous units emplaced onto the Western Gneiss Region during the Caledonian orogeny (Bailey 1989).

5. Geological history of the Western Gneiss Region

The Western Gneiss Region (WGR, fig. 10) is composed of felsic orthogneisses and interlayered mafic gneisses, amphibolites and paragneisses, intruded by various felsic and mafic intrusives (Austrheim & Mørk 1988). The main crust-forming event occurred between 1750 and 1450 Ma, with an orogenic event prior to ca. 1500 (Gothian) (Kullerud et al. 1986, Gorbatschev 1985). The Precambrian rocks, from the oldest to the youngest are paragneisses followed by orthogneisses, and after the migmatization (Gothian), there were intrusions of anorogenic granites, monzonites, mangerite-syenites and dolerites (Kullerud et al. 1986). Among the anorogenic rocks are anorthosite from Eikefjord-Sandane (Nordfjord) dated to be 1479±64 Ma (Rb-Sr), and mangerite-syenite from Stadt 1520±10 Ma (U-Pb) (Kullerud et al. 1986). Migmatitic gneisses of granitic to dioritic composition are the dominant rocks in the eastern parts of the WGR, while the abundance of mafic gneisses, paragneisses and amphibolites/eclogites increases toward the west. Paragneisses include mica-schist, quartzo-feldspathic schist, marbles, calc-silicate gneisses and quartzites (Bryhni 1989). Some of these paragneisses may be Caledonian nappe sequenses folded into the gneisses and deformed during the Caledonian orogeny (Bryhni 1989), while other presumed paragneisses are orthogneisses strongly deformed during the Caledonian orogeny (Milnes et al. 1988).

During the Sveconorwegian orogeny (ca. 1250 to 900 Ma) the intrusions are predominantly granites, but diorites, dolerites and pegmatites also developed (Kullerud et al. 1986). Intrusions were absent in the central and northern parts of the area (Tucker et al. 1990). The granites are typically coarse-grained and of quartz-monzonitic composition, and in western and northern parts of the Western Gneiss Region they have been transformed to augen gneisses due to the strong Caledonian deformation and metamorphism. The ages of the felsic intrusives are from ca. 1300 to 870 Ma, with a possible orogenic event at 1050 Ma (Kullerud et al. 1986).

The rocks of the WGR were usually strongly reworked during the Caledonian orogeny. The deformation and metamorphism increase towards west, where the rocks underwent eclogite facies metamorphism (420-410 Ma) and were subsequently retrogressed to amphibolites (400 - 390 Ma, Kullerud et al. 1986). In the eastern part of the Sognefjord area, the Caledonian deformation is almost absent, and is limited to lower-grade local amphibolite- and greenschist-facies shear zones.

On the bedrock map of Norway (Sigmond 1984) the dominant rock types in the Sogn and Sunnfjord areas are migmatitic gneiss of granitic and granodioritic composition. Other rock types are banded gneiss, mica gneiss and hornblende gneiss and to the west, amphibolites and banded gneisses occur in three separated areas between Dalsfjord and Sognefjord. Dietler (1985, 1987) did detailed mapping along the Sognefjord and divided the area into three structural regimes that are progressively Caledonized toward the west. In the eastern regime, the deformation is confined to local shear zones. Heterogeneous shear zones dominate in the middle regime where undeformed protoliths are only rarely preserved in tectonic lenses (10-100 m), and in the western regime, the Caledonian mylonitic foliation is the main foliation in the rocks and undeformed protoliths are rarely preserved. According to Dietler (1987), as well as my own field work, the protoliths preserved in the lenses are identical to the rocks in the eastern regime.

The Balestrand area in the middle of to the Sognefjord is composed of various gneisses, metagabbros, and quartzites. The protoliths to the gneisses can be recognised on a local scale. They range in composition from granite to granodiorite and syenite. The gneisses are in variable degrees metamorphosed to migmatites and intruded by granites and mafic dykes. The migmatites have been dated to ca. 1615 Ma (Gothian orogeny), while the youngest generation of undeformed granites is ca. 920 Ma, which is a late Sveconorwegian event (Milnes et al. 1988).

The Precambrian rocks are overprinted by the Caledonian foliation and deformed into gneisses and mylonites. The deformation increases toward the west, and the original protoliths can only be recognised when they occur as lenses in the gneisses.

The lithological units to the south of the Dalsfjord (Gjølanger- and Flekke Unit) and in the Lavik area (the Mafic Units) seems to be lithologically distinct from the rocks in the WGR in this area. The volumes of gabbroic and ultramafic rocks in the Gjølanger and Lavik area are very different compared to WGR as a whole, and Cuthbert (1985) and Bailey (1989) interpreted the units to be allochthonous. This interpretations fit with observations and data collected in this study.

6. Conclusions

Dalsfjord Region.

The Gjølanger Unit

* The protoliths to the grey and green gneisses are igneous rocks of dioritic to granitic composition, and have geochemical characteristics of rocks formed at an active continental margin.
* The gneisses formed around a minimum age 1500 Ma, with subsequent Sr-isotope disturbance. On an island in this area (Bårdsholmen) similar granitoids with granulite facies mineralogy are dated to be 1000 Ma (U-Pb age). This can represent the event of Sr-isotope disturbance.

Flekke Unit

* The protoliths of the mafic and ultramafic rocks have characteristics of layered mafic complexes. The gabbroic rocks of the complex are dated to be 1522±55 Ma (Sm-Nd age).

Sognefjord Region.

* The Middle and Upper Mafic Unit in the Lavik area are lithologically similar to the Gjølanger and Flekke Unit in the Dalsfjord area.
* The basement in the Sognefjord area is composed of orthogneisses of granitic to syenitic compositions, metagabbros and quartzites. The gneisses are partly migmatized in the Gothian orogeny, and all lithologies are cut by Sveconorwegian granitic and gabbroic intrusions.
* Caledonian deformation and metamorphism increase toward the west, where the protoliths of the basement lithologies are only preserved as tectonic lenses in gneisses with a Caledonian foliation.
* Protoliths of the basement gneisses, preserved in the tectonic lenses in the western part of the Sognefjord, are identical with the basement gneisses in the undeformed lithologies in the middle and eastern part of the Sognefjord.
* Both the Flekke and Gjølanger Unit in the Dalsfjord area and the Mafic Units in the Lavik area are interpret to be allocthonous.

References:

Austrheim, H. & Mørk, M. B. E. (1988): The lower continental crust of the Caledonian mountain chain. evidence from former deep crustal sections in western Norway. *Norges geologiske undersøkelse. Special Publication 3, 102-113.*

Bailey, D.E. (1989): Metamorphic evolution of the crust of southwestern Norway: an example from Sognefjord. *Unpubl. D. Doctoral thesis, Oxford University.*

Bryhni, I. (1989): Status of the supracrustal rocks in the Western Gneiss Region, S. Norway. In: *The Caledonide Geology of Scandinavia* (Gayer, R.A., ed.), Graham and Trotman (London), 221-228.

Cuthbert,S.J. (1985): Petrology and tectonic setting of relatively low temperature eclogites and related rocks in the Dalsfjord area, Sunnfjord, West Norway. *Unpubl. PhD Thesis, University of Sheffield.*

DePaolo, D.J. (1981): Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. *Nature* **291**, *193-196.*

Dietler, T.N. (1987): Strukturgeologische und tektonische Entwicklung der Western Gneiss Complexes im Sognefjord-Querschnitt, westliches Norwegen. *Doctoral thesis, ETH Zürich.*

Dietler, T.N., Koestler, A.G. & Milnes, A.G. (1985).: A preliminary structural profile through the Western Gneiss Complex, Sognefjord, southwestern Norway. *Norsk Geologisk Tidsskrift* **65**, 233-235.

Gorbatschev, R. (1985): Precambrian basement of the Scandinavian Caledonides. In: *The Caledonide Orogen-Scandinavia and Related Areas* (Gee, D.G. & Sturt, B.A., eds.), Wiley (Chichester, etc.), 197-212.

Gromet, L.P & Andersen, T.B. (1994): Eclogite intrusions in granite gneisses. Preservation of Precambrian intrusive relations in the eclogitized crust of Sunnfjord, SW Norway. *GSA-annual meeting, Seattle.*

Johansson, L. & Kullerud, L (1993): Late Sveconorwegian metamorphism and deformation in southwest Sweden. *Precambrian Research* **64**, *347-360.*

Kullerud, L., Tørudbakken, B.O. & Ilebekk, S. (1986): A compilation of radiometric age determinations from the Western Gneiss Region, South Norway. *Norwegian Geological Survey Bulletin* **406**, 17-42.

Milnes, A.G., Dietler, T.N. & Koestler, A.G. (1988): The Sognefjord north shore log - a 25 km depth section through Caledonized basement in Western Norway. *Norwegian Geological Survey Special Publication* **3**, 114-121.

Pearce, J.A., Harris, N.B.W. H. & Tindle, A.G. (1984): Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology 25, 956-983.*

Sigmond, E.M.O., Gustavson, M. & Roberts, D. (1984): Berggrunnskart over Norge M 1:1 million. Norges geologiske undersøkelser.

Tucker, R.D., Krogh, T.E. & Råheim, A. (1990): Proterozoic evolution and age-province boundaries in the central part of the Western Gneiss Region, Norway: results of U-Pb dating of accessory minerals from Trondheimsfjord to Geiranger. In: *Mid-Proterozoic Geology of the Southern Margin of Proto-Laurentia-Baltica* (Gower, C.F., Rivers, T. & Ryan, B., eds.), *Geological Association of Canada, Special Paper* **38**, 149-173.

York, D. (1969). Least square fitting of a straight line with correlated errors. *Earth Planetary Science Letters* **5**, *320-324.*

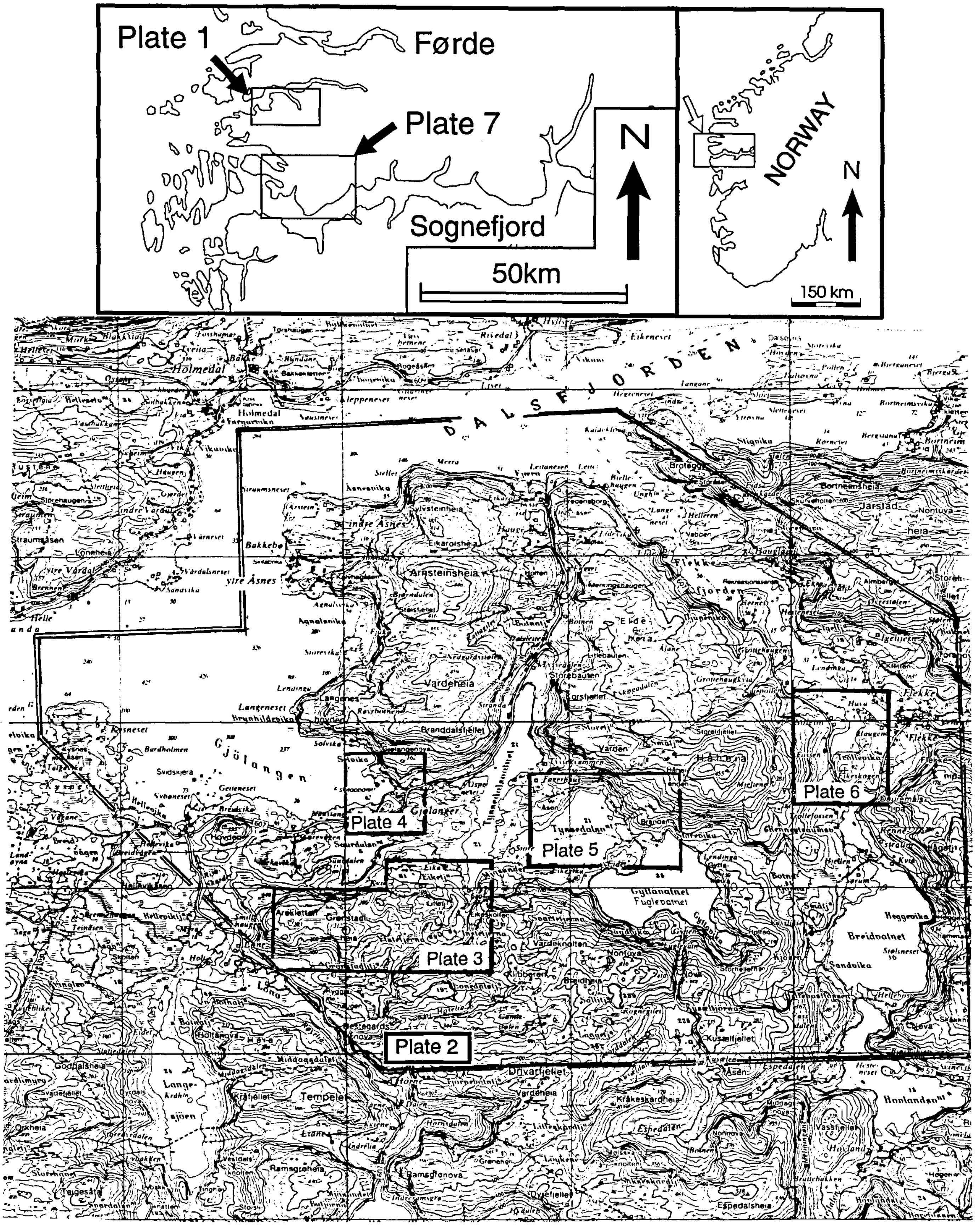


Plate 1. Location map for the Hellevik -Flekke area. The boxed areas show the locations of the geological maps Plate 2 - 6.

Topographic map M711.
Scale 1:50 000 1117 I Dale

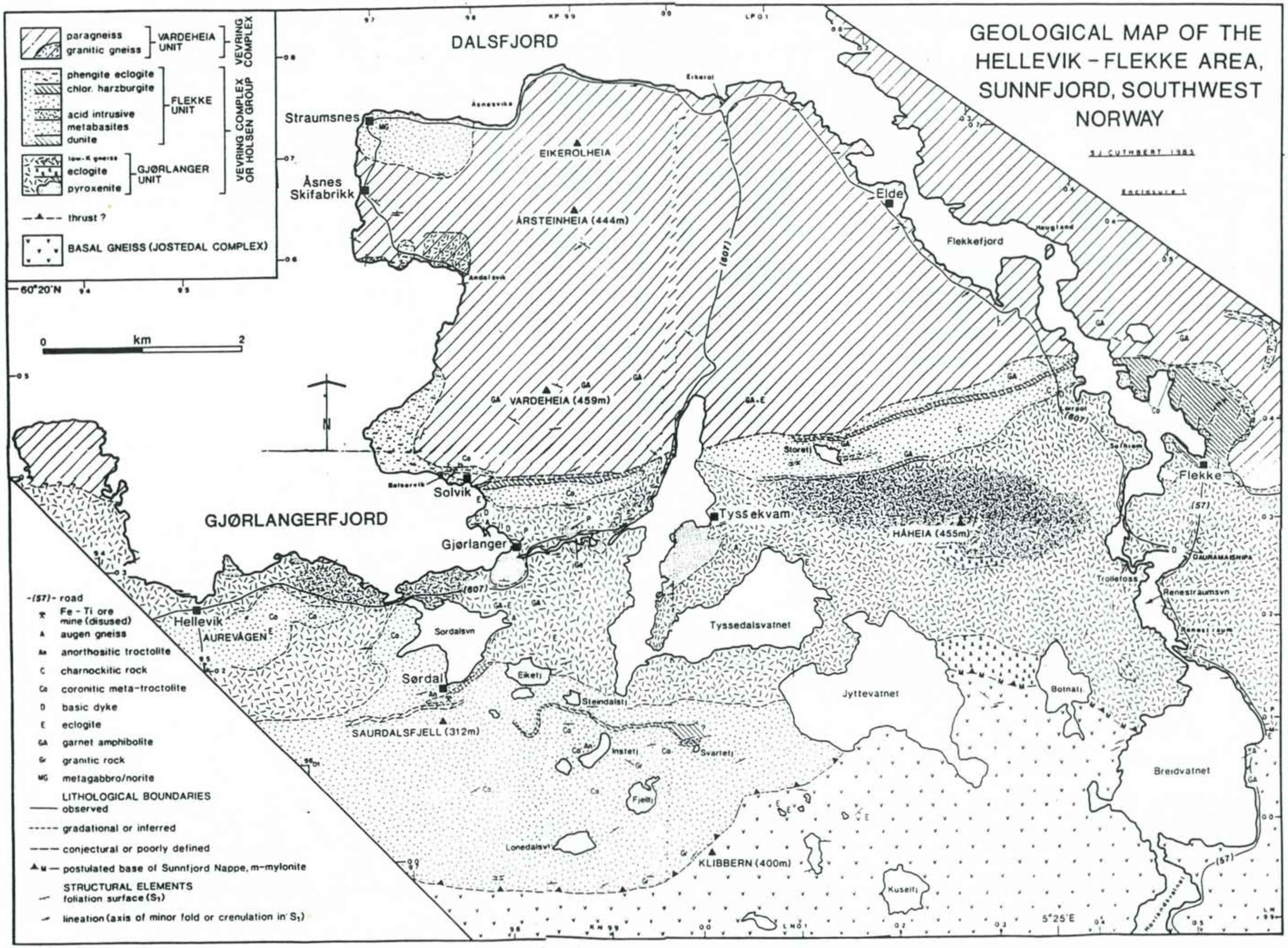


Plate 2. Geological map of the Hellevik - Flekke arear area (Cuthbert 1985).

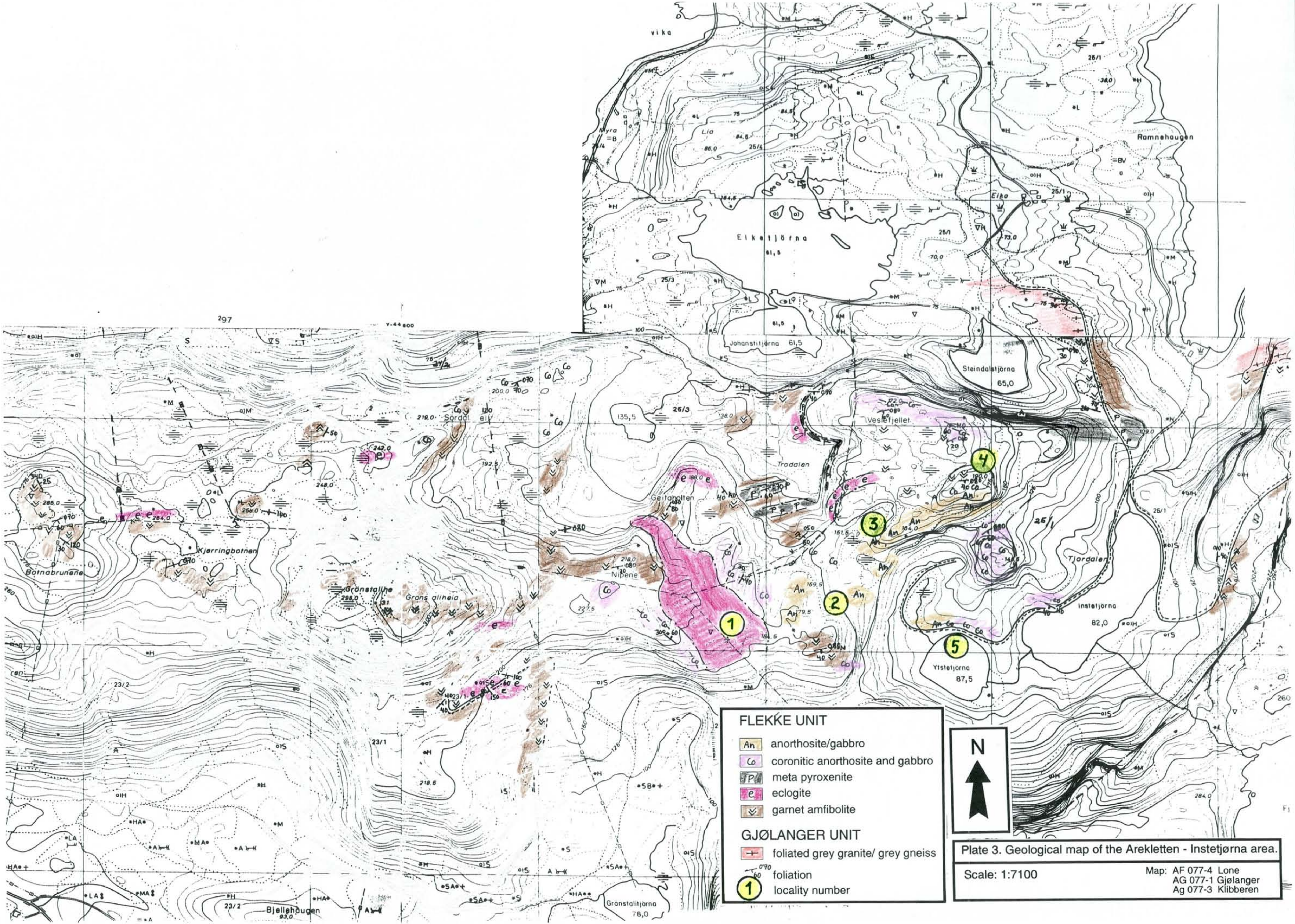


Plate 3. Geological map of the Arekletten - Instetjørna area.

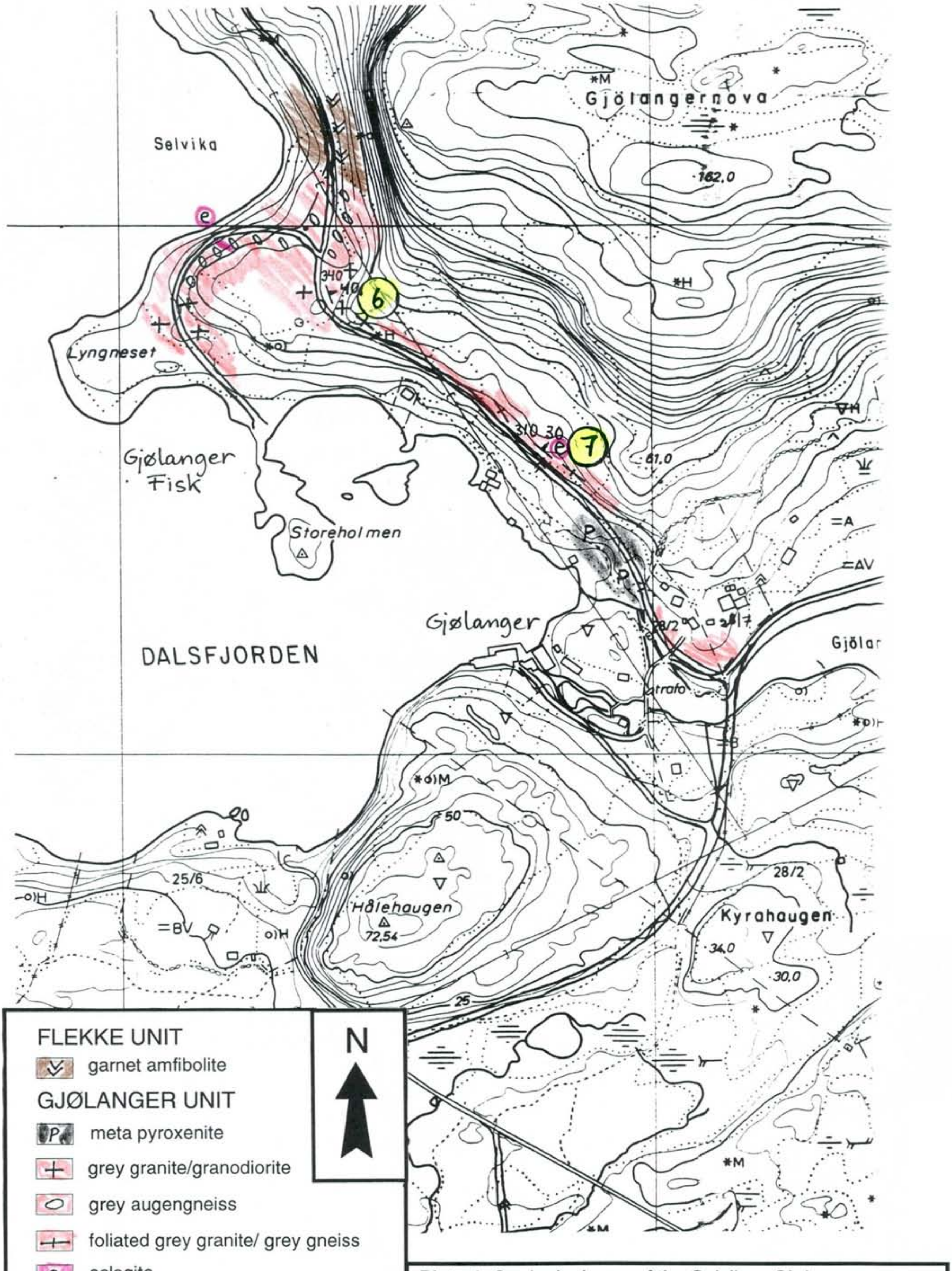


Plate 4. Geological map of the Selvika - Gjølanger area

Scale: 1:5000

Map: AG 077-1 Gjølanger

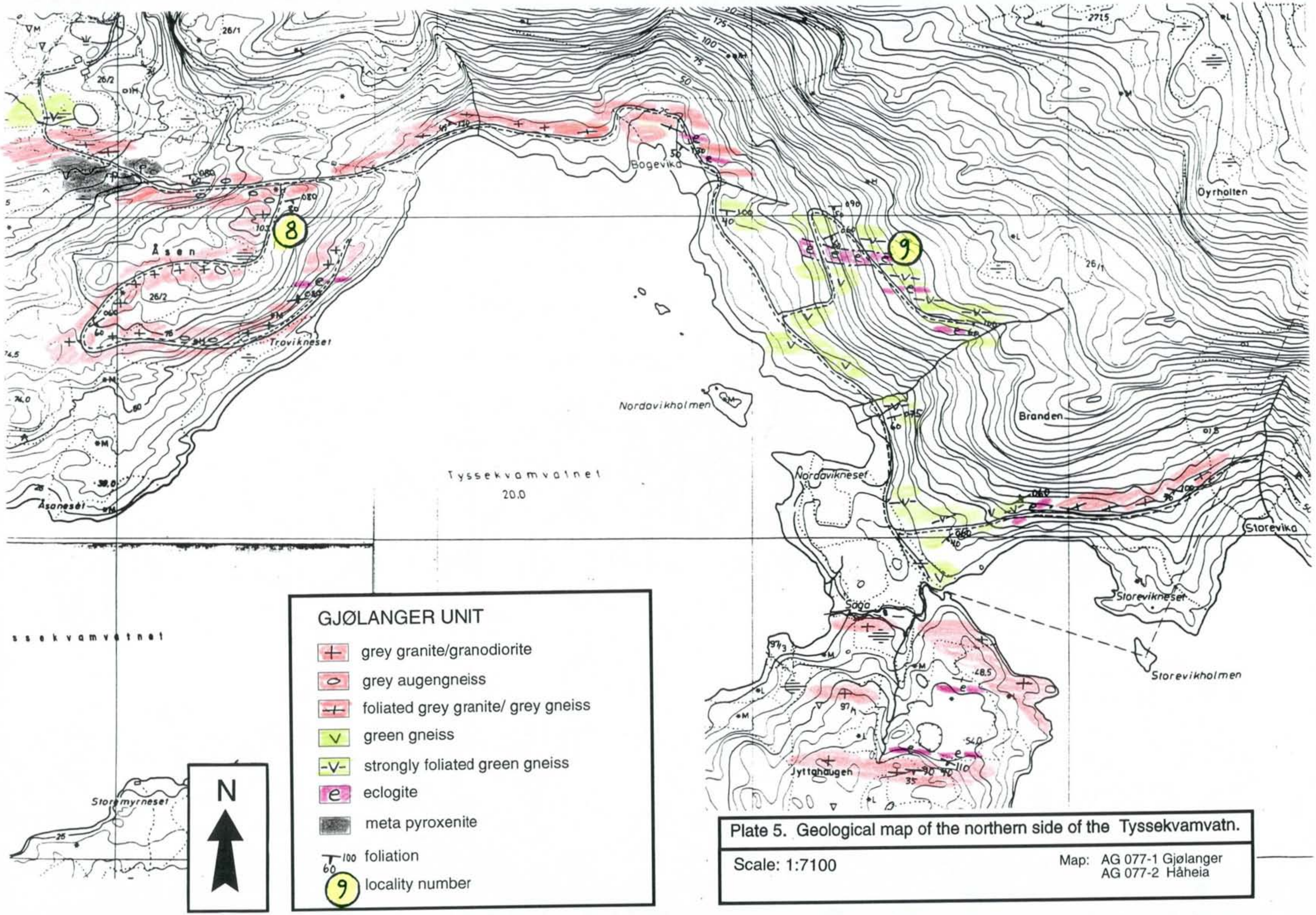
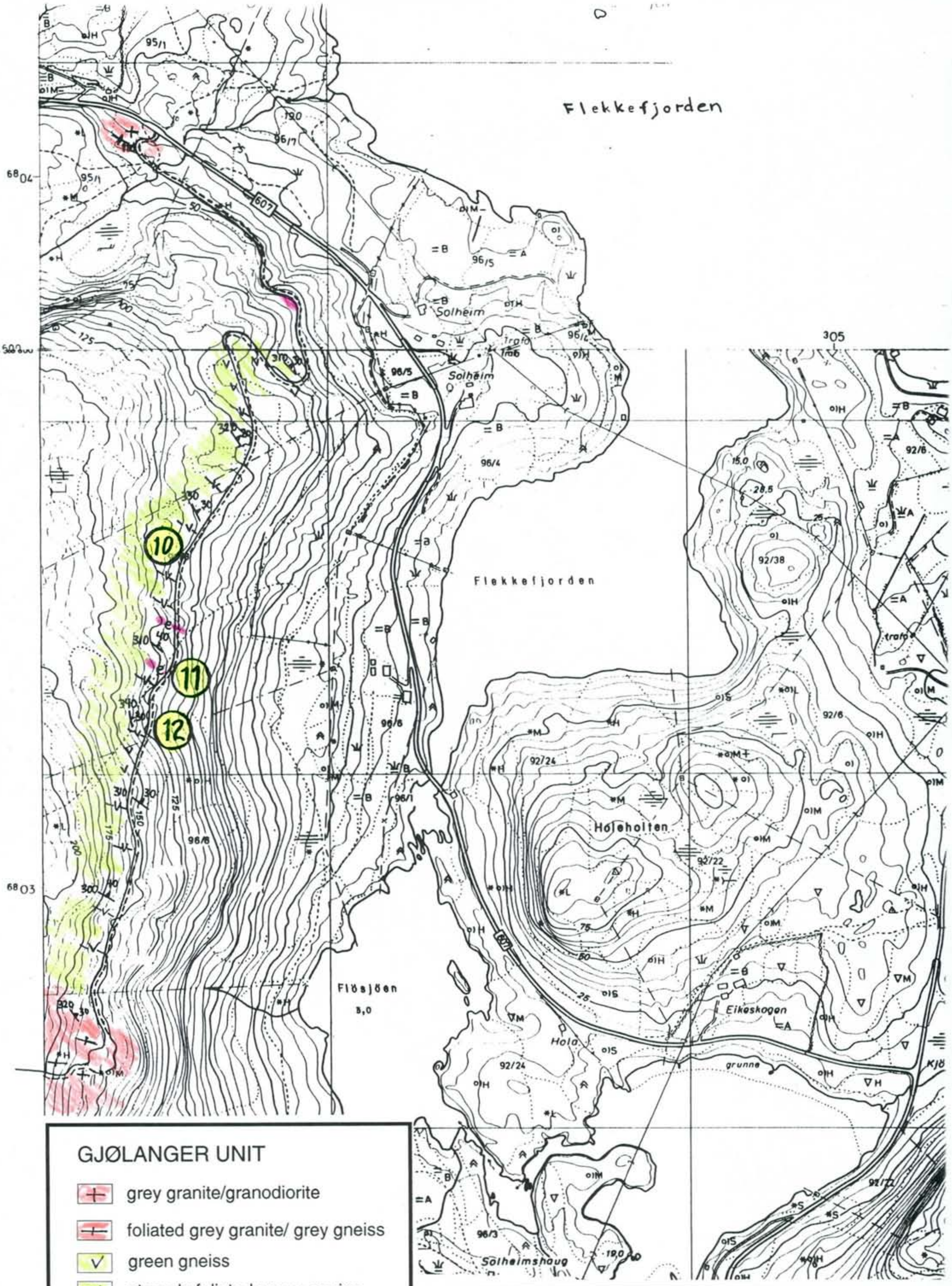


Plate 5. Geological map of the northern side of the Tyssekvamvatn.

Scale: 1:7100

Map: AG 077-1 Gjølanger
AG 077-2 Håheia



GJØLANGER UNIT

- grey granite/granodiorite
- foliated grey granite/ grey gneiss
- V green gneiss
- -V- strongly foliated green gneiss
- e eclogite
- 320 30 foliation
- 11 locality number

Plate 6. Geological map of the forest road to the south of Solheim, Flekke.

Scale: 1:7100

Map: AH 077-3 Rennestrum
AH 078-3 Igletjøn

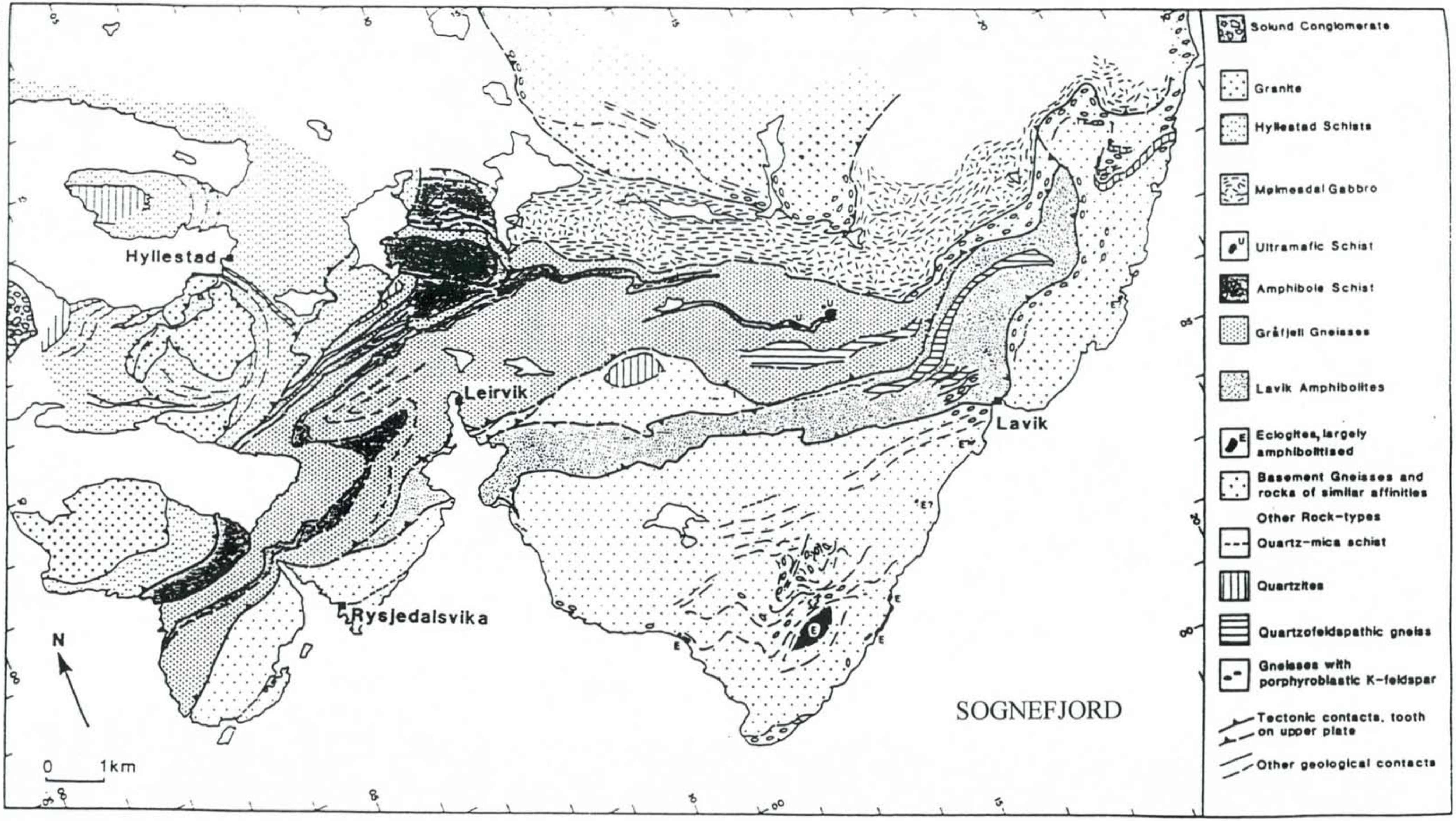


Plate 7 Geological map of the Hyllestad - Lavik area, Sognefjord (Bailey 1989)

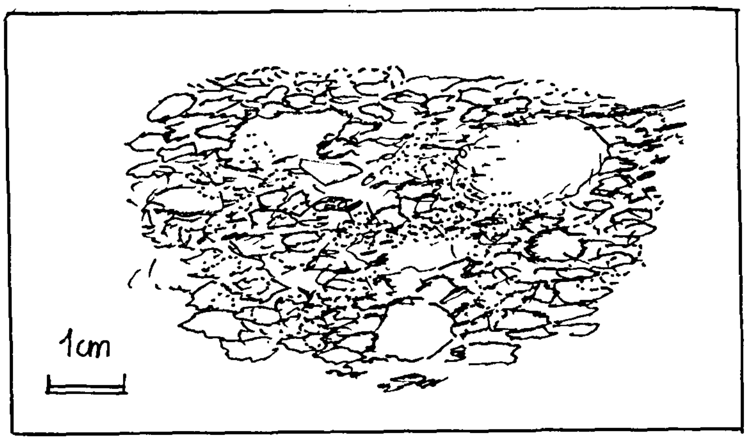


Figure 1. Protolith of the grey gneiss of the Gjølanger Unit, with a porphyritic texture at locality 6, Selvika (Plate 4).

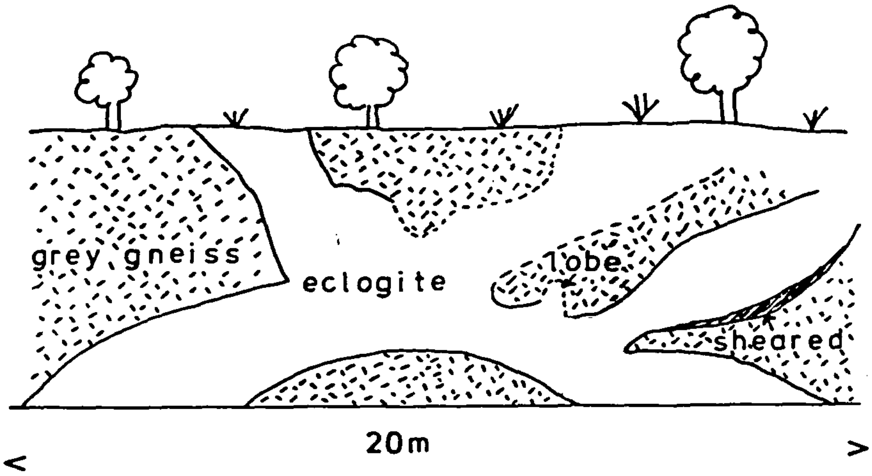


Figure 2. Metabasic dykes (eclogite) in the grey gneiss of the Gjølanger Unit at locality 7, Gjølanger (Plate 4). Sketch from Cuthbert 1985.

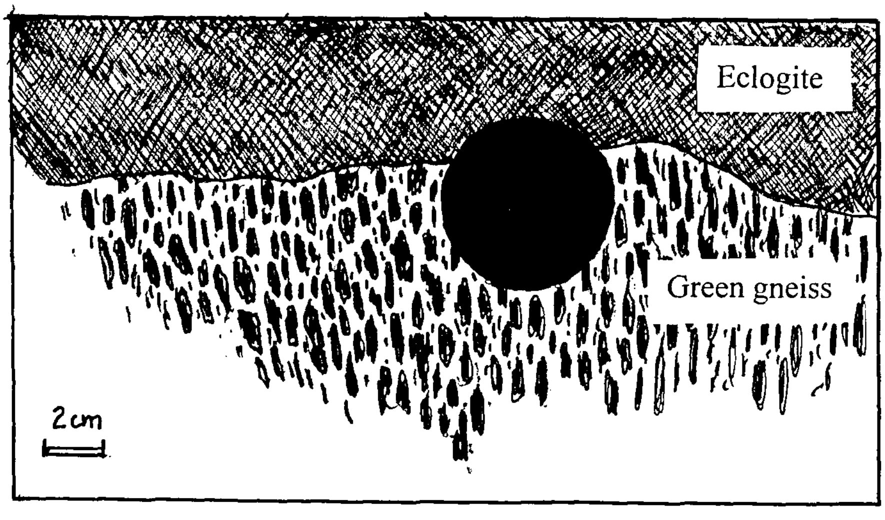


Figure 3. A metabasic dyke (fine-grained eclogite) that cuts the foliation in the green gneisses at locality 12, on the forest road west of Flekke (Plate 6).

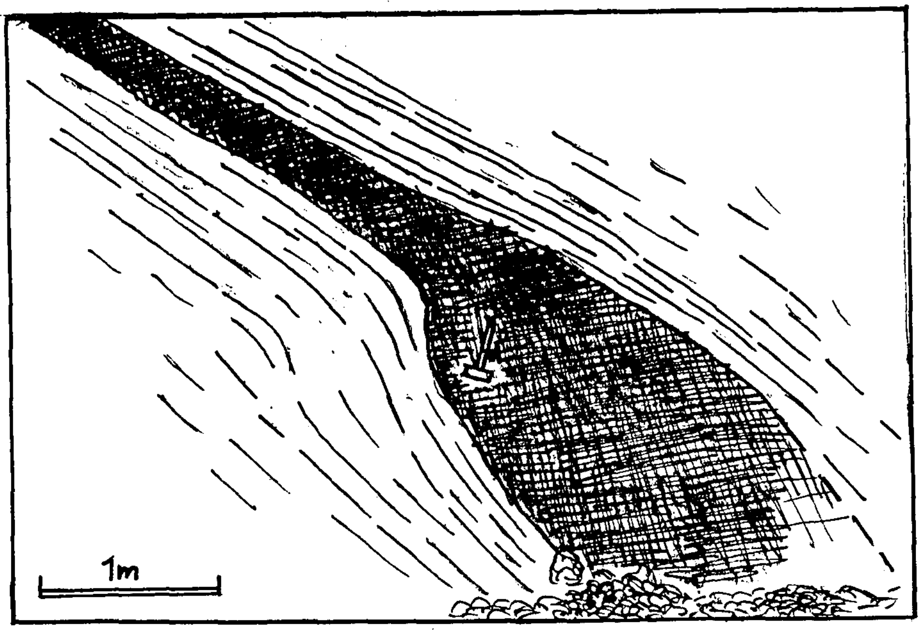


Figure 4. A lense of metabasic rock (fine-grained eclogite) in well-foliated green gneiss at locality 11, on the forest road west of Flekke (Plate 6).

Figure 5. Garnet-zoisite-amphibolite (metamorphic gabbro) with rhytmic graded igneous layering, north of Instetjørna between lokality 5 and 4 on Plate 3 (Cuthbert 1985).

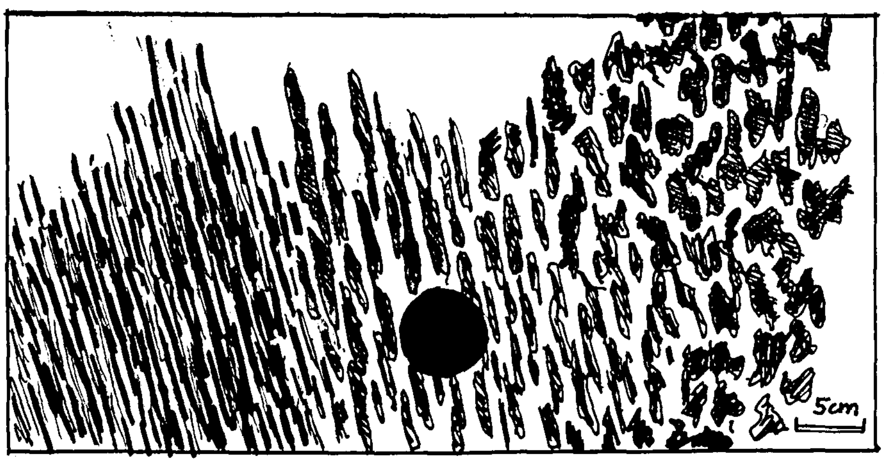


Figure 6. Coronitic gabbro becomes progressively deformated by shearing at the border of a body of undeformed coronitic gabbro and anorthosite. Locality 4 north of Ystetjørna, Plate 3.

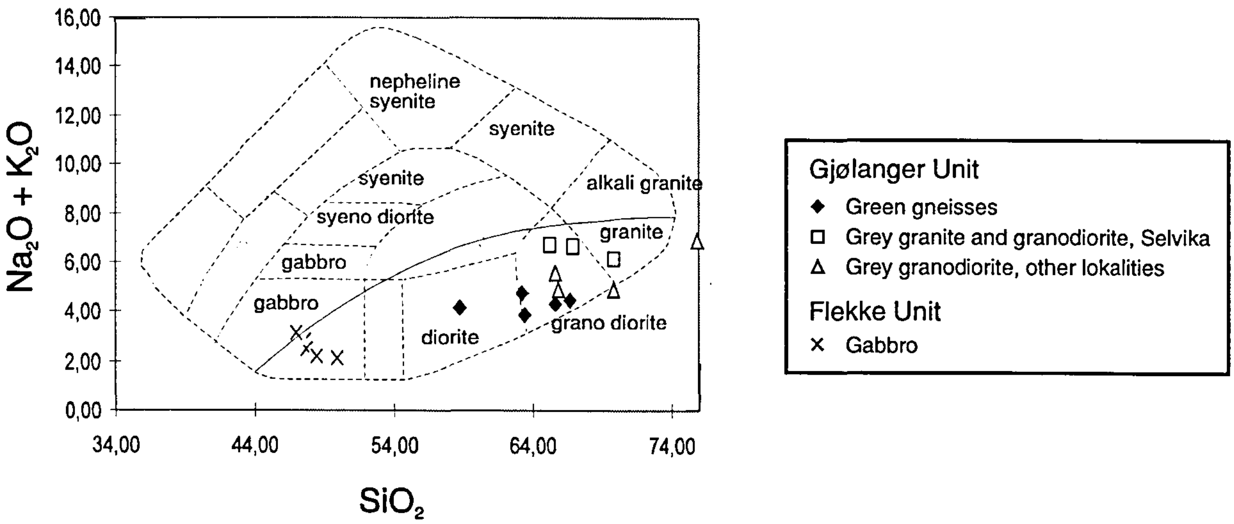


Figure 7. Classification of the grey and green gneisses of the Gjølanger Unit and the gabbros and anorthosites of the Flekke Unit. The diagram is from Wilson (1989).

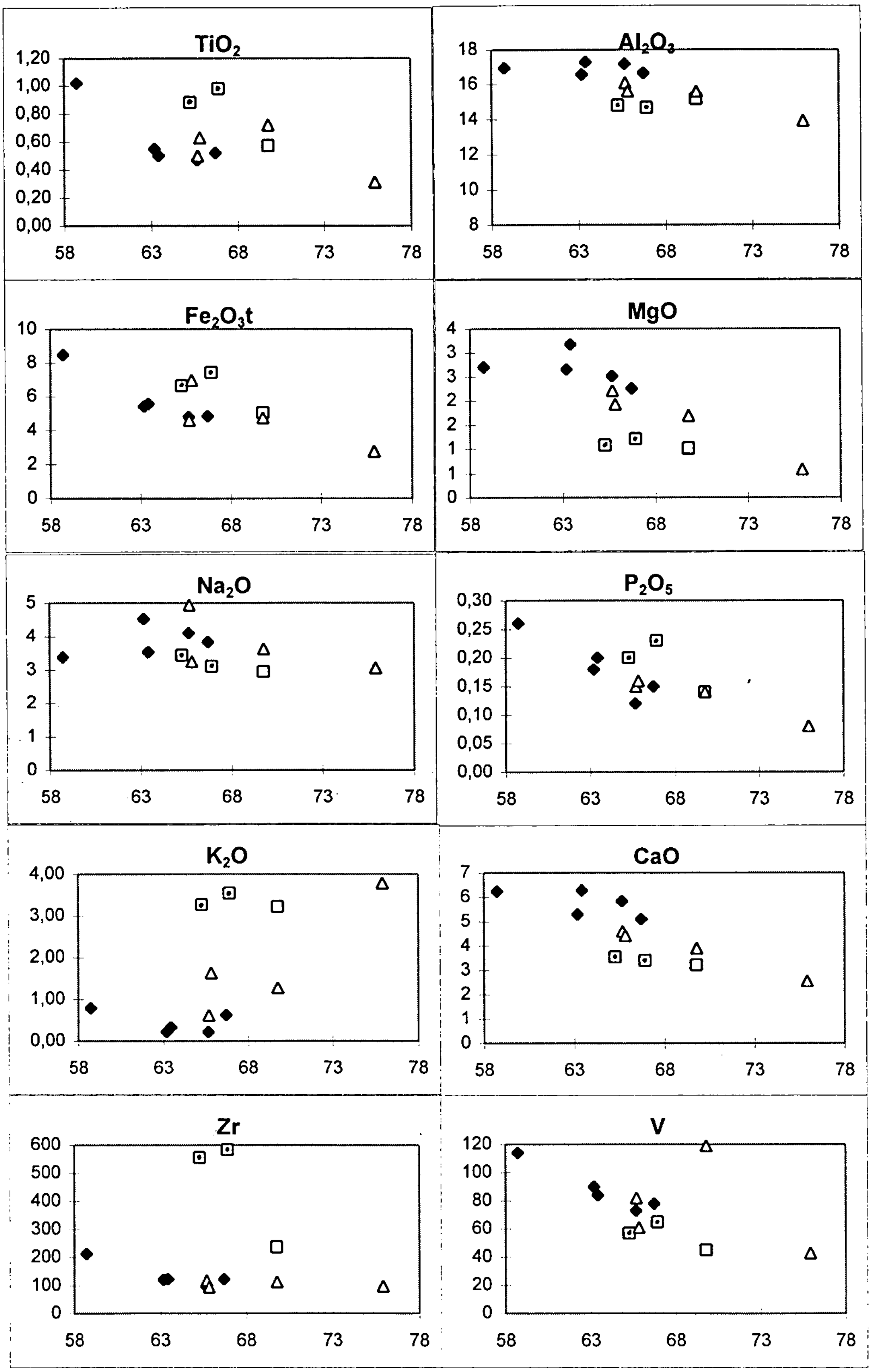
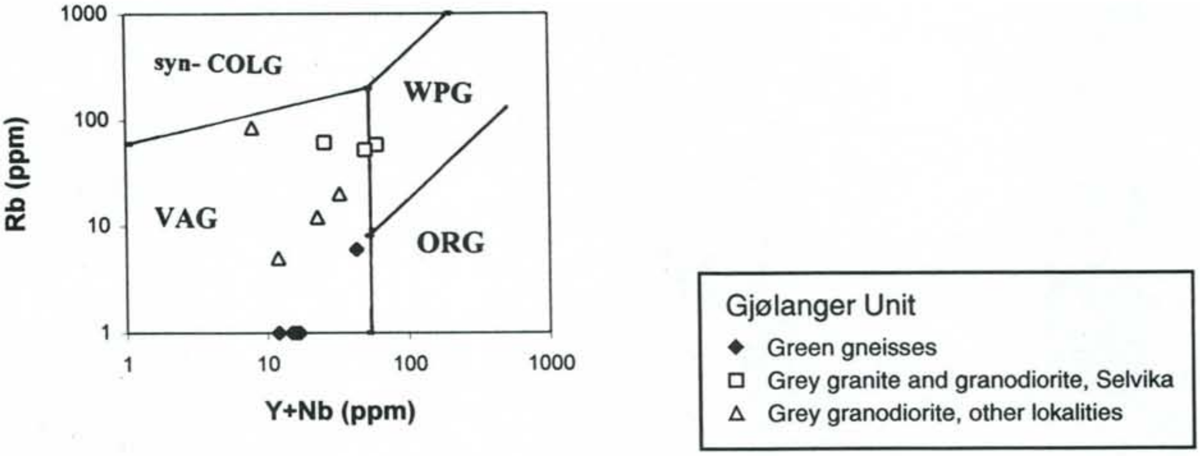


Figure 8. Major and some trace element consentrations of grey and green gneiss lithologies of the Gjølanger Unit plotted against SiO_2. Two Samples from Selvika (locality 6, Plate 4) that plot different from the other samples, are marked with dots.

Gjølanger Unit

- □ Grey granite and granodiorite, Selvika
- Δ Grey granodiorite, other lokalities
- ◆ Green gneisses



Syn-COLG = syn-collision granites, WPG = within plate granites,
VAG = volcanic arc granites, ORG = ocean ridge granites.

Figure 9. The granitoid rocks of the Gjølanger Unit plotted in geochemical discrimination-diagram (from Pearce et al. 1984).

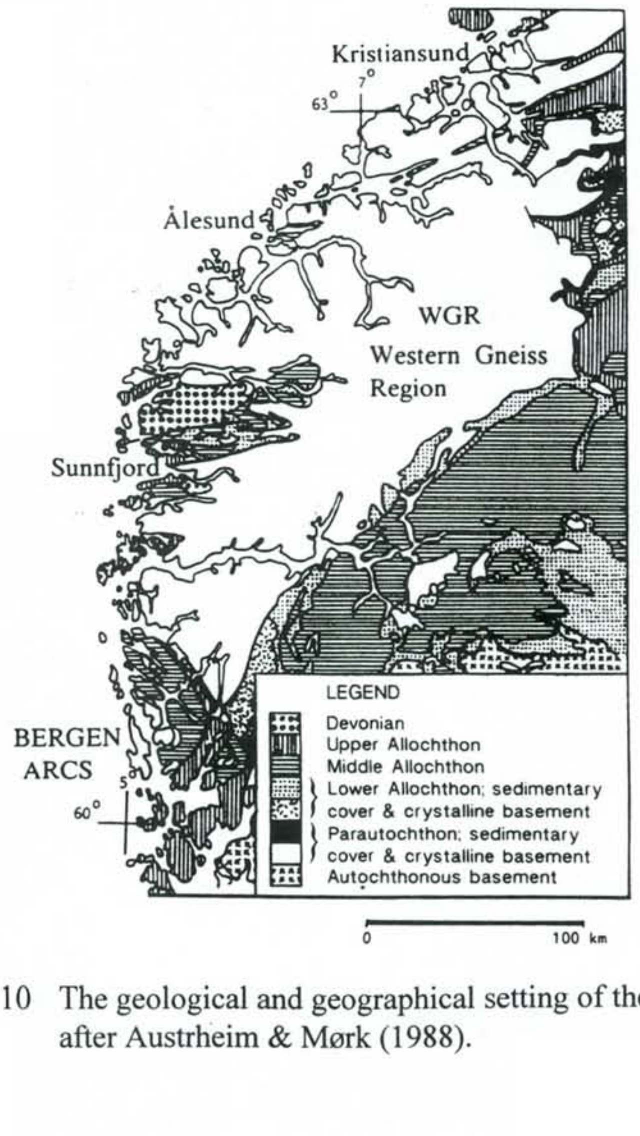


Figure 10 The geological and geographical setting of the Western Gneiss Region (WGR) after Austrheim & Mørk (1988).

Table 1 Whole-rock major and trace element analyses of the rocks.

The Gjølanger Unit

Sample	Rock	Locality	Map coordinates	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^t$	MnO	MgO	CaO	Na_2O	K_2O
ØS-95-49	Grey augengneiss	Selvika	(KP 980 034)	66.91	0.98	14.67	7.43	0.10	1.21	3.39	3.11	3.54
ØS-95-50	Grey granodiorite	Selvika	(KP 980 034)	65.26	0.88	14.79	6.64	0.10	1.08	3.55	3.44	3.27
ØS-95-51	Grey granite	Gjølanger Fisk	(KP 978 033)	69.77	0.57	15.16	5.03	0.07	1.02	3.22	2.95	3.22
ØS-95-83	Grey granodiorite	Jyttavatnet	(LP 016 023)	65.68	0.50	16.10	4.59	0.08	2.21	4.60	4.94	0.61
ØS-95-88	Grey granodiorite	Åsen. Tyssekvam	(LP 005 027)	65.82	0.63	15.61	6.95	0.09	1.93	4.42	3.25	1.63
ØS-95-91	Grey granite	Åsen. Tyssekvam	(LP 002 026)	75.91	0.31	13.93	2.75	0.03	0.59	2.56	3.06	3.79
ØS-95-92	Grey granodiorite	Åsen. Tyssekvam	(LP 005 026)	69.78	0.72	15.58	4.73	0.07	1.69	3.90	3.63	1.28

Sample	Rock	Locality	Map coordinates	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^t$	MnO	MgO	CaO	Na_2O	K_2O
ØS-95-48	Green gneiss	Tyssedalsvatn	(KP 996 034)	58.73	1.02	16.94	8.47	0.12	2.70	6.24	3.38	0.79
ØS-95-78	Green gneiss	Flekke	(LP 040 030)	63.20	0.55	16.57	5.41	0.08	2.65	5.30	4.53	0.22
ØS-95-79	Green gneiss	Flekke	(LP 040 032)	63.43	0.50	17.29	5.55	0.08	3.17	6.28	3.53	0.33
ØS-95-82	Green gneiss	Flekke	(LP 042 037)	65.65	0.47	17.17	4.78	0.07	2.51	5.84	4.10	0.21
ØS-95-85	Green gneiss	Jyttavatnet	(LP 016 023)	66.71	0.52	16.64	4.83	0.07	2.25	5.10	3.84	0.62

The Flekke Unit

Sample	Rock	Locality	Map coordinates	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^t$	MnO	MgO	CaO	Na_2O	K_2O
ØS-95-52	Gabbro	Ystetjørna	(KP 986 009)	47.60	0.11	21.87	7.41	0.09	9.71	10.10	2.71	0.12
ØS-95-53	Gabbro	Ystetjørna	(KP 986 009)	47.71	0.13	18.94	9.94	0.12	12.78	9.07	2.36	0.09
ØS-95-59	Foliated metagabbro	Langesjøen	(KP 952 995)	47.00	0.11	17.67	9.43	0.12	12.07	7.99	2.88	0.26
ØS-95-70	Gabbro	Ystetjønn	(KP 986 009)	49.94	0.32	17.37	7.22	0.12	10.46	13.18	2.06	0.06
ØS-95-71	Gabbro	Ystetjønn	(KP 986 009)	48.46	0.31	17.71	6.87	0.12	10.28	13.17	2.13	0.07

Sample	Rock	Locality	Map coordinates	SiO_2	TiO_2	Al_2O_3	$Fe_2O_3^t$	MnO	MgO	CaO	Na_2O	K_2O
ØS-95-105	Eclogite	Nipane	(KP 982 009)	44.44	2.85	14.02	18.28	0.22	8.67	8.73	1.67	0.05
ØS-95-109	Meta pyroxenite	Gjølanger	(KP 985 031)	49.06	0.43	2.97	10.36	0.10	19.59	16.65	0.08	0.12

The Gjølanger Unit

Sample	P_2O_5	LOI	Sum	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba	La	S	Ce	Nd
ØS-95-49	0.23	0.37	101.94	65	18	13	12	18	122	58	264	45	584	15	1635	18	0.030	38	33
ØS-95-50	0.20	0.43	99.64	57	16	12	9	10	107	52	272	37	556	13	1559	22	0.038	36	22
ØS-95-51	0.14	0.73	101.88	45	21	10	7	11	97	61	210	18	237	8	872	8	0.030	n.d.	5
ØS-95-83	0.15	0.57	100.03	82	60	13	27	21	68	5	576	7	118	5	342	10	0.026	29	15
ØS-95-88	0.16	0.63	101.12	61	48	17	12	17	121	12	306	19	95	4	1262	12	0.028	32	19
ØS-95-91	0.08	0.40	103.41	43	9	5	7	6	34	85	221	5	98	3	738	15	0.025	8	13
ØS-95-92	0.14	0.37	101.89	119	31	12	14	13	76	20	318	19	113	14	734	12	0.026	19	26

Sample	P_2O_5	LOI	Sum	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba	La	S	Ce	Nd
ØS-95-48	0.26	0.53	99.18	114	46	23	14	8	111	6	389	31	213	12	452	23	0.052	37	28
ØS-95-78	0.18	0.60	99.29	90	62	16	33	13	79	0	620	9	121	6	236	15	0.022	29	19
ØS-95-79	0.20	0.49	100.85	84	69	16	36	119	79	0	582	12	123	5	396	7	0.023	24	19
ØS-95-82	0.12	0.45	101.37	73	60	14	32	8	75	0	529	8	97	4	290	11	0.022	19	14
ØS-95-85	0.15	0.73	101.46	78	51	14	27	9	73	0	570	10	123	6	549	10	0.023	36	20

The Flekke Unit

Sample	P_2O_5	LOI	Sum	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba	La	S	Ce	Nd
ØS-95-52	0.03	0.20	99.95	15	36	40	202	18	47	0	294	n.d.	13	4	82	0	0.036	12	6
ØS-95-53	0.04	0.01	101.19	24	97	45	285	22	55	0	264	2	14	2	107	0	0.042	12	7
ØS-95-59	0.02	2.13	99.68	32	100	43	319	24	94	6	304	4	24	4	201	0	0.024	5	8
ØS-95-70	0.02	0.30	101.05	117	1723	40	159	18	40	0	203	9	15	3	94	0	0.032	7	8
ØS-95-71	0.02	0.36	99.50	122	1763	42	161	24	38	0	215	9	15	5	65	0	0.033	10	4

Sample	P_2O_5	LOI	Sum	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba	La	S	Ce	Nd
ØS-95-105	0.02	0.38	99.33	547	113	46	210	23	117	0	27	11	19	4	59	0	0.075	8	8
ØS-95-109	0.03	1.87	101.26	110	1939	60	354	115	99	0	57	15	33	5	55	0	0.112	23	12

Table 2 Sm-Nd isotopic analyses

	Sample No.	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$ [a]	$^{143}Nd/^{144}Nd$	.+/- SE[b]
Py	ØS-95-53	0.7542	1.6841	0.2708	0.513596	0.000007
Pl	ØS-95-53	0.2281	1.269	0.1086	0.511965	0.000004
Wr	ØS-95-53	0.2765	1.1072	0.1510	0.512449	0.000021
Py	ØS-95-70	1.783	4.0806	0.2642	0.513509	0.000006
PL	ØS-95-70	0.1404	0.7978	0.1064	0.511998	0.000027
Wr	ØS-95-70	0.7655	1.9932	0.2322	0.513224	0.000008

(a) The estimated analytical unsertainty is 0.5%

(b) SE = standard error

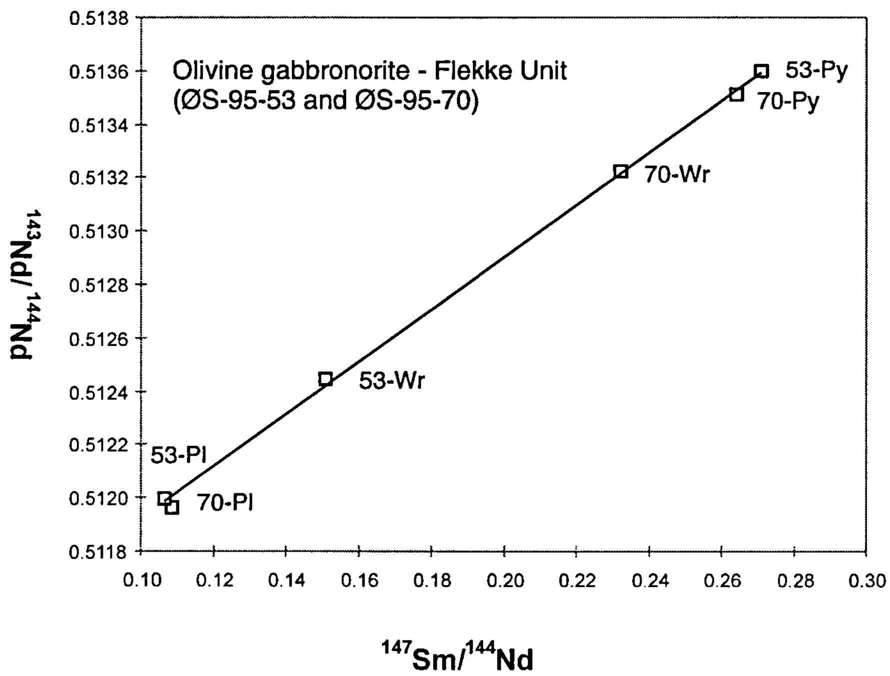


Figure 11. Sm-Nd isochron diagram for the anorthosite and gabbro in the Flekke Unit.

Age: 1522+/-55 Ma (95% conf.)
Initial ratio: 0.510886+/- 0.000065 (95% conf.)
MSDW: 13

Epsilon (CHUR) of initial ratio is 4.3
using present-day CHUR $^{143}Nd/^{144}Nd$ =0.512636 and $^{147}Sm/^{144}Nd$ = 0.1967