The age of the Lødingen granite and its possible regional significance

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A new 11 point Rb-Sr whole rock isochron age from the foliated Lødingen granite has yielded an age of 1644 + 36 Ma (MSWD = 3.4) and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70780. The age is interpreted as the crystallisation age of the pluton. This age is higher than previously published ages and links the Lødingen granite to the emplacement of the mangerite–charnockite suite of the Lofoten-Vesterålen-Tysfjord Province. The initial $^{87}Sr/^{86}Sr$ ratio for the Lødingen granite differs significantly from the initial ratios obtained on the non-mangeritic Tysfjord and Rombak granites. The boundary between the granulite facies rocks in the Lofoten-Vesterålen-Hamarøy area and the normal granites further east, including the Lødingen granite, is interpreted as a fossil isothermal surface now dipping eastwards.

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The Lofoten-Vesterålen Islands represent part of a large region of Precambrian crystalline rocks occurring immediately west of outcrops of Caledonian geosynclinal rocks in North Norway (Fig. 1). The Archean and Early Proterozoic crustal evolution of the Lofoten-Vesterålen terrane is known through detailed geochemical and geochronological work conducted during the last 20 years by Heier and co-workers (Heier 1960, Griffin et al. 1978, Taylor 1975, Jacobsen & Wasserburg 1978). The Middle to Late Proterozoic as well as the Caledonian history of this western segment of Precambrian basement rocks, however, is less well documented and understood (Tull 1977, Griffin et al. 1978, Bartley 1981a, b). The purpose of this paper is to present new Rb/Sr data on the youngest Middle to Late Proterozoic igneous activity in the Lofoten-Vesterålen region and to discuss these data in relation to recent geochronological and structural studies in the Tysfjord-Ofoten-Rombak area (Fig. 2).

General geologic setting

In North Norway, a regionally extensive north-south trending synform (Ofoten Synform), developed largely within allochthonous Caledonian geosynclinal rocks, separates the Lofoten-Vesterålen-Tysfjord Precambrian Basement Province to the west from the autochthonous Precambrian basement of the Norrbotten Province (Baltic Shield) to the east (Fig. 1). Precambrian basement rocks also outcrop in the large Rombak Window (1400 km^2) (Figs. 1 & 2). The basement rocks of the Rombak Window show great similarities to the rocks of the Norrbotten Province; both are composed of minor volumes of supracrustal rocks intruded by large volumes of granitic rocks. Lithologic similarities also exist between the basement rocks of the Rombak Window and the *eastern* portion of the Lofoten-Vesterålen-Tysfjord Basement Province (Vogt 1942, Gustavson 1966). The intrusives of the Rombak Window were emplaced around 1700–1800 Ma ago (Heier & Compston 1969, Gunner 1981). Most commonly geologists have believed that the three basement regions are connected beneath the Caledonian cover rocks, and not separated by any major tectonic breaks. Tull (1973, 1977), on the other hand, favours a model in which the Lofoten-Vesterålen region has moved at least 100 km to the east relative to the Baltic Shield. A similar model was recently postulated by Hodges et al. (1982). In this latter model a low angle, westerly dipping, reverse fault is placed between the basement rocks of the Rombak Window and the Tysfjord-Lofoten-Vesterålen region.

The rocks of the Lofoten-Vesterålen area show a complex geologic history that goes back into the Archean (Griffin et al. 1978, Jacobsen & Wasserburg 1978, Tveten 1978), and they are among the oldest rocks yet reported from Scandinavia. The geologically oldest rocks in the Lofoten-Vesterålen area are migmatitic granulite and amphibolite facies gneisses of generally in-

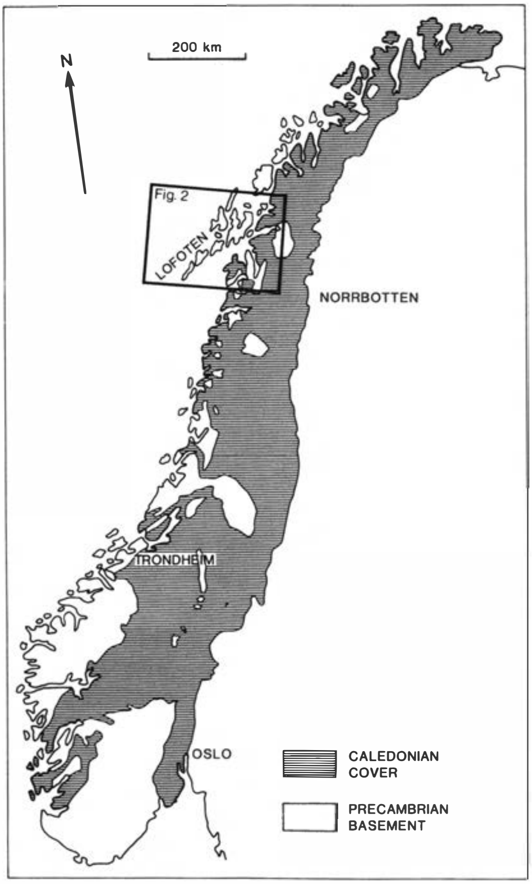

Fig. 1. Index map showing the approximate distribution of Precambrian basement rocks and Caledonian cover rocks in Norway and part of Sweden. Box indicates area covered by Fig. 2.

termediate composition, overlain by a series of early Proterozoic supracrustal rocks (Griffin et al. 1978) (Fig. 2). The migmatites were apparently derived largely by anatexis of an Archean supracrustal sequence (Griffin et al. 1978). The most recent isotopic studies indicate that the protoliths of the migmatite gneisses formed around 2600 Ma ago (Jacobsen & Wasserburg 1978).

The Archean migmatite complex and the Early Proterozoic supracrustal sequence were subjected to regional metamorphism which reached granulite facies over most of the Lofoten-Vesterålen region about 1830 Ma ago. During and after the later part of this metamorphic event, both groups of gneisses were intruded by large volumes of basic, intermediate and acidic magma, most of which crystallised with granulite facies mineralogy. These intrusives cover about half of the Lofoten-Vesterålen area (Fig. 2). Southeastern Hinnøy in Vesterålen is an extensive area of granite and granitic gneiss known as the Lødingen granite. Griffin et al. (1978) suggested emplacement of a dolerite dike swarm (Misra & Griffin 1972) *prior* to intrusion of the Lødingen granite, but definitive field evidence for this relationship is not known to exist. Our own field observations from Tjeldøy and Hamarøy show that basic dikes in these areas post-date the emplacement of granites in the Tysfjord-Hamarøy Tjeldøy region.

Rb-Sr whole rock isotope data from granites in the Tysfjord-Hamarøy-Lødingen area led Heier & Compston (1969) to conclude that emplacement of these plutons took place around 1520 ± 35 Ma before present. More recent data by Griffin et al. (1978) suggested that the Lødingen granite was emplaced around 1380 ± 30 Ma. Neither of the isochron plots from these two studies, however, defines statistically valid isochron ages (Brooks et al. 1972).

Sr and Pb isotope data from the 1800–1700 Ma old mangerite intrusions of the Lofoten-Vesterålen region (Malm & Ormaasen 1978) exclude the possibility that these originated by extensive anatexis of the surrounding older continental crust. The variation in initial ratio of the different mangerite bodies suggests some involvement of crustal material in the genesis of some of them. The Lødingen granite, on the other hand, has a high initial $^{87}Sr/^{87}Sr$ ratio of 0.719 (Griffin et al. 1978), compatible with it being derived by anatexis from the surrounding mangerites at its time of formation. Griffin et al. (1978) considered the Lødingen granite to represent a separate magmatic event unrelated to the emplacement of the mangerites.

Several lines of evidence suggest that the isotopically determined 'ages' of the Lødingen granite do not date a meaningful geologic event. These include: (1) the discrepancy between the two previously published age dates on the Lødingen granite; (2) the date published by Griffin et al. (1978) failed to define a true isochron; (3) the lack of plutons of similar age in the nearby basement areas (Heier & Compston 1969, Wilson & Nicholson 1973, Gunner 1981); and (4) the lithologic similarities of the Lødingen granite to some of the granites located farther east, which are dated at around 1700 Ma (Heier & Compston 1969, Gunner 1981, Andresen & Tull in prep.).

The youngest Precambrian (?) rocks of the

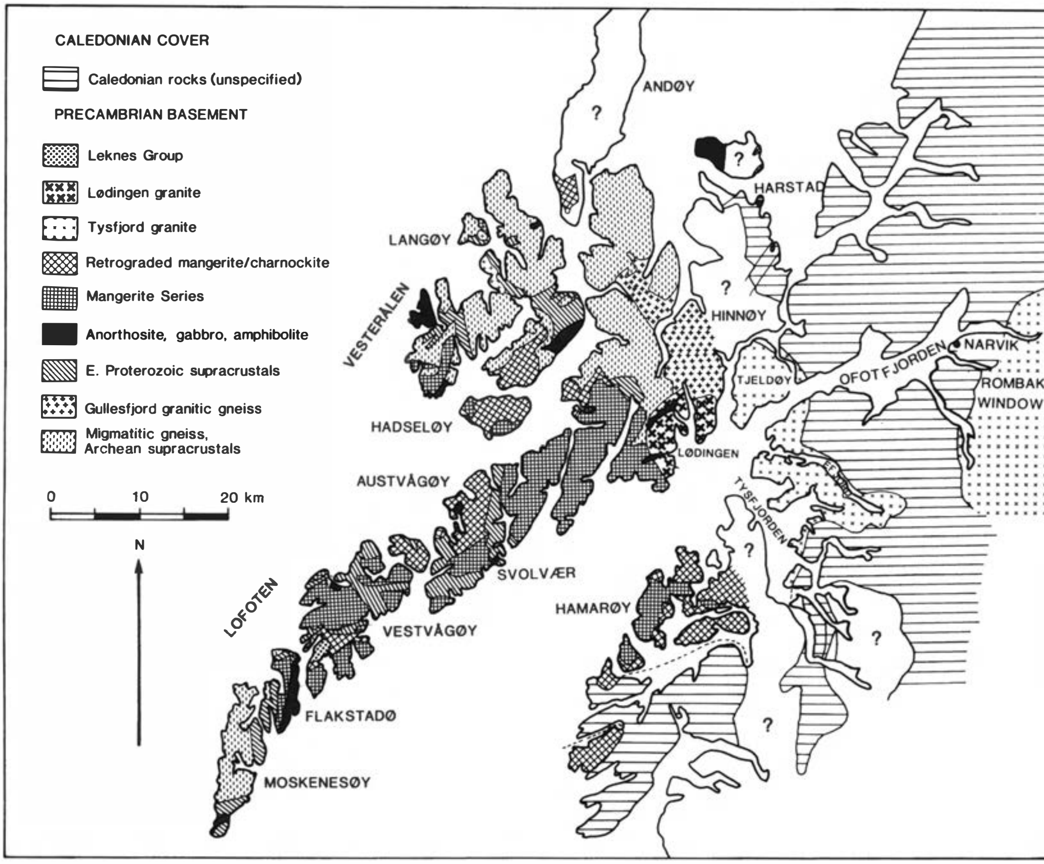

Fig. 2. Simplified geologic map of the Lofoten-Vesterålen-Tysfjord Province (after Griffin et al. 1978 and Tveten 1978) showing the location of the Lødingen granite.

Lofoten-Vesterålen islands are a thin sequence of pelitic to semipelitic metasediments, referred to as the Leknes Group (Fig. 2) by Tull 1973, 1977). Similar rocks occur on Værøy (Griffin & Taylor 1979). A Rb/Sr whole rock 'errorchron' of 1140 Ma obtained on the supracrustals of the Leknes Group has been interpreted as dating an amphibolite facies metamorphism observed in the region (Griffin et al. 1978). A slightly lower age (900–1000 Ma) was obtained for the amphibolite facies metamorphism of the supracrustal rocks on Værøy (Griffin & Taylor 1979). Widespread retrogression frequently observed in the mangerites is considered to be associated with this amphibolite facies metamorphism (Tull 1973, 1977, Griffin et al. 1978). Griffin & Taylor (1978) interpreted the post-amphibolite facies mylonitisation on Værøy to be of late Precambrian or early Caledonian age.

Except for the early Caledonian fabric at the contact with the overlying Caledonian cover rocks on east Hinnøy (Fig. 2), Griffin et al. (1978) considered the main part of the Lofoten-Vesterålen terrane to be only slightly affected by Caledonian deformation and metamorphism.

Lødingen granite

The Lødingen granite, the subject of this study, underlies an area north of Vestfjorden and east of the Raftsund mangerite (Fig. 2). It is commonly heterogeneous, even on outcrop scale, with lenses and bands of mafic inclusions, but is dominantly granitic in composition (see Appendix). The ubiquitous presence of a marked foliation and the common occurrence of K-feldspar porphyroclasts (?) distinguish the body from the red granites of Langøy which have clear affinities with the mangerite series (Malm & Ormaasen

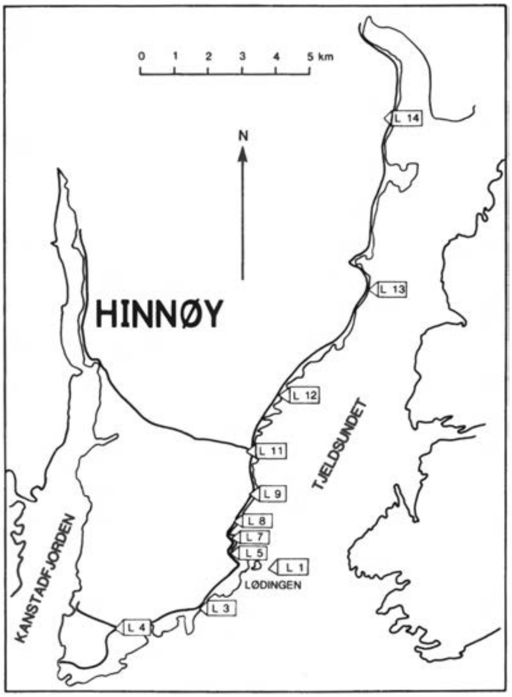

Fig. 3. Map of Lødingen and vicinity showing sample locations.

1978). The age of the foliation is not clear. Griffin et al. (1978) have suggested that it may be related to the 1100 Ma metamorphic event believed to have affected the Leknes Group, but equivalent fabrics in the Tysfjord gneiss granite to the east on the mainland are considered to be of Caledonian age (Tull et al. 1981). The Lødingen granite intrudes the Raftsund mangerite which has been dated at 1705 Ma (Griffin et al. 1975). The contact relationship between the Lødingen granite and the foliated granites on Tjeldøy and in Tysfjord are unclear. If an intrusive relationship exists, it must be found in the Ofotfjord.

Geochronology

Sampling and analytical methods

Fourteen samples representing a great variety of different lithologies of the Lødingen granite were collected along the road through the village of Lødingen (Fig. 3). A brief petrographic description of the analysed samples is given in Appendix 1. As can be seen from Fig. 3, the samples are spread across a fairly large area of the Lødingen granite.

Each sample, which weighed 4–10 kg, was crushed in a steel jaw crusher. A split of the resulting gravels was finely ground in a tungsten carbide swingmill. Rb and Sr content in the finely ground whole rock samples were determined by duplicate X-ray fluorescence spectrography on all 14 samples following the methods described by Norrish & Chappell (1967) (Table 1). Unspiked measurements of $^{87}Sr/^{86}Sr$ were made for 11 of the samples (Table 1) using the V6 Micromass 30 mass spectrometer at the Mineralogisk-Geologisk Museum, University of Oslo, and procedures similar to those described by Pankhurst & O'Nions (1973). Variable mass discrimination in $^{87}Sr/^{86}Sr$ was corrected by normalizing $^{88}Sr/^{86}Sr$ to 8.3752 (Faure & Hurley 1963). The ^{87}Rb decay constant used in age calculations is $1.42 \times 10^{-11} Yr^{-1}$ Steiger & Jäger 1977). All

Table 1. Rb, Sr data for the Lødingen granite.

Sample no.	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ (SE = 1 σ
Lø 1.	128.71	187.71	1.9940	0.75536 ± 0.00012
Lø 3.	118.09	206.73	1.6583	0.74677 ± 0.00008
Lø 5.	177.55	44.51	11.7886	0.98484 ± 0.00007
Lø 7.	145.39	21.35	20.6162	1.18165 ± 0.00009
Lø 8.	115.41	166.45	2.0142	0.75491 ± 0.00005
Lø 9.	133.96	145.02	2.6694	0.77048 ± 0.00009
Lø 11.	141.52	119.68	3.4417	0.79065 ± 0.00009
Lø 12.	168.10	105.20	4.6216	0.82003 ± 0.00006
Lø 13.	175.48	31.38	16.8059	1.10777 ± 0.00007
Lø 14.	159.95	49.10	3.1186	0.78004 ± 0.00007
*Lø 4.	120.87	194.73	1.80483	0.75412 ± 0.00041

* Not included in the regression analysis

other Rb-Sr age dates cited in this paper have been recalculated using this decay constant. Regression lines were calculated using the technique of York (1969). Following Brooks et al. (1972), a quality of fit number (MSWD) of 2.5 has been used as a cut-off level for a straight line, where the scattering of data points about the best-fit line is due only to experimental error. In assigning errors to the regression points, the coefficient of variance for Rb/Sr is taken as 1 %. The standard errors for $^{87}Sr/^{86}Sr$ (1 σ) for each sample are listed in Table 1. All other errors quoted in this paper are two sigma errors.

Analytical results

Figure 4 and Table 1 show the Rb and Sr data obtained on the 11 whole-rock samples. A best-fit line through 10 of the sample points, not including Lø 4, gives an isochron age of 1644 ± 36 Ma with a MSWD = 3.4 and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70780 ± 0.00074. Sample Lø 4, despite its position on the best-fit line, has been excluded from the calculations due to analytical problems reflected in its large errors (Table 1). If included in the calculations, it does not change the age significantly but increases the 2 sigma error (to ± 50 Ma) as well as the MSWD. The MSWD value of 3.4 is slightly higher than expected from analytical errors and indicates some amount of isotopic disequilibrium between the analysed samples.

Geologic interpretation of the isotope data

Despite the slight isotopic disequilibrium that exists between the analysed samples, the best-fit isochron line of 1644 ± 36 Ma is interpreted as dating a meaningful and significant geologic event. The most likely interpretation is to consider the 1644 ± 36 Ma age as the intrusive age of the Lødingen granite, or more correctly, the Lødingen plutonic complex, since samples from several intrusive bodies are apparently involved in the investigation. This interpretation is in agreement with field observations which show that the Lødingen granite is intruded into the 1705 Ma old Raftsund mangerite (Griffin et al. 1975, 1978). The scatter of data points along the best-fit line can be due either to variable initial $^{87}Sr/^{86}Sr$ ratios in the different plutons of the Lødingen plutonic complex at the time of emplacement, or it may be related to opening of the Sr-isotope system during the foliation forming event, or a combination of the two. An emplacement age of 1644 ± 36 for the Lødingen granite, as proposed here, is distinctly older than the previously quoted age of 1380 ± 80 Ma (Griffin et al. 1978). The few data points and the large error (80 Ma) associated with the 1380 Ma isochron age indicate that this age is not representative of any major geologic event in the Lofoten-Vesterålen terrane but instead represents an 'errorchron'.

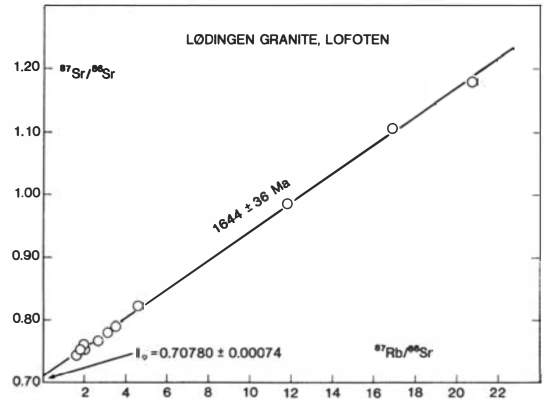

Fig. 4. Isochron plot of the Lødingen granite samples.

The Lødingen granite in a regional context

The isotopic data presented above suggest that the emplacement of the Lødingen granite is slightly but distinctly younger than the mangerite and charnockite intrusions which invaded wide areas of the Lofoten-Vesterålen terrane around 1800-1700 Ma ago. A genetic link of some sort between the two episodes of magmatism is therefore likely. One possibility is that the mangerites and related high-pressure rocks were derived from mantle rocks and emplaced in the lower continental crust 1800–1700 Ma ago (Griffin et al. 1978). The emplacement of large volumes of hot magma in the lower crust as indicated by the geobarometry (Krogh 1977, Ormaasen 1977, Griffin et al. 1978) would then result in a temperature increase in the surrounding continental crust high enough to cause anatexis.

The crystallisation age of 1644 ± 36 for the Lødingen granite is essentially the same as that obtained by Brueckner (1971) from the Torset granite (1665 ± 80 Ma) on Langøy (Fig. 3). The initial $^{87}Sr/^{86}Sr$ ratios for the two granites, 0.7078 ± 7 and 0.7057 ± 35, respectively, also overlap.

The age obtained from the Lødingen granite is slightly but distinctly younger than the recently obtained ages on the Tysfjord and Rombak granites. A Rb-Sr whole-rock study of the Tysfjord gneiss granite along Efjord (Fig. 2) has yielded an age of 1742 ± 46 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7115 ± 25 (Andresen & Tull, in prep.). Gunner (1981), in a study of the granites of the Rombak Window, obtained an age of 1780 ± 85 Ma; the initial ratio was 0.700 ± 6. The existing data thus indicate, despite petrographic similarities, that the non-mangeritic Svecofennian granites in the Lofoten-Vesterålen-Rombak area derived at different times from a heterogenous crustal source. If mantle-derived material from an isotopically normal mantle is involved, it must have been contaminated by various proportions of crustal material. Gunner (1981), following Lundqvist (1979), has proposed that the apparent eastward increase in initial $^{87}Sr/^{86}Sr$ ratios of Svecofennian igneous rocks in northern Scandinavia reflects an E-W variation in parent rock type related to an eastward dipping subduction zone. The age and initial ratio of the Lødingen granite do not contradict this model.

Despite the fact that some of the foliated granites on Hamarøy may be retrograded mangerites (Griffin et al. 1978), it seems clear that the P-T conditions under which the 1800-1700 Ma old plutons in the Lofoten-Vesterålen region (Griffin et al. 1978) and the Tysfjord-Hamarøy region (Malm & Ormaasen 1978) crystallised were different. Since the ages of the various plutons are essentially the same, they may represent magmas that solidified at different levels in the continental crust. The boundary between the mangerite-charnockite series to the west and the ordinary granites to the east may represent a 1700 Ma old isothermal surface, once possibly subhorizontal but now dipping eastwards.

The relative as well as absolute age of the dolerite dike swarms and their significance in the evolution of the Lofoten-Tysfjord region are not clear. Griffin et al. (1978) considered the large swarm of vertical dolerite dikes in the Austvågøy-SW Hinnøy area to post-date the mangerites, but to predate the Lødingen granite. If this relative age relationship is correct it implies that these dolerite dikes were emplaced in the time interval 1700-1650 Ma before present. If these dikes are then of the *same age* as those on Tjeldøy (Gabrielsen pers. comm. 1981) and around Tysfjord, it implies that the normal granites, now weakly foliated, which occur in these areas represent granites *older* than the Lødingen granite. Until the age and initial $^{87}Sr/^{86}Sr$ ratios of the granitic rocks on Tjeldøy and in Tysfjord are determined, the possibility that there are two generations of basic dikes cannot be ruled out. A third possibility is that all the dolerite dikes are younger than the Lødingen granite, but that they never intruded the continental crust now occupied by the Lødingen granite. However, the back-veining observed between the dolerite dikes and the mangerites they intrude on Austvågøy (Griffin et al. 1978) suggests that these dikes cannot have been emplaced long after the mangerite emplacement.

Conclusions

The new Rb and Sr isotope data presented above indicate that the Lødingen granite is 1644 ± 36 Ma old and thus significantly older than previously suggested. The initial $^{87}Sr/^{86}Sr$ ratio of 0.7078 indicates a derivation from within the continental crust, most probably associated with the subjacent emplacement of large volumes of mangerites and associated high pressure rocks in the lower crust, now making up the Lofoten-Vesterålen islands. It is further suggested that the transition from the Lofoten-Vesterålen granulite facies terrane to the granites of Tysfjord, Rombak and further east into Sweden reflects the crossing of a fossil isothermal surface. The obtained age and initial ratio also indicate that the petrographically similar Lødingen and Tysfjord granites are isotopically different and did not crystallise from the same magma. The basic dike swarms that invade certain areas of the Lofoten-Tysfjord region are not *all* necessarily older than the Lødingen granite. There may be two generations of basic dike swarms; one predating and the other post-dating the emplacement of the Lødingen granite.

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Appendix I

Sample L-1 Weakly foliated, medium-grained granite with up to 2 cm long flesh coloured K-feldspar megacrysts. The foliation is defined by elongated aggregates of mafic minerals and parallel-oriented K-feldspar megacrysts. Major minerals are K-feldspar (50 %), quartz (20 %), biotite (15 %) plagioclase (10 %) and amphibole (5 %), Epidote occurs as an accessory mineral.

Sample L-3 Weakly foliated medium grained granite, petrographically similar to L-1.

Sample L-4 Fine- to medium-grained porphyric granite with an indistinct planar fabric, defined by elongate aggregates of mafic minerals. K-feldspar (45 %), biotite (15 %), plagioclase (10 %) and amphibole (5–10 %) are the rock forming minerals. Zircon and epidote occur in accessory amounts.

Sample L-5 Weakly foliated, lightly pink-coloured, leucocratic, fine- to medium-grained granite. Foliation is defined by elongated aggregates of mafic minerals. The larger quartz and feldspar grains are partly recrystallised along the edges. Biotite (10 %), locally partly chloritised, is the only rock-forming mafic mineral Epidote occurs in accessory amounts.

Sample L-7 Leucocratic, lightly pink-coloured, fine grained granite. K-feldspar (45–50 %), quartz (25 %) and plagioclase (20–25 %) define an equigranular texture. Brown biotite (5–10 %) occurs as evenly distributed euhedral grains. Some biotite is altered to chlorite.

Sample L-8 Well-foliated, fine- to medium-grained granite, with 1–2 cm large porphyroclasts (?) of K-feldspar. The foliation is interpreted as a recrystallised mylonitic fabric. K-feldspar (40–45 %), quartz (20–25 %), plagioclase (20 %) and biotite (15 %) make up the bulk of the rock. Amphibole (<5 %) occurs as 3–4 mm large poikilitic grains. Epidote is a common secondary mineral.

Sample L-9 Well-foliated, fine- to medium-grained granite with large flesh coloured megacrysts of K-feldspar. K-feldspar makes up 55–60 % of the rock. Other minerals are quartz (25 %), biotite (10–15 %), plagioclase (15 %), poikilitic amphibole (3–4 %) and epidote (2 %). The subhedral biotite flakes form a planar fabric.

Sample L-11 Foliated medium-grained granite with some flesh-coloured K-feldspar megacrysts. K-feldspar makes up 45–50 % of the rock. Other rock forming minerals are quartz (20–25 %), plagioclase (20–25 %), and biotite (10–12 %). Zircon and epidote occur in accessory amounts. Biotite is locally altered to chlorite.

Sample L-12 Foliated medium-grained granite with some flesh-coloured K-feldspar megacrysts. Petrographically indistinguishable from Sample L-11.

Sample L-13 Well-foliated, fine- to medium-grained granite. K-feldspar (40 %), quartz (20 %), plagioclase (25 %), biotite (7–8 %) and amphibole (5–6 %) are the dominant minerals. Epidote occurs in accessory amounts.

Sample L-14 Strongly foliated, fine-grained gneiss granite with some large flesh-coloured K-feldspar porphyroclasts. K-feldspar (50 %), quartz (20 %), plagioclase (15 %) and biotite (15 %) are the dominant minerals. Epidote, sericite, sphene and chlorite (after biotite) occur in accessory amounts. Large (2–3 mm) euhedral magnetite grains occur locally.

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