

# The Caledonian tectono-metamorphic evolution of the Lindås Nappe: Constraints from U-Pb, Sm-Nd and Rb-Sr ages of granitoid dykes

Alexander Kühn, Johannes Glodny, Håkon Austrheim & Arne Råheim

Kühn, A., Glodny, J., Austrheim, H. and Råheim, A. 2000: The Caledonian tectono-metamorphic evolution of the Lindås Nappe: Constraints from U-Pb, Sm-Nd and Rb-Sr ages of granitoid dykes. *Norsk Geologisk Tidsskrift*, Vol. 82, pp. 45–57. Trondheim 2002. ISSN 029-196X.

Petrological and isotopic (Rb-Sr, Sm-Nd and U-Pb) investigations of garnet bearing pegmatites and trondhjemites in the northernmost Lindås Nappe, Bergen Arcs, Norway are reported. The formation of these pegmatites (sample sites Håkjerringa and Ervik) is dated to around 425 Ma by means of Rb/Sr and Sm/Nd mineral isochrons. U-Pb dating of zircons from a trondhjemitic dyke (sample site Fonnes quay) yields a lower intercept age of  $418 \pm 9$  Ma. Based on field observations, negative  $\epsilon_{\text{Nd}}$  values and a comparatively high initial  $^{87}\text{Sr}/^{86}\text{Sr}$  for the Håkjerringa pegmatite, we suggest a crustal-anatectic source for the pegmatite-forming melts. The ages are interpreted to represent the time of crystallization of the granitic melts at mid-crustal levels (8–10 kbar, 650 to 700 °C). The partial melts formed due to the addition of a fluid phase that lowered the solidus of the rocks during a major phase of Scandian deformation in the Lindås Nappe. Fluid mediated eclogitization (17 kbar, 700 °C) took place in the western part (Holsnøy), contemporaneously with the formation of the granitoid dykes. This either means very rapid exhumation from depths corresponding to 17 kbars to 10 kbars. Or, and more likely, that the Lindås Nappe represents a part of a former crustal section where the bottom parts (Holsnøy) and the shallower north-eastern parts (Lindås-Austrheim) experienced hydration at the same time.

Alexander Kühn and Håkon Austrheim, Mineralogical Geological Museum, University of Oslo, Sars'gate 1, NO-0562 Oslo, Norway  
Johannes Glodny, GeoForschungsZentrum Potsdam, PB 3.1, Telegrafenberg C2, DE-14473 Potsdam, Germany  
Arne Råheim, Institute for Energy Technology, P.O. Box 40, NO-2027 Kjeller, Oslo.

## Introduction

The Lindås Nappe forms what is volumetrically the most important unit of the Bergen Arcs, a series of Caledonian thrust sheets centred around the city of Bergen (Sturt et al. 1975). These units are interpreted as far-travelled nappes (Fig. 1) thrust onto the autochthonous/parautochthonous Precambrian basement, represented by the Øygarden Gneiss Complex in the west and the Western Gneiss Region in the east. From west to east the units of the Bergen Arcs are the Minor Bergen Arc, the Ulriken Gneiss, the Lindås Nappe and the Major Bergen Arc (Fig. 1). The Kvalsida gneiss, as defined by Henriksen (1979), is situated at the contact between the Major Bergen Arc and the Western Gneiss Region. The Major and Minor Arcs have been interpreted to be part of the Upper Allochthon containing dismembered ophiolite fragments, e.g. the Gulffjellet Ophiolite and associated metasediments of oceanic affinity (Furnes et al. 1980; Thon 1985; Wennberg et al. 1998). The Ulriken Gneiss consists of a Precambrian granitic/migmatitic complex and a greenschist facies sedimentary cover and is also regarded as part of the Upper Allochthon.

The Lindås Nappe is composed of rocks belonging to the anorthosite-mangerite-charnockite-granite suite

(AMCG-suite). The crystallization ages that have been determined for this intrusive suite range between  $1237 \pm 43$ –35 Ma and  $951 \pm 2$  Ma (Bingen et al. in press, and references therein). These rocks experienced a granulite facies metamorphism during the Grenvillian Orogeny, between 929 Ma (Bingen et al. in press) and  $910 \pm 10$  Ma ago (Cohen et al. 1988). In addition to the rocks of the AMCG suite, the Lindås Nappe contains granulite facies gneisses of unknown origin. During the Caledonian orogeny the rocks were overprinted by eclogite facies and amphibolite-facies metamorphism along fractures and shear zones (Griffin 1972; Austrheim & Griffin 1985; Austrheim 1987). During eclogite facies conditions quartz-omphacite veins are recognized on Holsnøy and crucially linked to the high-pressure eclogite-facies metamorphism (Andersen et al. 1990).

The position of the Lindås Nappe in the Caledonian tectonostratigraphy of Western Norway and its tectono-metamorphic history is a matter of debate that has been addressed in several recent contributions (Boundy et al. 1996; Boundy et al. 1997a; Bingen et al. (2001); Wennberg et al. 1998a; Milnes & Wennberg 1997; Fossen & Dunlap 1998). Based on lithological similarities, the rocks from the Lindås Nappe have traditionally been correlated with the Jotun Nappe and consequently regarded as part of the

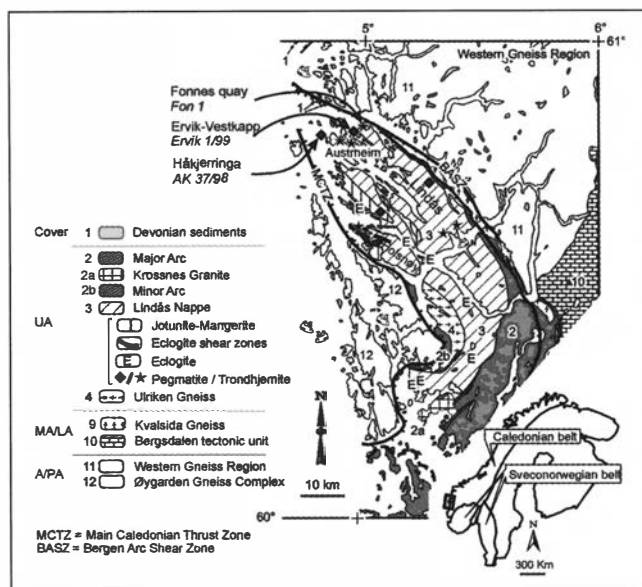


Figure 1. General geological map of the Bergen Arc area. The location of the studied localities in the northernmost part of the Lindås Nappe is indicated. The map is modified after Ragnhildsveit and Helliksen (1997) and Milnes & Wennberg (1997). UA: Upper Allochthon, MA/LA: Middle-/Lower Allochthon, A/PA: Autochthon/Parautochthon.

Middle Allochthon. However, Wennberg et al. (1998a) pointed out that the Lindås Nappe differs from the Jotun rocks in several aspects such as the Pre-Scandian eclogite-facies metamorphism, the higher degree of internal amphibolite-facies deformation and the numerous occurrences of Caledonian dykes of trondhjemitic to granitic composition. In contrast, the granitoid dykes (called Trondhjemites by Goldschmidt 1916) from the Jotun area have been dated to a late Grenvillian age of  $887 \pm 101$  Ma and  $769 \pm 260$  Ma (Koestler 1982). Therefore the Lindås Nappe is also interpreted as part of the Upper Allochthon and regarded to represent fragments of micro-continents from Iapetus.

Based on Ar-Ar, Rb-Sr and U-Pb geochronology, Boundy et al. (1996, 1997a) suggested that the eclogites from the Lindås Nappe are Pre-Scandian (older than 450 Ma) in age and are thus older than the eclogites from the Western Gneiss Region. According to their interpretation, the rocks experienced an early Caledonian (>450 Ma; Ar-Ar hornblende) eclogite-facies metamorphism followed by rapid exhumation and cooling below 325 °C at around 430 Ma (Ar-Ar muscovite). However, Bingen et al. (1998) reported metamorphic zircon U/Pb ages of ca.  $420 \pm 4$  Ma, and Cohen et al. (1988) presented a Rb/Sr age of  $421 \pm 68$  Ma based on WR- and mineral separates, supposed to represent the age of eclogite-facies metamorphism. Although Bingen et al. (2001) reinterpreted these data in accordance with the work of Boundy et al. (1996, 1997) the timing of eclogite-facies metamorphism is still a matter of discussion. Altogether the age data available for the eclogite facies and subsequent amphibolite-facies metamorphism (Table 4) apparently are inconclusive and contradictory.

Isotopic dating of dykes with clear relation to metamorphism and deformation helps to constrain the evolution of poly-metamorphic terrains. The dykes investigated crosscut granulite-facies structures, but locally they appear reworked by amphibolite-facies shear zones. The possibility of resolving the questions concerning the timing of both the eclogite facies and amphibolite-facies metamorphism and deformation by dating of granitoid dykes inspired the present study.

## Geological setting and field relationships

The rocks of the Lindås Nappe and adjacent areas of the Major Bergen Arc are intruded by numerous pegmatites, fine-grained granitic to trondhjemitic dykes and sheets ('white granites', Kolderup & Kolderup 1940) and granitic bodies (e.g. Krossnes granite, Fossen & Austrheim 1988). The relatively large Krossnes granite has been dated by means of Rb-Sr whole rock analysis to an age of  $430 \pm 6$  Ma (Fossen & Austrheim 1988). The area investigated in our study is situated in the northernmost part of the Lindås Nappe and consists of granulite- and amphibolite-

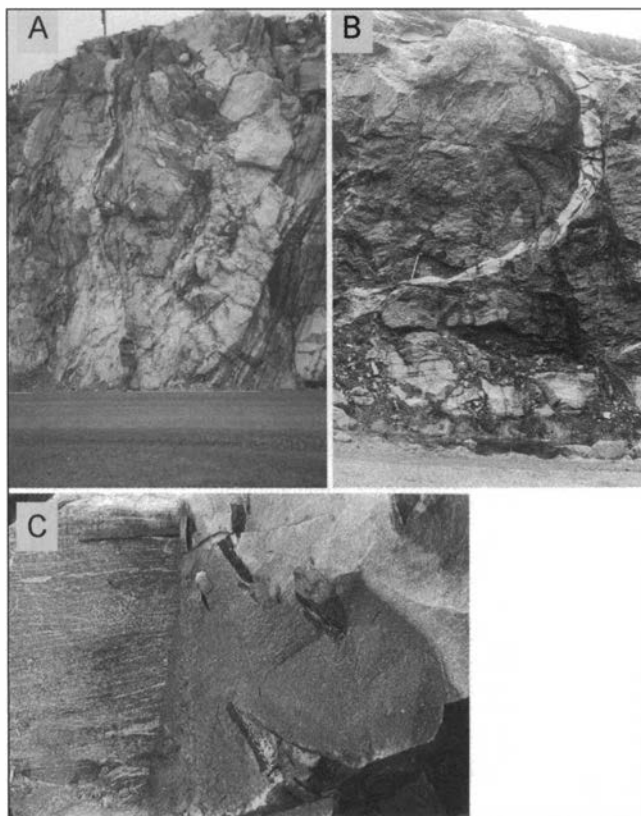


Figure 2. (A) Pegmatite dyke on Håkjerringa island, northernmost Lindås Nappe. (B) Trondhjemite dyke, deformed by an amphibolite-facies shear zone, Ulvøya, northern Lindås Peninsula. (C) fine-grained trondhjemite dyke with angular, mafic xenoliths (restites), crosscutting the foliated granulite-facies granulite, Fossnes quarry, northern Lindås peninsula. The hammer used for scale (upper left corner) is approximately 40 cm long.

**Table 1. Geochronological data available on rocks and minerals from the Lindås Nappe.**

System	Location	Age (Ma)	Event dated	Reference
<b>U/Pb zircon, ID-TIMS</b>				
eclogite	Holsnøy	456 +/- 7	eclogite facies metamorphism	Bingen et al., 2001
eclogite	Holsnøy	419 +/- 4	eclogite facies metamorphism?	Bingen et al., 2001
<b>U/Pb zircon, SIMS</b>				
eclogite	Holsnøy	455 +/- 32	eclogite facies metamorphism	Bingen et al., 2001
<b>U/Pb titanite-epidot-zircon, ID-TIMS</b>				
eclogite	Holsnøy	450 +/- 10	eclogite facies	Boundy et al., 1997
eclogite	Holsnøy	462 +/- 42	eclogite facies	Boundy et al., 1997
grt-amphibolite	Bakkøyni	470	amph-fac. (8-12 kbar), cooling 500°C	Boundy et al., 1997
<b>Sm/Nd, whole rock &amp; minerals</b>				
eclogitic qtz-vein	Radøy	440 +/- 12	eclogite facies	Boundy et al., 1997
<b>Ar/Ar amphibole</b>				
Grt-amphibolite	Bakkøyni	455 +/- 2 & 439 +/- 4	amph-fac. (8-12 kbar), cooling 500°C	Boundy et al., 1996
eclogite	Holsnøy	448 +/- 4	cooling 500°C	Boundy et al., 1996
<b>Ar/Ar muscovite</b>				
eclogite	Holsnøy	463 +/- 1	excess argon	Boundy et al., 1996
eclogite	Holsnøy	451 +/- 1	excess argon	Boundy et al., 1996
eclogite	Holsnøy	433 +/- 4 to 430 +/- 1	cooling 375°C	Boundy et al., 1996
<b>Ar/Ar biotite</b>				
sheared dyke	Bergen	433 +/- 3	cooling 375°C	Fossen and Dunlap, 1998
<b>Rb/Sr mineral isochrone</b>				
eclogite	Holsnøy	421 +/- 68	eclogite-facies shearing	Cohen et al., 1988
amphibolite/biotite	Radøy	409 +/- 8	shearing	Austrheim, 1990
pegmatite	Håkjerringa	422 +/- 6	intrusion	this study
pegmatite	Ervik	428 +/- 6	intrusion	this study
granite	Krossnes	430 +/- 6	intrusion	Fossen & Austrheim, 1988
<b>Sm/Nd, whole rock &amp; garnet</b>				
pegmatite	Håkjerringa	431 +/- 5	intrusion	this study
pegmatite	Ervik	422 +/- 17	intrusion	this study
<b>U/Pb zircon, ID-TIMS</b>				
trondhjemite	Fonnes	418 +/- 9	anatexis/shearing	this study

facies anorthosites, metagabbros and heterogeneous garnet-, clinopyroxene- and orthopyroxene-bearing granulites and gneisses, presumably Precambrian. In this area no eclogite-facies rocks are known. Only amphibolite-facies reworking and retrogression occur and assemblages containing amphibole, plagioclase, kyanite, staurolite and garnet recording medium-grade conditions are observed. But as on Holsnøy, in the western segment of the Lindås Nappe (Fig. 1) where the eclogite-facies metamorphic reactions are restricted to intense fluid infiltration and deformation, all the metamorphic changes in the studied

area are caused by the addition of fluids and/or by deformation. Areas that escaped fluid infiltration remain unreacted with their original Grenvillian mineral assemblages preserved.

The granitoid dykes and pegmatites cut the granulite facies foliation and crosscut each other. They become deformed, sheared, folded and boudinaged in amphibolite-facies shear zones ranging from one to several tens of metres in width. The intrusion of the dykes therefore predates or is contemporaneous with the final stages of amphibolite-facies deformation. The majority of the

granitoid veins are between 10 and 20 cm across but occasionally they are up to several metres wide. In areas with a low degree of deformation, the dykes appear undeformed and can be followed over several hundreds of metres. In the vicinity of the granitic dykes, the granulites become strongly affected by the intruding dyke. In some parts they become deformed and contain quartz-rich schlieren associated with biotite formation suggesting partial melting in the country rock. At the immediate contact to granitic dykes, the host rocks become partly digested, and gradual changes in metamorphic grade towards the dykes can be observed.

We investigated three dykes in the northern part of the Lindås Nappe, one fine-grained trondhemite (Fonnes quay) and two representative granitic pegmatites from Håkjerringa and Ervik.

## Sample characterization

### Pegmatitic dykes

Pegmatitic dykes intrude the granulite-facies country rocks particularly in the central to eastern part of Lindås Peninsula as outlined in Fig. 1. Similar dykes are also known from areas in the western parts of Lindås and Radøy (Arnesen 1997). Their mineral assemblage includes quartz, plagioclase, alkali-feldspar, muscovite, biotite, garnet, tourmaline, and epidote in varying modal amounts. In places the pegmatites exhibit zonation, with large quartz crystals constituting their central parts. Muscovite occurs as fist-sized booklets up to approx. 10 cm in length. Garnet is dispersed in the pegmatites, forming euhedral reddish crystals with an average grain size of about 10–15 mm. Occasionally garnet is intergrown with quartz. While in some pegmatites indications of post-crystallization plastic deformation are at least locally absent, others clearly experienced a tectonic overprint. In areas that are intensively reworked by amphibolite-facies deformation, pegmatitic veins can be followed into amphibolite facies shear zones, where they become parallel to the new foliation and partly boudinaged.

We sampled two representative pegmatitic dykes, at Håkjerringa island and at Ervik (see Fig. 1). The Håkjerringa pegmatite (samples AK 37/98 and AK 103/98) is located on an island in the Rongevær area in Austrheim municipality (UTM coordinates 32VKN721485). This pegmatite is particularly coarse-grained and contains quartz, plagioclase, k-feldspar, muscovite, garnet, epidote and tourmaline. It crosscuts the granulite-facies foliation (Fig. 2a) and shows no signs of granulite-facies mineralogy. The samples selected for analysis exhibit igneous textures and show no indications of metamorphic reactions or deformation.

The Ervik pegmatite (sample Ervik 1/99) crops out in a recently blasted roadcut near Ervik on the northern Lindås peninsula (UTM coordinates 32VKN805475). It contains quartz, plagioclase, k-feldspar, muscovite, gar-

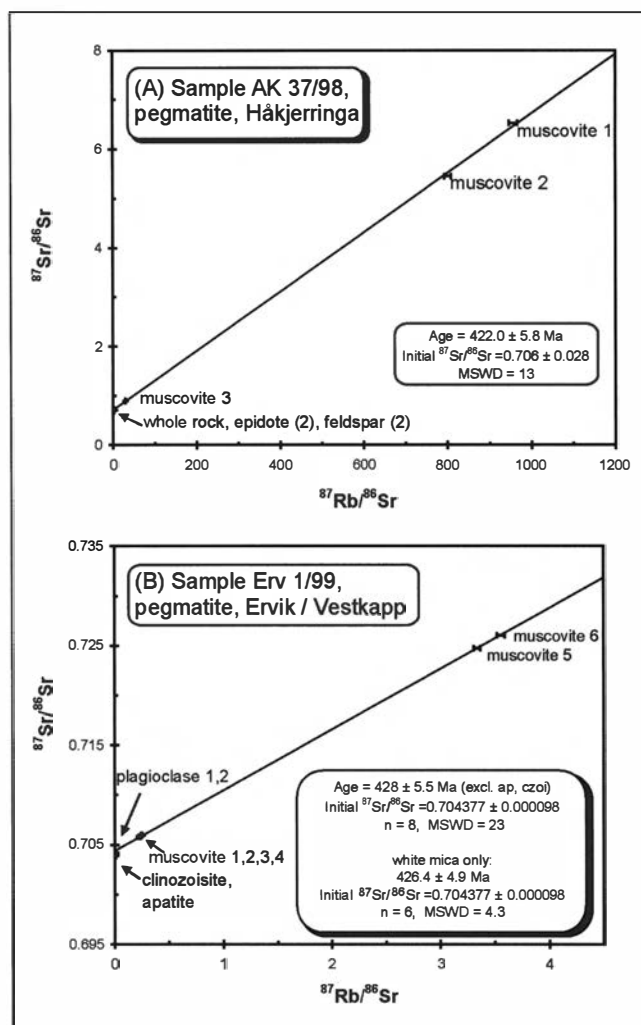


Figure 3. Rb-Sr isochron diagrams.

net and epidote/clinozoisite. The dyke crosscuts banded mafic, garnet-bearing granulite-facies rocks with linear, sharp intrusive contacts. The pegmatite dyke is connected to a fine-grained aplitic vein (sample AK 34/99) containing plagioclase, muscovite, quartz, garnet, biotite and epidote, indicating an intimate linking between the pegmatites and the finer grained aplites. We therefore interpret the aplites and the pegmatites as being comagmatic, with the pegmatites representing a higher degree of differentiation. Indications of any subsequent metamorphic overprint and deformation, are absent in the aplite.

### Trondhjemitic / aplitic dykes

Trondhjemitic and aplitic dykes intrude granulite-facies rocks in the northern, western and in southern parts of the Lindås peninsula as well as on islands along the eastern coast of Holsnøy. They are not restricted to the area near the contact between the Bergen Arcs Shear Zone and the rocks of the Lindås Nappe, as described by Wennberg et al. (1998b). In an undeformed state they may contain partly digested fragments of mafic, granulite-

Table 2. Whole rock and mineral chemistry of selected typical phases.

[illegible]

Table 2. Whole rock analysis, and typical mineral chemistry of representative minerals. Tourmaline analyses are recalculated to the sum of 15 cations (T+X+Y).

tic xenoliths and crosscut the Grenvillian granulite facies foliation, as shown in Fig. 2c. Some dykes can be traced from granulite-facies domains where they crosscut the foliation; into areas where they become deformed and dragged into amphibolite facies shear zones (Fig. 2b). This implies that intrusion of the dykes took place prior to or during amphibolite-facies metamorphism. We dated one trondhjemitic dyke from Fonnes quay (sample Fon 1, UTM coordinates 32VKN809485, see Fig. 2c), sampled at a place where the country rocks experienced only little or no amphibolite facies retrogression and deformation. The trondhjemitic sample consists of fine- to medium-grained plagioclase, quartz, alkali-feldspar, muscovite, epidote, apatite and locally garnet in variable amounts. There are no signs of granulite-facies mineral assemblages or structures in the trondhjemitic dyke, suggesting that it intruded after the granulite-facies event.

## Mineral chemistry

Mineral analyses were performed on a Cameca Camebax Microprobe at the Mineralogical-Geological Museum at the University of Oslo. An acceleration voltage of 15 kV, a beam current of 20 nA and a focused electron beam were used for all analyses except for white mica/muscovite and biotite, which were measured with an acceleration voltage of 15 kV, a beam current of 10 nA and a defocused electron beam. Natural and synthetic phases were used as standards. Data reduction was carried out using a CAMECA PAP software package.

Analysed garnet from the Håkjerringa pegmatite is red-brown and typically 10 to 13 mm in diameter. Often it occurs in euhedral or subhedral form, adjacent to quartz, plagioclase and k-feldspar and in some cases to muscovite. Its grain boundaries are distinct, without any signs of resorption or reaction. The analysed garnet is a solid solution between almandine, spessartine and grossular, with spessartine as a major component. The Fe/Mn ratios are around 4 in certain parts of the garnet rim and 1.4 in the Mn-rich the core of the mineral. The typical core composition is ca.  $\text{Alm}_{42}\text{Andr}_8\text{Grs}_{19}\text{Pyp}_2\text{Sps}_{29}$  (see Table 2). Variations in MnO and CaO content can be observed, with an increase in CaO on the expense of MnO towards the rims of garnet. Garnets from the Ervik pegmatite are also slightly zoned but display lower MnO contents than those from the Håkjerringa pegmatite. The garnet in the associated aplite in the Ervik outcrop possesses considerably lower MnO-contents than those mentioned above, with 6 wt.% as a maximum. Instead these garnet show a higher FeO-content and corresponding garnet composition of  $\text{Alm}_{65}\text{Andr}_4\text{Grs}_{16}\text{Pyp}_{10}\text{Spss}_5$ .

Two textural types of white mica/muscovite can be distinguished in the pegmatites: large muscovite books and smaller, dispersed grains/flakes. The composition of both the large booklets and smaller grains is homogeneous

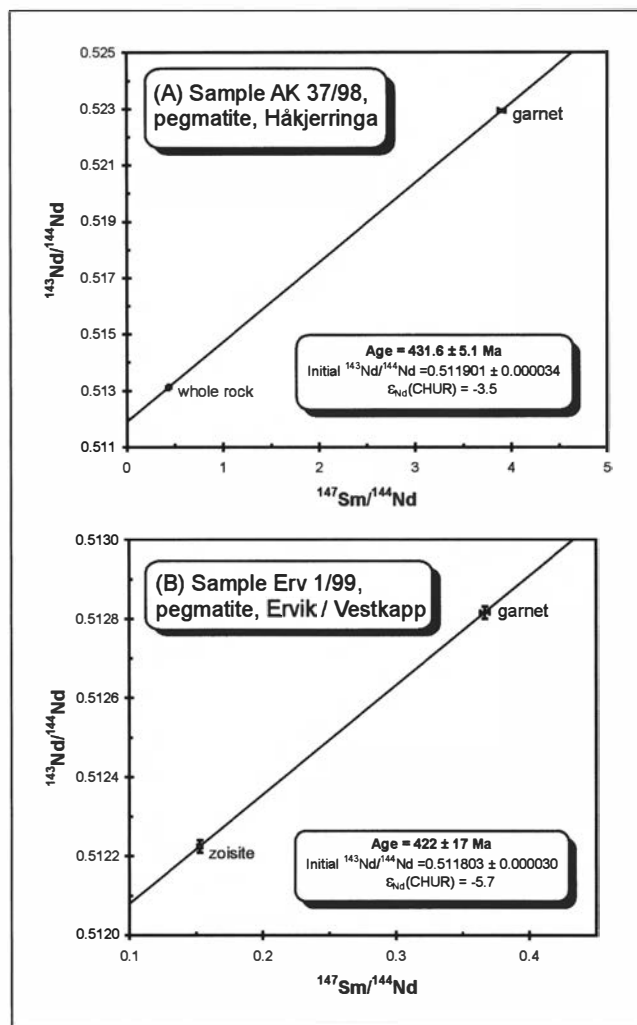


Figure 4. Sm-Nd isochron diagrams.

with the Si contents in the area 6.45 apfu, (recalculated to 22 oxygen, table 2) and Mg/Mg+Fe ratios of 0.25 to 0.29. Small, needle-shaped, black aggregates of Fe-rich tourmaline that are classified as schörl occur dispersed in the Håkjerringa pegmatite (see also the analyses in Table 2).

## P/T estimates

Thermometric calculations based on the Mg/Fe partitioning between white mica and coexisting garnet (Krogh & Råheim 1978; Green & Hellman 1982) in the pegmatites are difficult due to the high Mn and correspondingly low Mg contents. Crystallization temperatures ranging between 430 °C for the Mn-depleted garnet to 630 °C for garnets rich in Mn were calculated. These results are not very reliable and should be regarded with great caution. Since the host rock was in contact with the pegmatite, becomes partly migmatized, temperatures of 650 °C or higher can be assumed.

Garnet may crystallize from a melt, as a magmatic phase (Green 1976, 1977). Using experimentally derived

**Table 3. Rb-Sr, Sm-Nd data from Håkjerringa and Ervik pegmatites.**

Pegmatite	Material	Rb (ppm)	Sr (ppm)	<sup>87</sup> Rb/ <sup>86</sup> Sr	% err	<sup>87</sup> Sr/ <sup>86</sup> Sr	% err	Apparent age (Ma)
<b>AK37/98; Pegmatite Håkjerringa</b>								
OS104	plagioclase 1	25,04	242,51	0,2988	1	0,708617	0,005	
OS101	epidote 1	58,54	499,38	0,3392	1	0,708833	0,005	
PS164	epidote 2	33,07	224,13	0,4270	1	0,709420	0,005	
PS162	whole rock	30,20	54,59	1,6022	1	0,716161	0,005	
PS211	muscovite 3	233,99	19,04	36,3231	1	0,925373	0,005	
OS102	muscovite 1	650,04	3,08	957,5840	1	6,526929	0,007	
PS38	muscovite 2	677,92	3,59	800,5501	1	5,449705	0,005	
OS103	plagioclase 2	9,03	259,40	0,1007	1	0,707298	0,005	422 +/- 5.8
<b>ERV 1/99; Pegmatite Ervik/Westkapp</b>								
PS275	musc 6 (1,5 cm)	142,94	116,52	3,5555	1	0,726021	0,005	
PS219	musc 5 (1cm)	138,66	120,38	3,3382	1	0,724733	0,005	
PS276	musc 3 (1cm)	91,44	1074,15	0,2463	1	0,705997	0,005	
PS217	musc 4 (5 cm)	89,89	1153,47	0,2237	1	0,705780	0,005	
PS221	plagioclase 1	0,90	2060,68	0,0013	1	0,704284	0,005	
PS220	plagioclase 2	1,72	2108,64	0,0024	1	0,704256	0,005	
PS218	musc 2 (1 cm)	91,28	1049,30	0,2516	1	0,705992	0,005	
PS277	musc 1 (6 cm)	90,33	1108,09	0,2358	1	0,705830	0,005	
PS223	clinozoisite	1,18	6989,67	0,0005	1	0,703947	0,005	428 +/- 5.5 Ma [excl. Czo, Ap]
PS222	apatite	1,23	1806,38	0,0020	1	0,704028	0,005	426.4 +/- 4.9 [white mica only]
		Sm (ppm)	Nd (ppm)	<sup>147</sup> Sm/ <sup>144</sup> Nd	% err	<sup>143</sup> Nd/ <sup>144</sup> Nd	% err	Apparent age (Ma)
<b>AK37/98; Pegmatite Håkjerringa</b>								
ON22	garnet	0,7089	0,1108	3,9059	1	0,522941	0,007	
PS386	whole rock	0,054	0,0765	0,4271	1	0,513108	0,005	431 +/- 5.1
<b>ERV 1/99; Pegmatite Ervik/Westkapp</b>								
PS392	garnet	0,0972	0,1602	0,3666	1	0,512816	0,003	
PS393	zoisite	14,9973	59,3808	0,1527	1	0,512225	0,003	422 +/- 17

data, Green (1976) was able to show that precipitation of almandine garnet requires minimum pressures of at least 7 kbar.

This crystallization depth is less than the depth obtained with barometric estimates based on the Si-content of white micas. On the assumption of crystallization temperatures around 650 °C, the Si contents of the analysed micas from both pegmatites indicate crystallization pressures around 6-7 kbar using the calibration by Massonne & Schreyer (1987).

Pressure and temperature calculations were also made in the host rocks with mineral assemblages that are clearly a result of heating and fluid infiltration during intrusion. Migmatitic rocks from beside the Håkjerringa pegmatite comprise quartz-rich schlieren and flakes of mafic zones representing leucosome and paleosome clearly formed during the intrusion event. In other places the rocks are affected by fluid infiltration and comprise garnet, biotite, plagioclase, hornblende, rutile, ilmenite and apatite assemblages in the vicinity of the dykes.

Thermobarometric estimates in these rocks (sample AK 35/99; Håkjerringa), that became affected by heating

and fluid infiltration during pegmatite intrusion, reveal temperatures around 690°C using garnet-biotite thermometry (Ferry & Spear 1978), and pressures of approximately 9 to 10 kbar using the GRIPS barometer (Bohlen & Liotta 1986). The compositions of the minerals used for thermobarometric calculations are summarized in Table 2. The amphibolite-facies shear zones responsible for the deformation of the dykes contain hornblende, garnet, plagioclase, sphene, quartz, apatite, rutile and ilmenite. Thermobarometric estimates of 620-690 °C and 8 to 12 kbar for Caledonian amphibolite-facies shear zones have been reported by Boundy et al. (1996).

## Isotopic Investigations

### Methods

For the purpose of Rb-Sr and Sm-Nd isotope analyses, mineral concentrates of white mica, zoisite/epidote, garnet, feldspar and apatite as well as whole rock powders were prepared. Great care was taken to avoid material



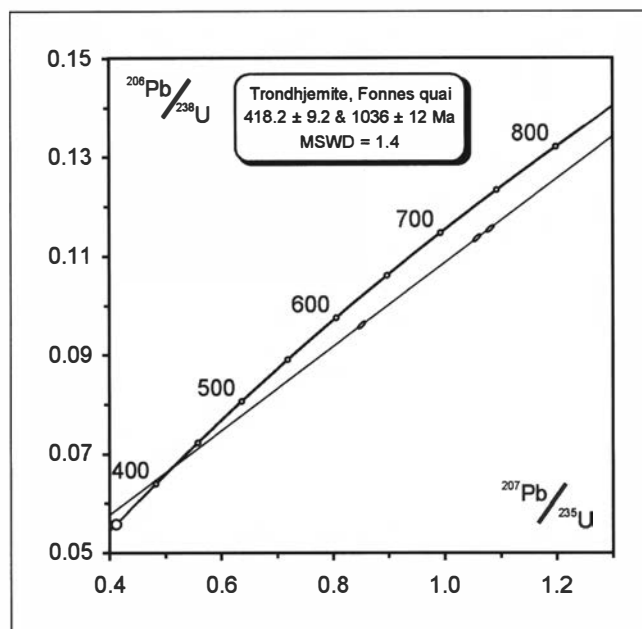


Figure 5. U-Pb concordia diagram on three fractions of zircon from a trondhjemitic dyke, Fonnes quay, Lindås peninsula.

altered by weathering. Final purification of the minerals was done by hand-picking under a binocular microscope. Garnet fractions were further purified by a washing and etching procedure involving treatment in diluted HF. Whole rock powders were prepared in an agate mill. Samples were analysed for Rb, Sr, Sm, and Nd contents by isotope dilution. They were weighted into Savillex screw-top containers, spiked with suitable mixed  $^{87}\text{Rb}$ ,  $^{84}\text{Sr}$  and  $^{149}\text{Sm}$ ,  $^{150}\text{Nd}$  spike solutions, and dissolved in a mixture of HF and  $\text{HNO}_3$ . Solutions were processed by standard cation-exchange techniques. Determination of Sr isotope ratios was carried out on a VG Sector 54 multi-collector thermal ionization mass spectrometer (GeoForschungsZentrum Potsdam) in dynamic mode. For some samples, analyses were carried out on a Finnigan MAT 262 TIMS (Mineralogical Geological Museum, University of Oslo) in static mode. The value obtained for  $^{87}\text{Sr}/^{86}\text{Sr}$  of the NBS standard SRM 987 during the period of analytical work was  $0.710266 \pm 0.000012$  ( $n = 25$ ) for the Potsdam instrument and  $0.710170 \pm 0.000015$  ( $n = 14$ ) for the Oslo instrument. From the systematic deviation between the results on the two instruments a correction factor was determined and applied to the results of the static mode analyses. All isotopic ratios were normalized to an  $^{86}\text{Sr}/^{88}\text{Sr}$  ratio of 0.1194. Rb analyses were done on a VG Isomass 54 single collector TIMS instrument at the GeoForschungsZentrum Potsdam. The observed ratios were corrected for 0.25 % per a.m.u. mass fractionation. Total procedural blanks were consistently below 0.15 ng for both Rb and Sr, and in the range of 0.1 ng for both Sm and Nd. Due to low and highly variable blank values, a useful blank correction is not applicable. For age calculations, an uncertainty of  $\pm 1$  %, as derived from replicate analyses of natural mica

samples is assigned to the  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios.  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are reported with their  $2\sigma$  internal precision plus uncertainties from spike correction. In the calculations of isochron parameters, a standard error of  $\pm 0.005$  % for  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios was applied if individual errors were smaller than this value. This error estimate ( $2\sigma$ ) was derived from reproducibility tests for Sr isotope ratios on the two instruments used. Sm, Nd isotope analyses were carried out on a Finnigan MAT 262 at GeoForschungs-Zentrum Potsdam. Nd was analysed in dynamic, Sm in static mode. The value obtained for  $^{143}\text{Nd}/^{144}\text{Nd}$  of the La Jolla standard during the period of analytical work was  $0.511852 \pm 0.0000062$  ( $n = 6$ ). For age calculations, standard errors of  $\pm 0.003$  % for  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios and  $\pm 1$  % for  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios were assigned to the results. Expanded errors were used for  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios in case where the individual analytical errors were higher than  $\pm 0.003$  % or where the amount of Nd used for analysis was extremely low (samples PS386, ON22) implying elevated blank/sample ratio. Regression lines are calculated using ISOPLOT/EX 2.06 (Ludwig 1998). Decay constants for Rb of  $1.42 \cdot 10^{-11} \text{a}^{-1}$  (Neumann & Huster 1974) and for Sm of  $6.54 \cdot 10^{-12} \text{a}^{-1}$  (Lugmair & Marti 1978) were used for the age calculations.

For U/Pb dating, zircons were handpicked and abraded following the methods described by Krogh (1982). Zircon was dissolved with HF in Teflon capsules. After the addition of a mixed  $^{205}\text{Pb}/^{235}\text{U}$  spike (Krogh & Davis 1975) U and Pb were separated using the technique of Krogh (1973). U and Pb isotopic ratios were measured on a VG-30 thermal ionization mass spectrometer (Oslo University) on single Re filaments using the phosphoric acid/silica gel loading technique (Cameron et al. 1969). All isotopic ratios were corrected for  $1.0 \pm 0.05$  ‰ per a.m.u.. Pb and U isotopic fractionation factors were determined by periodic runs of the NBS SRM 981 and the NBS SRM 500 uranium standards. Total procedural blanks for Pb and U ranged between 20 to 39 pg and 10 to 25 pg, respectively. Composition of initial common Pb in the zircon was calculated using the model of Stacey & Kramers (1975) assuming an age of 950 Ma. Data regression was performed using the program by Ludwig (1998), the decay constants are those reported by Steiger & Jäger (1977). Uncertainties of 0.1 % and 0.5 % were assigned to the measured  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios and U/Pb ratios respectively. Errors on the calculated age are reported at true  $2\sigma$  confidence level.

## Results

**Rb-Sr data** from the Håkjerringa pegmatite, reported in Table 3 and illustrated in Fig. 4a, were obtained from whole rock powder and handpicked mineral separates. Two out of three analysed muscovites have very high  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios of 958 and 801, respectively. Regression analysis of 8 data points (2 feldspar crystals, 3 white mica crystals, 2 epidote separates and whole rock) yields a



good correlation in an Sr isochron diagram, resulting in an age of  $422 \pm 5.8$  Ma (MSWD = 13) with an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.706 \pm 0.028$ . The disequilibrium represented by the high MSWD value may reflect primary isotopic inhomogeneities that are often found in pegmatites forming from evolved granitic melts.

For the Ervik pegmatite Rb/Sr analyses were carried out for 6 different crystals of white mica, 2 plagioclase crystals, clinozoisite and apatite. Excluding clinozoisite and apatite, an age of  $428 \pm 5.5$  Ma ( $N = 8$ , MSWD = 23) with initial  $^{87}\text{Sr}/^{86}\text{Sr}$  of  $0.704377 \pm 0.000098$  can be calculated. Calculating an isochron age with the white mica data alone, an age of  $426.4 \pm 4.9$  Ma ( $N = 6$ , MSWD = 4.3) is obtained. For these age calculations, only the mineral phases present in large crystals were used, these include plagioclase and white mica that clearly form the pegmatitic assemblage. Clinozoisite and apatite were not considered in calculating the Rb/Sr isochron age, since their genetic relation to the coarse-grained pegmatitic phases is not clear and since they are significantly out of equilibrium with the pegmatitic minerals with respect to their Sr isotopic composition. These isotopic differences are thought to be primary inhomogeneities, due to involvement of at least two, Sr-isotopically different components in the petrogenesis of the dyke and due to incomplete mixing of those. Such components may be migrating granitic melt, in interaction with locally-derived anatectic melt or with crystals assimilated from the wall rock.

Although primary disequilibria are clearly present, the validity of the age information is not affected since the isochron slope is almost exclusively defined by the white mica data.

**Sm-Nd data.** For the Håkjerringa pegmatite, Sm-Nd isotopic data from garnet and whole rock, as reported in Table 2 and illustrated in Fig. 4a, allow the calculation of a two-point isochron age of  $431.6 \pm 5.1$  Ma, with initial  $^{143}\text{Nd}/^{144}\text{Nd}$  of  $0.511901 \pm 0.000034$ . ( $\epsilon_{\text{Nd}}(\text{CHUR}) = -3.5$ ). The analysed garnet separate yields an extraordinarily high  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of 3.9059 so that the age is well constrained. The presence of slight initial Nd-isotopic disequilibria in the rock would not affect the age information.

The Sm/Nd ratio for the garnet from the Ervik Pegmatite is much lower than in the Håkjerringa garnet. Sm-Nd data obtained from zoisite and garnet (Fig. 4b) yield an apparent age of  $422 \pm 17$  Ma and an initial  $^{143}\text{Nd}/^{144}\text{Nd}$  of  $0.511803 \pm 0.000030$  ( $\epsilon_{\text{Nd}}(\text{CHUR}) = -5.7$ ). This two-point isochron has to be interpreted with caution since we have no control over possible initial Nd-isotopic inhomogeneities, and because initial Sr-isotopic disequilibria are present in the same sample (see Fig. 3b). However, within limits of error, the age is identical to the other Sm-Nd and Rb-Sr ages. Therefore we interpret it as a meaningful age.

**U-Pb isotopic data** of three abraded fractions of zircons from the trondhjemitic dyke sampled at Fonnes quai (Sample Fon 1), as reported in Table 2 and illustrated in Fig. 5, define a discordia line with intercept ages of

$1036 \pm 12$  Ma and  $418 \pm 9$  Ma. The lower intercept age represents an important event of either lead loss from the zircons and/or the presence of a second, 418 Ma generation of zircons in addition to the old, 1036 Ma grains. We suggest that the lower intercept age dates the trondhjemitic generation and crystallization.

## Discussion

### *Derivation of granitic melts*

Granitoid rocks are generally thought to be formed by one of the following different processes: 1) anatectic melting of crustal rocks, 2) fractional crystallization of mantle-derived magmas, 3) assimilation/mixing of crustal rocks by/with mantle-derived magmas and 4) decompressional melting.

In case of the Lindås pegmatites, the initial Sr and Nd isotopic ratios can be used as petrogenetic indicators. Calculated for an age of crystallization initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of  $0.706 \pm 0.028$  (derived from only the phases with the lowest Rb/Sr-ratios) for the Håkjerringa pegmatite and  $0.70438 \pm 0.00010$  for the Ervik pegmatite are obtained. Together with negative  $\epsilon_{\text{Nd}}$  values ( $-3.5$ ,  $-5.7$ ), this suggests anatectic melting of crustal rocks rather than exclusive granitoid formation from a mantle-derived I-type igneous source. The presence of inherited zircon grains in the associated fine-grained trondhjemites/aplites similarly indicates a dominant crustal component in the granitic melts.

Migmatitic structures in the host rocks of both the Håkjerringa and Ervik pegmatite, with schlieren of quartz and the occurrence of strongly deformed biotite-rich zones in the host rock in the vicinity of the pegmatite dykes give further evidence of this crustal source.

All these observations point to a pegmatite-forming melt that contained a significant crustal component of anatectic origin. An additional mantle-derived component in the melt cannot be excluded, but an exclusive formation by advection and crystallization of an I-type, directly mantle-derived magma can be ruled out. Wennberg et al. (1998b) present  $\epsilon_{\text{Nd}}$  values between  $-0.7$  and  $-1.2$  for granitoid dykes from the Lindås Nappe and the adjacent Major Bergen Arc and argue for a mixing between a mantle and a crustal component.

The Rb/Sr and Sm/Nd datasets show that the garnet from the Ervik pegmatite has a much lower Sm/Nd ratio than the garnet analysed from the Håkjerringa pegmatite. In addition, the feldspar as well as the muscovite crystals from Ervik have lower Rb/Sr ratios than respective crystals from the Håkjerringa pegmatite. Obviously the Ervik pegmatite crystallized from a more primitive, less differentiated magma. This interpretation is also supported by the observed lower spessartine component in the garnets from the Ervik pegmatite.

Isotopic disequilibria on the mineral scale, as observed in both the Håkjerringa and Ervik pegmatites, will

occur when the time required for equilibration of primary disequilibria by volume diffusion is greater than the time during which the systems stay open (Harris & Ayres, 1998). The preservation of disequilibrium in these pegmatites indicates that the magmas did not reach a stage of complete internal isotopic homogenization. This may either point to a rather short-lived magmatic event, involving incomplete homogenization of different magma batches during crystallization, or it may simply reflect late contamination during crystallization, possibly derived from the immediate wall rock. Melt generation may either have been caused by heating of the rocks, or via a shift of the solidus towards lower temperatures due to fluid influx.

Several scenarios are favoured that would lead to heating of rocks, for example, advective heating from intrusion of basic magmas (Huppert & Sparks 1988) or by the obduction of hot oceanic lithosphere (Tommasini & Davies 1995). However, advective heating due to those processes seems to be unlikely in the case of the Lindås Nappe since we observe no evidence for basic magmatism of appropriate age or for obduction of oceanic lithosphere. England et al. (1992) suggested dissipative heating as an alternative mechanism for melting. Dissipative or frictional heating during active thrusting as suggested by Wennberg et al. (1998b) and Wennberg & Skjerli (1999) could actually result in increasing temperatures in the Lindås Nappe, depending on the distance to the thrust. They argue that the number of observed granitoid dykes and veins increases towards the boundary between the Lindås Nappe and the Major Bergen Arc. Due to the deformation of these dykes by amphibolite facies shear zones they also favour a syn-tectonic emplacement. Therefore they conclude that dissipative/shear heating could be a reasonable explanation for melt generation. The shearing could probably be related to the movements during juxtaposition of these different tectono-stratigraphic units. But as mentioned above, the occurrence of granitoid dykes in the Lindås Nappe is not restricted to the areas adjacent to the Major Bergen Arc and the Ber-

gen Arc Shear Zone. Therefore, this mechanism of heating and melt generation would not explain the widespread magmatic activity in the Lindås Nappe. We conclude that there is neither an appropriate mechanism for melt generation by heating, nor convincing geologic evidence for a distinct heating event at around 425 Ma.

We suggest that the formation of partial melts in these rocks that were originally dry is due to the addition of a fluid phase that lowered the solidus of the rocks. Evidence of intensive fluid infiltration during amphibolite facies retrogression is ubiquitous in the rocks of the Lindås Nappe. The addition of fluids may have established favourable conditions for partial melting. The fact that the observed pegmatites carry a lot of mica and that the dykes apart from the host rocks also become affected by fluids as documented by the formation of biotite support the interpretation of the granitoids as melts, generated by influx of fluids during subduction.

### *Tectonic evolution*

If one assumes that all trondhjemite dykes and veins have been formed at the same time, amphibolite facies shearing must be younger or similarly old than the  $418 \pm 9$  Ma of the Fonnes trondhjemite. This means that the deformation and metamorphism affecting these dykes in the large amphibolite facies shear zones, observed on Lindås peninsula, must be Scandian, i.e. post-419 Ma. Late Caledonian ages, which may constrain the timing of amphibolite-facies metamorphism, are reported by Austrheim (1990). He obtained an Rb-Sr mineral isochron age of  $409 \pm 8$  Ma (derived from biotite, amphibole, whole rock and apatite) for a reworked mangerite from Radøy. This provides a minimum age for the deformation of these rocks since the Rb/Sr system of biotite is readily reset by any ductile deformation or by fluid-driven mineral reactions. Therefore, we conclude that the amphibolite-facies ductile deformation and metamorphism is confined to the time frame between ca. 425 Ma and  $409 \pm 8$  Ma.

**Table 4. U-Pb data of zircons from the Fonnes trondhjemite.**

[1]	wt (mg)	[2]	[3]	[4]	[5]	[5]	[6]	[6]	[6]
Fon 1; Trondhjemite, Fonnes quay		U [ppm]	Pb [ppm]	<sup>206</sup> Pb/ <sup>204</sup> Pb	<sup>207</sup> Pb/ <sup>206</sup> Pb	<sup>208</sup> Pb/ <sup>206</sup> Pb	<sup>206</sup> Pb/ <sup>238</sup> U	<sup>207</sup> Pb/ <sup>235</sup> U	<sup>207</sup> Pb/ <sup>206</sup> Pb - age [Ma]
zircon, cl	0,798	176	20,9	7087	0,14303	0,135	0,1155	1,0814	865
zircon, cl, s	1,161	100	10,1	8873	0,15169	0,156	0,0961	0,8522	751
zircon, cl	0,992	125	14,9	4043	0,14072	0,16	0,1137	1,0587	853

[1] cl = clear, s = small

[2] Concentrations are known to +/-0.5% for sample weights over 1mg, +/- 1-2% for sample weights between 1.0 and 0.2 mg.

[3] Corrected for 0.177 mole fraction of common Pb in the 205Pb spike.

[4] Measured ratio corrected for common Pb in the spike.

[5] Corrected for fractionation, blank and spike; U blank=23pg, Pb blank=33pg, Pb and U fractionation correction = 1%/amu.

[6] Corrected for fractionation, spike, blank and initial common Pb; error is estimated at 0.25% for Pb/U and 0.1% for 207Pb/206Pb at the 2-sigma level.

Older Ar-Ar ages of 455 Ma (Boundy et al. 1997a) from amphibole from a shear zone (Fig. 2c, Bakkøy / Ulvøy) cannot reflect the latest, pegmatite-deforming shearing event. The obvious discrepancy between the Ar-Ar age mentioned and our granitoid crystallization ages may be due to presence of excess Ar in the amphiboles. Further, Boundy et al. (1996) argues for rapid exhumation and cooling. According to them the rocks of the Lindås Nappe would have been cooled to temperatures around 325 °C at 430 Ma, as deduced from Ar-Ar ages of eclogite-facies muscovites. Besides the granitoid magmatism around 425 Ma, an additional argument against the interpretation of the 430 Ma age as cooling age is provided by Boundy et al. (1997b). These authors present data indicating that eclogite-facies phengite preserved fine-scale isotopic heterogeneities created during growth of the mineral. So if it is known that a white mica may retain prograde growth heterogeneities through high-grade metamorphism, there is no reason to accept the 430 Ma white mica age as a cooling age unless additional evidence for such an interpretation is provided. In contrast, the 430 Ma muscovite Ar/Ar age may mean that eclogite-facies metamorphism could be as young as 430 Ma since crystallisation and not the cooling of the mineral has been dated. The U-Pb data by Bingen et al. (1998) of  $419 \pm 4$  Ma and the Rb/Sr data of Cohen et al. (1988) of  $421 \pm 68$  Ma suggest that eclogite formation was contemporaneous with the emplacement of the granitoid dykes (see Table 1, summary of available age data for the Caledonian metamorphism in the Lindås Nappe). Thus, the eclogite would display an age almost similar to or only slightly older than that obtained for the granitoid dykes dated in this work. This also suggests that the deformation in the Lindås Nappe is not Pre-Scandian in age, but Scandian and hence related to the main collision during the Caledonian orogeny.

Based on these data two scenarios are suggested for the tectono-metamorphic evolution of the Lindås Nappe. Following the conventional opinion about the evolution of the Lindås Nappe, eclogite-facies HP metamorphism occurred at 430 Ma (17 kbar, 700°C). Thus the rocks from the Lindås Complex may have been brought to depth and eclogite-facies conditions during the main phase of the Caledonian continent-continent collision. After subduction the complex experienced a very rapid exhumation. Coupled with intensive fluid infiltration that is ubiquitous in all retrogressive rocks from this unit, this led to partial melting and formation of the pegmatites and trondhjemites. This magmatic activity has been dated to around 425 Ma (8-10 kbar, 650-690 °C). The pegmatite intrusion was later followed by intensive amphibolite-facies retrogression and deformation at around 425 to 410 Ma. This retrogression is documented by large shear zones and affects all lithologies. This major phase of deformation forms the huge amounts of banded gneisses with the arcuate foliation and lineation following the structure of the Bergen Arc complex. Similar amphibolite-facies conditions are

reported for rocks from the Major Bergen Arc (Fossen, 1988). That could suggest that these movements are related to the juxtaposition of these two units. The fact that kyanite has been described from rocks at the southern contact between these two nappes also advocates a simultaneous amphibolite-facies metamorphism. Final exhumation of the Bergen Arcs probably occurred between 410 and 395 Ma, contemporaneously with the main phase of late- to post-orogenic extension (Chauvet & Dallmeyer 1992) that exhumed the basement gneisses of the Western Gneiss Region.

Alternatively, and more likely in our view, we may be dealing with a crustal section in which different parts experienced a different tectono-metamorphic evolution. Whereas the western section of the nappe (e.g. Holsnøy, Fig. 1) was subducted to a depth corresponding to more than 50 km and experienced hydration-induced eclogitization (age interval 430 to 419 Ma), the eastern area (Austrheim, Lindås) was hydrated at depth corresponding to amphibolite-facies conditions. This hydration led to a lowering of the solidus and partial melts were formed. The Precambrian rocks became intruded by numerous dykes around 425 Ma (8-10 kbar, 650-690 °C). The fact that parts of the dykes exhibit ductile deformation, whereas other parts remain undeformed and un-metamorphosed suggests pre- to syntectonic emplacement and a very localized pattern of hydration and deformation. Thermobarometric estimates suggest that deformation continued after intrusion and reached upper amphibolite-facies conditions (10-12 kbar, 650°C) as discussed above.

#### *Tectonostratigraphic position of the Lindås Nappe*

The present work does not allow us to definitely place the Lindås Nappe in the Caledonian tectonostratigraphy. However, regarding the correlation between the Lindås and the Jotun Nappe we, in accordance with Bingen et al. (2001), consider that the similarity in the lithologies, Precambrian metamorphism and age ranges obtained from the two areas suggest a close relationship between these two nappe units. The arguments listed by Wennberg et al. (1998b) do not change this impression of a strong genetical link between the two units. The Precambrian age of the trondhjemites is based on a poor Rb-Sr whole rock isochron with an uncertainty of 260 Ma. Until this is redone we may equally well rely on the  $448 \pm 30$  Ma given by Berthomier et al. (1972) or  $430 \pm 5$  Ma by Schärer (1980) for the same dykes. Further we notice that the Caledonian metamorphism of the Lindås Nappe is localized and that large areas do not record this metamorphism. Localized reactions are typical for the anhydrous rocks from the Lindås Nappe undergoing metamorphism. This phenomenon is well displayed on the island of Holsnøy where hydrated eclogite-facies shear zones transect meta-stable granulite facies rocks, and it also applies to the amphibolite facies retrogression and

deformation. Metamorphic reaction and deformation always coincide with hydration. In volumes of rocks, which remained dry during amphibolite-facies conditions, the original granulite facies mineralogy is preserved.

## Conclusions

Emplacement and crystallization of the pegmatites in the high-grade metamorphic units of the Lindås nappe is constrained by Rb/Sr, Sm/Nd mineral isotopic ratios of two coarse-grained pegmatites and by U-Pb data of zircon from a fine-grained trondhjemitic. The obtained Sm/Nd and Rb/Sr mineral ages for the Håkjerringa pegmatite, northern most Lindås Nappe, are  $431 \pm 5$  and  $422 \pm 6$  Ma, respectively. Similar ages of  $422 \pm 17$  Ma (Sm/Nd), and  $428 \pm 5$  Ma, (Rb/Sr) were obtained for the Ervik pegmatite. Three fractions of zircon from a trondhjemitic dyke at Fonnes quay define a lower intercept age of  $418 \pm 9$  Ma that is, within limits of error, identical to the Rb/Sr and Sm/Nd-ages of the pegmatites.

Elevated initial Sr isotopic composition for the Håkjerringa pegmatite, together with the obtained  $\epsilon_{\text{Nd}}$  values of  $-3.5$  and  $-5.7$  indicate a crustal source for the investigated pegmatites. Inherited zircons and mafic xenoliths in the trondhjemitic suggest also a crustal contribution to the melts.

The Rb-Sr and Sm-Nd data suggest different degrees of differentiation for the two investigated pegmatites. The Ervik pegmatite seems to be more primitive and less differentiated than the pegmatite from Håkjerringa island.

Thermobarometric estimates point to intrusion depth corresponding to ca. 8 to 10 kbar. Intrusion temperatures must have been above 650 °C since surrounding granulites became migmatitized and partly digested at the rim of the pegmatites.

Summarizing all available age data for the Caledonian development of the Lindås Nappe (see Table 1) a new tectonic scenario for the Lindås Nappe is suggested. Contemporaneously with the high-pressure metamorphism at 430-420 Ma (17 kbar, 700 °C) in the bottom parts of the nappe, the higher parts became subjected to amphibolite-facies conditions. There, fluid infiltration led to partial melting and to formation of the observed pegmatites and trondhjemites (clustering around 425 Ma, 8-10 kbar and 650-700 °C).

**Acknowledgements.** - Discussions with Mats Lund during fieldwork are very much appreciated. We thank Fernando Corfu and Muriel Erambert for valuable comments on an earlier version of this manuscript. Critical reviews by W.L. Griffin, R.B. Pedersen, Å. Johanson and the editor Ø. Nordgulen, which helped to improve the manuscript, are appreciated. A. Kühn is grateful for a grant by the DAAD (German Academic Exchange Service). J. Glodny gratefully acknowledges a European Commission TMR grant as well as the support provided by

the GeoForschungsZentrum Potsdam for completion of this work. The fieldwork has been supported by funding from the Research Council of Norway (NFR) for the project 107603/410 'Fluid induced Metamorphism and Geodynamic Processes'.

## References

- Arnesen, N. 1997: Retrograd metamorfose av granulitt facies mangelitt, Radøy – Nordhordland. Unpublished cand. scient. thesis, University of Oslo.
- Andersen, T., Austrheim, H. & Burke, E.A.J. 1990: Fluid inclusions in granulites and eclogites from the Bergen Arcs, Caledonides of W-Norway. *Mineralogical Magazine* 54, 145-158.
- Austrheim, H. 1990: Fluid induced processes in the lower crust as evidenced by Caledonian eclogitization of Precambrian granulites, Bergen Arcs, Western Norway. PhD thesis, University of Oslo.
- Austrheim, H. 1987: Eclogitization of lower crustal granulites by fluid migration through shear zones. *Earth and Planetary Science Letters* 81, 221-232.
- Austrheim, H. & Griffin, W.L. 1985: Shear deformation and eclogite formation within granulite-facies anorthosites of the Bergen Arcs, western Norway. *Chemical Geology* 50, 267-281.
- Berthomier, C., Lacour, A., Leutwein, F., Maillot, J. & Sonet, J. 1972: Sur quelques trondhjemites de Norvège: étude géochronologique et géochimique. *Science de la Terre* 17, 341-351.
- Bingen, B., Davis, W. J. & Austrheim, H. 1998: Zircon growth during fluid induced Caledonian/Scandian eclogite-facies metamorphism of the Lindås Nappe, Caledonides of W-Norway. *Mineralogical Magazine* 62A, 161-162.
- Bingen, B., Davis, W.J. & Austrheim, H. 2001: Zircon U-Pb geochronology in the Bergen Arc eclogites and their Proterozoic protoliths, and implications for the Pre-Scandian evolution of the Caledonides in western Norway. *Geological Society of America Bulletin* 113, 640-649.
- Bohlen, S.R. & Liotta, J.J. 1986: A barometer for garnet amphibolites and garnet granulites. *Journal of Petrology* 27, 1025-1034.
- Boundy, T. M., Essene, E. J., Hall, C. M., Austrheim, H. & Halliday, A. N. 1996: Rapid exhumation of lower crust during continent-continent collision and late extension: Evidence from  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental heating of hornblendes and muscovites, Caledonian orogen, western Norway. *Geological Society of America Bulletin* 108, 1425-1437.
- Boundy, T. M., Mezger, K. & Essene, E. J. 1997a: Temporal and tectonic evolution of the granulite-eclogite association from the Bergen Arcs, western Norway. *Lithos* 39, 159-178.
- Boundy, T. M., Hall, C. M., Li, G., Essene, E. J. & Halliday, A. N. 1997b: Fine-scale isotopic heterogeneities and fluids in the deep crust: a  $^{40}\text{Ar}/^{39}\text{Ar}$  laser ablation and TEM study of muscovites from a granulite-eclogite transition zone. *Earth and Planetary Science Letters* 148, 223-242.
- Cameron, A.E., Smith, D.H. and Walker, R.L. 1969: Mass spectrometry of nanogram-size samples of lead. *Analytical Chemistry* 41, 525-526.
- Chauvet, A. & Dallmeyer, R.D. 1992:  $^{40}\text{Ar}/^{39}\text{Ar}$  mineral dates related to Devonian extension in the southwestern Scandinavian Caledonides. *Tectonophysics* 210, 155-177.
- Cohen, A. S., O'Nions, R. K., Siegenthaler, R. & Griffin, W. L. 1988: Chronology of the pressure-temperature history recorded by a granulite terrain. *Contributions to Mineralogy and Petrology* 98, 303-311.
- England, P., Le Fort, P., Molnar, P. & Pecher, A. 1992: Heat sources for Tertiary magmatism anatexis in the Annapurna-Manaslu region of central Nepal. *Journal of Geophysical Research* 97, 2107-2128.

- Ferry, J. M. & Spear, F. S., 1978: Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contributions to Mineralogy and Petrology* 66, 113-117.
- Fossen, H., 1988: Metamorphic history of the Bergen Arcs, Norway, as determined from amphibole chemistry. *Norsk Geologisk Tidsskrift* 68, 223-239.
- Fossen, H. & Austrheim, H., 1988: Age of the Krossnes granite. *NGU Bulletin* 413, 61-65.
- Fossen, H. & Dunlap, W.J., 1998: Timing and kinematics of Caledonian thrusting and extensional collapse, southern Norway: evidence from  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronology. *Journal of Structural Geology* 20, 765-781.
- Furnes, H., Roberts, D., Sturt, B.A., Thon, A. & Gale, G., 1980: Ophiolite fragments in the Scandinavian Caledonides. *Proceedings of the International Ophiolite Symposium, Nicosia, Cyprus 1979*, 295-307.
- Goldschmidt, V.M., 1916: Geologisch-Petrographische Studien im Hochgebirge des südlichen Norwegen. *Norske Videnskaps Akademiets Skrifter* 1, no. 2, 1-140.
- Green, T.H., 1976: Experimental generation of cordierite or garnet bearing granitic liquids from a pelitic composition. *Geology* 4, 85-88.
- Green, T.H., 1977: Garnet in silicic liquids and its possible use as a P-T indicator. *Contributions to Mineralogy and Petrology* 65, 59-67.
- Green, T.H. & Hellman, P.L., 1982: Fe-Mg partitioning between coexisting garnet and phengite at high pressure, and comments on a garnet-phengite geobarometer. *Lithos* 15, 253-266.
- Griffin, W.L., 1972: Formation of eclogites and the coronas in anorthosites, Bergen Arcs, Norway. *Geological Society of America, Memoir* 135, 37-63.
- Harris, N. & Ayres, M., 1998: The implications of Sr-isotope disequilibrium for rates of prograde metamorphism and melt extraction in anatexis terranes. In Treloar, P.J. & O'Brien, P.J. (eds.): *What drives metamorphism and metamorphic reactions?* Geological Society, London, Special Publications 138, 171-182.
- Henriksen, H., 1979: Structural geology and metamorphism on northern Osterøy. Unpublished cand. real. Thesis, University of Bergen, 452pp.
- Huppert, H.E. & Sparks, R.J., 1988: The generation of granitic magmas by intrusion of basalt into continental crust. *Journal of Petrology* 29, 599-624.
- Koestler, A.G., 1982: A Precambrian age for the Ofredal granodiorite intrusion, Central Jotun Nappe, Sogn, Norway. *Norsk Geologisk Tidsskrift* 62, 225-228.
- Kolderup, C.F. and Kolderup, N.H., 1940: Geology of the Bergen Arc System. *Bergens Museum Skrifter* Nr.20, 137p.
- Krogh, T.E., 1982: Improved accuracy of the U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. *Geochimica et Cosmochimica Acta* 46, 637-649.
- Krogh, T.E. & Davis, G.L., 1975: The production and preparation of  $^{205}\text{Pb}$  for use as a tracer for isotope dilution analysis. *Carnegie Inst. Yearb.* 74, 416-417.
- Krogh, E.J. & Råheim, A., 1978: Temperature and pressure dependence of Fe-Mg partitioning between garnet and phengite, with particular reference to eclogites. *Contributions to Mineralogy and Petrology* 66, 75-80.
- Ludwig, K.R., 1998: Isoplot/Ex. A Geochronological Toolkit for Microsoft Excel. *Berkeley Geochronology Center, Special Publication No. 1*.
- Lugmair, G.W. & Marti, K., 1978: Lunar initial  $^{143}\text{Nd}/^{144}\text{Nd}$ ; differential evolution of the lunar crust and mantle. *Earth and Planetary Science Letters* 39, 349-357.
- Massone, H.-J. & Schreyer, W., 1987: Phengite geobarometry based on the limiting assemblage K-feldspar, phlogopite, and quartz. *Contributions to Mineralogy and Petrology* 96, 212-224.
- Milnes, A.G. & Wennberg, O.P., 1997: Tectonic evolution of the Bergen area. *Geonytt* 24-1, 6-9.
- Neumann, W. & Huster, E., 1974: The half life of  $^{87}\text{Rb}$  measured as difference between the isotopes  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$ . *Z. Physik* 270, 121-127.
- Ragnhildsveit, J. & Helliksen, D., 1997: Geologisk kart over Norge, Berggrunnskart Bergen, 1:250000. *Norges geologiske undersøkelse*.
- Schärer, U., 1980: U-Pb and Rb-Sr dating of a polymetamorphic nappe terrain: the Caledonian Jotun nappe, southern Norway. *Earth and Planetary Science Letters* 49, 205-218.
- Stacey, J.S. & Kramers, J.D., 1975: Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters* 26, 207-221.
- Steiger, R.H. & Jäger, E., 1977: Subcommission on geochronology; convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters* 36, 359-362.
- Sturt, B.A., Skarpenes, O., Ohanian, A. T. & Pringle, I. R., 1975: Reconnaissance Rb/Sr isochron study in the Bergen Arc System and regional implications. *Nature* 253, 595-599.
- Thon, A., 1985: The Gullfjellet Ophiolite Complex and the structural evolution of the Bergen Arcs, western Norway. In Gee, D.G. & Sturt, B.A. (eds.): *The Caledonide Orogen – Scandinavia and Related Areas*, 671-677. Wiley & Sons, Chichester.
- Tommasini, S. & Davies, G.R., 1995: Isotopic disequilibrium during anatexis; consequences for radiogenic isotopic systems. *Terra Abstracts* 7, 154.
- Wennberg, O.P., Milnes, A.G. & Winswold, I., 1998a: The northern Bergen Arc Shear Zone – an oblique-lateral ramp in the Devonian extensional detachment system of western Norway. *Norsk Geologisk Tidsskrift* 78, 169-184.
- Wennberg, O.P., Skjerlie, K.P. & Dilek, Y., 1998b: Shear heating, inverted metamorphic gradient and anatexis at the base of a Caledonian nappe, Western Norway. In: Wennberg, O.P.: *The Bergen Arc Shear Zone: Kinematic analysis and implications for the tectonic evolution of the Bergen Arc area*. PhD thesis, University of Bergen.
- Wennberg, O.P. & Skjerlie, K.P., 1999: Opptrreden og petrogenese av granitiske ganger i Lindås, Nord-Hordaland. NGF Vintermøte, *Geonytt*, 101-102.