A Precambrian age for an early gabbro-monzonitic intrusive on the Øksfjord peninsula, Seiland Igneous Province, northern Norway

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Seven out of nine samples of metagabbro and monzonite from the Øksfjord peninsula, West Finnmark, give a Rb–Sr age of 829 ± 18 Ma (2σ, MSWD = 1.4), with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70272 ± 4 (2σ). This age is interpreted as the age of intrusion, the source being a depleted mantle reservoir. These results, together with other recent and previous radiometric dates from the area, imply that the period of magmatic activity in the Seiland Igneous Province lasted for at least 300 Ma.

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The Seiland Igneous Province (SIP), forming part of the uppermost structural unit of the Kalak Nappe Complex in western Finnmark (Fig. 1), comprises a suite of deep-seated magmatic rocks ranging in composition from ultrabasic to nepheline syenitic and carbonatitic. These plutons have intruded older paragneisses of unknown age, and the area shows a complex igneous, metamorphic and structural history. The timing of the intrusive stages has been controversial. The earlier interpretation has been that the province was synorogenic, formed during the Caledonian orogeny (Sturt & Ramsay 1965; Robins & Gardner 1975; Sturt et al. 1975, 1978). Isotopic dating of the intrusions of 540–490 Ma established the Late Cambrian to Early Ordovician age of this event – the Finnmarkian orogenic phase (Sturt et al. 1967; Pringle & Sturt 1969; Sturt et al. 1978). However, Brueckner (1973) reported a Rb–Sr whole-rock isochron age of 611 Ma (recalculated with updated decay constant, Steiger & Jäger 1977) on a massive syenite perthosite from the Øksfjord area, and Pringle (1975) reported similar results. Brueckner (1973) described these discordant syenites as having 'clear intrusive relationships to the enclosing metagabbro' and as post-dating the granulite-facies metamorphism of the adjacent gabbro gneiss and other foliated igneous rocks that make up the bulk of the province. More recent datings on the igneous rocks of the SIP have yielded intrusion ages ranging from 700 ± 33 Ma for the Hasvik gabbro, 612 ± 33 Ma and 604 ± 44 Ma for the Kvalfjord and Storvik gabbros, respectively (Sm–Nd mineral–whole-rock isochrons; Aitcheson et al. 1989; Daly et al. 1990), 550 ± 34 Ma for ultramafic rocks between Øksfjordbotn and Tappeluft (Sm–Nd mineral–whole-rock isochron; Mørk & Stabel 1988, 1990 (this issue)), 559 ± 36 and 513 ± 24 Ma on the olivine gabbro envelope to the Melkevann Ultramafic Complex (Sm–Nd internal isochrons; Snow et al. 1986), and 531 ± 2 and 523 ± 2 Ma on two late stage nepheline syenite dykes from Seiland and Stjernøy (U–Pb zircon; Pedersen et al. 1989). Apparent metamorphic ages of 531 ± 10 Ma on a coarse-grained garnet-rich granulite (metamonzonite) on Klubbneset, Øksfjord, and 502 ± 28 Ma on a fine-grained mafic granulite (metagabbro) from Storvik, Øksfjord peninsula (Sm–Nd mineral–whole-rock isochrons; Mørk & Stabel 1988, 1990 (this issue)) are interpreted to date the garnet-forming episode and the recrystallization of the rocks at high-grade metamorphism, respectively. The latter age is in accordance with hornblende Ar–Ar cooling ages (490 ± 5 Ma) from metamorphic rocks elsewhere in the province (Dallmeyer 1988). Rb–Sr whole-rock and U–Pb zircon ages from two granites within the Kalak Nappe Complex on Porsangerhalvøya indicate intrusion at or before 800 Ma (Aitcheson et al.

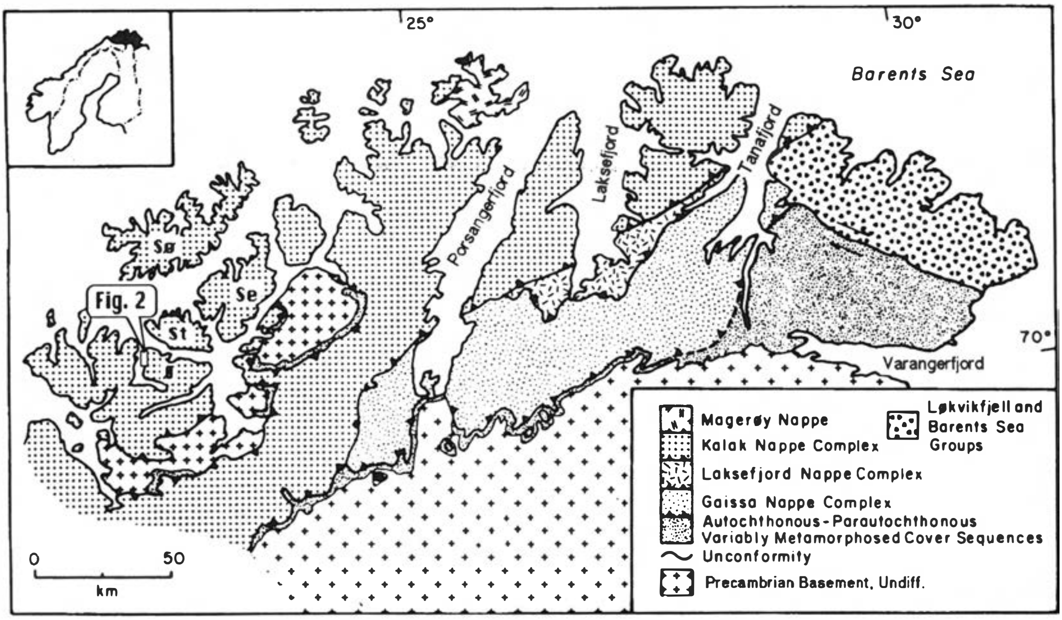

Fig. 1. Generalized geological map of the Caledonides in Finnmark, North Norway (modified after Dallmeyer 1988), showing the location of the investigated area. Sø – Sørøy; Se – Seiland; St – Stjernøy; Ø – Øksfjord.

1989, Daly et al. 1990), and Aitcheson & Taylor (1989) have concluded that numerous mafic and ultramafic plutons intruded the upper part of the Kalak Nappe Complex over the period 850–520 Ma.

This paper presents an Rb–Sr age on a gabbro-monzonitic gneiss interlayered with metasediments of unknown age.

Field relations

The dated rocks occur as a layered metagabbro–monzonite complex along the northeastern part of Øksfjord (Figs. 1 & 2). These rocks belong to the 'gabbro-gneiss III' of Krauskopf (1954) and are equivalent to the syn-D_2 syenogabbro suite of Robins & Gardner (1975). Garnetiferous quartz-feldspathic gneiss and metalimestone are interlayered with, and partly enclosed within, the gabbro-monzonite gneiss. The analyzed rock is a compositionally layered gabbro-monzonite gneiss, with layering defined by variation in the relative amount of feldspars and mafic minerals (mainly two pyroxenes and hornblende). The foliation, defined by parallel-oriented aggregates of mafic minerals in a groundmass of mainly plagioclase and/or alkali feldspar, is parallel to the main foliation of the interlayered paragneiss. The foliated gabbro-monzonite locally shows evidence for partial melting giving the rock a migmatitic appearance. The neosomes are feldspar-rich

Table 1. Modal composition of the analysed rocks. An content of plagioclase is given in parentheses.

	Plag	A.fsp	Amph	Cpx	Opx	Ol	Bio	FeTiOx	Ap
Ø4.6A	50%(An_{50})	0	45%	0	0	0	tr	5%	tr
Ø4.6B & D	72%(An_{25})	5%	13%	3%	5%	0	tr	2%	1%
Ø4.6C	75%(An_{20})	10%	10%	2%	2%	0	tr	1%	tr
Ø4.7A	tr?	90%	7%	3%	tr	0	tr	tr	tr
Ø4.7B & C	15%(An_{20})	65%	15%	4%	1%	0	tr	tr	tr
Ø4.7D	50%(An_{20})	30%	tr	8%	7%	tr	tr	tr	tr
Ø4.8A	tr	85%	10%	3%	2%	0	tr	tr	tr

tr – less than 1%

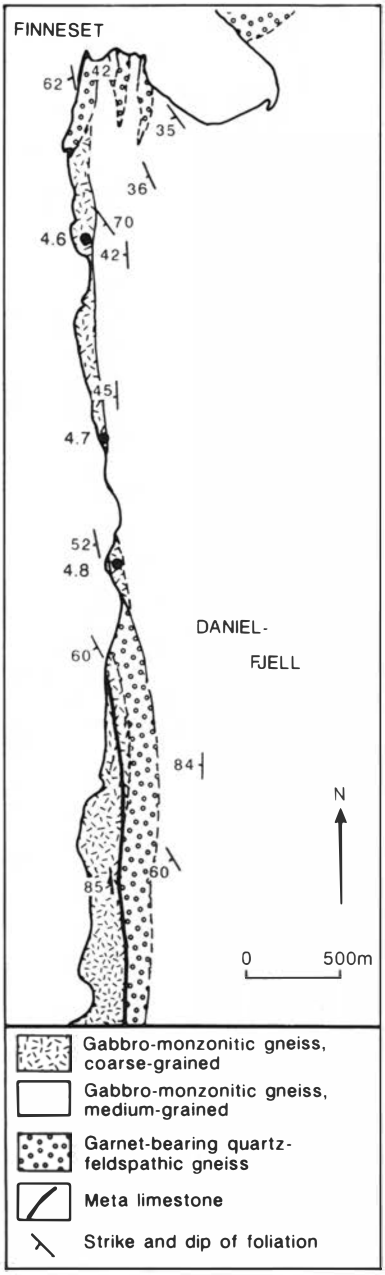

Fig. 2. Detailed map of the sampled area, with sample localities.

(perthositic) in composition, similar to those described by Brueckner (1973). Narrow shear zones ranging in width from less than 1 mm up to 30 cm post-date the migmatite formation, and are also seen cross-cutting massive ultramafic rocks and nepheline–syenite pegmatites. In the shear zones, the new foliation in intermediate to mafic rocks is defined by garnet + two pyroxenes + plagioclase ± quartz, thus defining the transition from two-pyroxene (intermediate pressure) to garnet–clinopyroxene (high-pressure) granulite facies (Elvevold 1990; Krogh et al. 1990). A similar evolution has also been found in the quartz-feldspathic gneisses of the area. The correlation of the main metamorphic foliation in the investigated area with the regional deformations established elsewhere in the Sørøy–Seiland Nappe (Ramsay 1971) seems to be difficult. Thus we will in this paper mainly focus on the relationships we have investigated on the Øksfjord Peninsula.

Samples Ø4.6A to Ø4.6D were collected from a roadcut ca. 1 km S of Finneset (Fig. 2; UTM 5045 9165). Modal compositions of the analysed samples are given in Table 1. Sample Ø4.6A is coarse to medium grained, foliated and consists mainly of plagioclase and hornblende. Samples Ø4.6B, C and D are medium grained, strongly foliated and consist mainly of plagioclase (ca. 75%) and parallel-oriented, strongly flattened aggregates of amphibole and pyroxene. Samples Ø4.7A to Ø4.7D were collected from two roadcuts ca. 1 km S of the first locality (UTM 5055 9050). Samples Ø4.7A, B and C are all strongly foliated monzonitic gneisses, while sample Ø4.7D is massive. They all mainly consist of brownish green feldspar with smaller amounts of mafic minerals. Sample Ø4.8A is a monzonitic gneiss collected ca. 3 km S of Finneset (Fig. 2; UTM 5060 8985), close to the garnet-bearing quartzo-feldspathic gneiss.

Petrographic description

The analysed samples, except Ø4.7D and Ø4.8A, are texturally similar. The rocks have a heterogranular granoblastic texture, with average grain size of 0.8–1.2 mm. Aggregates of amphibole and pyroxene are parallel oriented and define a foliation. The relative amount of feldspar/mafic minerals varies from ca. 50/50 (Ø4.6A) to 90/10 (Ø4.7A). Plagioclase and perthitic alkali feldspar appear as 0.5–2.0 mm equidimensional grains exhibiting mortar texture. Both plagioclase and alkali feldspar show varying degrees of sericitization. Two generations of amphibole are observed. Older brownish green amphibole (7–45%) occurs as 0.25–1.25 mm large grains oriented parallel to the foliation. Along the grain boundaries of these amphiboles a secondary aggregate of fine-grained blue-green amphibole and Fe–Ti oxide is commonly present. Clinopyroxene, when present, occurs as 0.15–1 mm large grains, either as inclusions in older amphibole or as separate grains in the matrix. Pleochroic orthopyroxene occurs either as separate grains in aggregates together with amphibole, or as rims on clinopyroxenes. In one sample, orthopyroxene seems to be overgrown by clinopyroxene. Fine-grained biotite grows locally along the rims of the other mafic minerals. Sample Ø4.8A shows a larger degree of straining and recrystallization of the feldspar than the other samples, resulting in parallel-oriented bands (ribbons) of recrystallized plagioclase and K-feldspar with average grain size of <0.2 mm.

Sample Ø4.7D shows a heterogranular, polygonal texture, with feldspar grains varying from 0.1–4 mm. Perthitic feldspar makes up the largest grains. Plagioclase occurs as equidimensional grains of average size 0.75 mm. Perthitic feldspar occurs as lath-formed grains up to 4 mm long. No secondary alteration of the feldspars is observed. Clinopyroxene has a faint green colour, and forms prismatic grains from 0.2–2 mm across. Orthopyroxene shows pleochroism, and occurs as 0.2–1 mm large hypidiomorphic grains. Both pyroxenes are rimmed by a blue-green secondary amphibole. Trace amounts of anhedral olivine are present in this rock, as are dark brown biotite. In the field and in hand specimen it is, however, difficult to distinguish this sample from the other feldspar-rich samples described here. Nevertheless, we suspect that sample Ø4.7D belongs to a separate, probably younger intrusion, although we have not been able to recognize any contact relationships. This is mainly due to insufficient exposure in the area of interest. Due to its similarity to the other samples we have decided to include the sample in our work.

Analytical procedures

The sizes of the analysed samples were on the order of 10–15 kg. All weathered surfaces were carefully removed before crushing and pulverizing. Major elements were analysed on fused Li-tetraborate pellets, and pressed pellets were analysed for trace elements (including Rb and Sr, after the method described by Norrish & Chappel 1967) on a Philips PW1400 X-ray spectrometer at the Department of Biology and Geology, University of Tromsø. The analytical precision of the Rb/Sr ratio, based on ten repeated measurements and recalculated to ^{87}Rb/^{86}Sr, is given in Table 3. Sr-isotope ratios were analysed at the isotope laboratory at the Mineralogical-Geological Museum, University of Oslo, using a VG 354 5-collector solid source instrument. These analyses were kindly performed by A. Stabel. Isochron calculations followed the procedure of York (1969). A decay constant of 1.42×10^{-11} yr^{-1} (Steiger & Jäger 1977) has been used in the age calculations.

Analytical results

Major, minor and trace element analyses are given in Table 2. Complete isotopic results are presented in Table 3, and the data are plotted in a standard Rb–Sr isochron diagram in Fig. 3. Seven of the nine samples yield a well defined isochron of 829 ± 18 Ma with an initial ^{87}Sr/^{86}Sr ratio of 0.70272 ± 4, all uncertainties at the 2σ level. The MSWD value (1.4) is better than the accepted limit of 2.5 (Brooks et al. 1972) for an

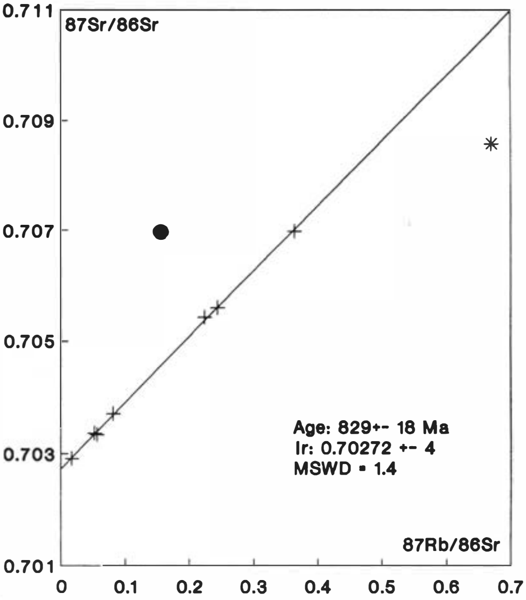

Fig. 3. Whole-rock Rb–Sr isochron for foliated gabbros and monzonites, based on the data from Table 2. Two of the points (Ø4.8A – *; Ø4.7D – ●) have been omitted from the regression. Uncertainties are given at the 2σ level.

Table 2. Whole-rock chemistry (XRF) for foliated gabbro-monzonite gneiss, Øksfjord peninsula.

Sample	Ø4.6A	Ø4.6B	Ø4.6C	Ø4.6D	Ø4.7A	Ø4.7B	Ø4.7C	Ø4.7D	Ø4.8A
	Major elements – wt% oxide								
SiO_2	42.34	47.20	52.39	47.88	61.04	56.73	56.86	56.81	59.38
TiO_2	3.29	1.81	1.25	2.12	0.34	1.09	1.04	1.19	0.90
Al_2O_3	17.27	18.00	18.55	17.99	18.83	17.74	18.49	19.16	17.45
$Fe_2O_3^{-}$	15.19	11.59	9.94	11.18	3.85	8.66	7.97	6.75	7.29
MnO	0.18	0.22	0.19	0.20	0.10	0.20	0.18	0.14	0.17
MgO	5.32	4.04	2.76	3.90	0.53	1.39	1.18	1.25	0.86
CaO	10.76	9.23	6.56	8.45	2.59	4.85	4.64	4.93	2.75
Na_2O	3.30	4.38	5.36	4.62	5.99	5.89	6.16	4.93	5.70
K_2O	0.68	1.02	1.58	1.12	5.03	3.07	2.86	3.94	4.72
P_2O_5	0.45	1.68	0.65	1.17	0.10	0.42	0.39	0.42	0.35
Total	98.78	99.17	99.23	98.63	98.40	100.04	99.77	99.52	99.57
	Trace elements – ppm								
V	356	62	60	21	7	1	1	35	1
Cr	67	76	94	92	76	75	78	85	74
Co	49	23	24	15	2	3	5	6	3
Ni	10	7	13	10	4	1	1	3	3
Y	21	32	31	20	14	46	37	17	35
Zr	67	36	73	46	76	415	245	26	233
Nb	34	33	50	22	33	93	80	26	94

Table 3. Rb–Sr data for foliated gabbro-monzonite gneiss, Øksfjord peninsula.

Sample	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$ (2σ)	$^{87}Sr/^{86}Sr$ (2σ)
Ø4.6A	6.3	1075	0.0169 ± 0.0026	0.70291 ± 6
Ø4.6B	23.0	1280	0.0520 ± 0.0038	0.70336 ± 4
Ø4.6C	32.7	1165	0.0812 ± 0.0030	0.70371 ± 4
Ø4.6D	23.9	1218	0.0567 ± 0.0034	0.70334 ± 4
Ø4.7A	66.3	528	0.3632 ± 0.0062	0.70698 ± 4
Ø4.7B	39.2	464	0.2444 ± 0.0102	0.70560 ± 4
Ø4.7C	37.0	478	0.2239 ± 0.0112	0.70543 ± 4
Ø4.7D	39.1	741	0.1526 ± 0.0081	0.70683 ± 4
Ø4.8A	55.3	239	0.6694 ± 0.0150	0.70857 ± 4

isochron. Two of the samples, Ø4.7D and Ø4.8A, plot well off the regression curve, and are excluded from the regression. Sample Ø4.8A is mineralogically similar to the seven other samples, but shows evidence for stronger deformation and recrystallization, and this may have been associated with a disturbance of the bulk chemical and isotopic system of this sample. Sample Ø4.7D, which is massive and only weakly retrogressed compared to the other samples, probably represents a separate intrusion as indicated above.

Discussion

From field evidence (strong foliation, migmatization) the dated rocks appear to be the oldest intrusive phase present in the investigated area. The calculated isochron for the layered meta-gabbro-monzonite from Øksfjord most probably represents the time of intrusion for these rocks into a metasedimentary sequence. The low $(^{87}Sr/^{86}Sr)_i$ indicates the source to be a depleted mantle reservoir. Alternative interpretations, for example the array of points representing a mixing line, can be ruled out from the available data.

Table 4. Rb–Sr XRF analyses and recommended values (Govindaraju 1989) of two international standards.

Std	Rb (ppm)	Sr (ppm)
DR-N (anal.)	75 ± 1	392 ± 1
(rec.)	73	400
BE-N (anal.)	49 ± 0.5	1380 ± 2
(rec.)	47	1370

Then followed an episode of strong deformation and recrystallization/high-grade (2-pyroxene granulite facies) metamorphism, probably culminating in migmatization. Later higher-P (garnet–clinopyroxene granulite facies) ductile shear-zones transect both the main foliation and the migmatites.

The present work, together with other previous and recent isotope studies from the Seiland Igneous Province, indicates a long and complex history for this segment of the Scandinavian Caledonides, a conclusion also put forward by Aitcheson & Taylor (1989) and Daly et al. (1990). Mantel-derived igneous rocks of gabbroic to monzonitic composition intruded a sedimentary sequence at 829 ± 18 Ma. Data from these metasediments indicate an Rb–Sr age of ca. 1000 Ma which has been interpreted as a provenance age (Brueckner 1973). The magmatic activity continued with separate intrusions in various parts of the SIP dated to 700 ± 33 Ma (Aitcheson et al. 1989; Daly et al. 1990), ca. 611 Ma (Brueckner 1973), 612 ± 33 Ma and 604 ± 44 Ma (Daly et al. 1990), 559 ± 36 Ma and 513 ± 24 Ma (Snow et al. 1986), 550 ± 34 Ma (Mørk & Stabel 1988, 1990 (this issue)), 531 ± 2 and 523 ± 2 Ma (Pedersen et al. 1989). The last two ages are on late-stage nepheline syenite pegmatite dikes, and probably represent the termination of the magmatic activity in the province, although Pedersen et al. (1989) mention even younger mafic dikes in the area. These late nepheline syenite pegmatite dikes clearly cut the regional gneiss foliation of the metagabbros (Pedersen et al. 1989), but are in turn cut by late high-pressure shear-zones (F. Bjørklund, in prep.). Mørk & Stabel (1988, 1990 (this issue)) report a Sm–Nd mineral age on a metamorphic assemblage of 531 ± 10 Ma, which is interpreted to represent the timing of garnet formation in the rock. A younger metamorphic event related to the foliation-forming deformation and metamorphism in the metagabbros occurred at 502 ± 28 Ma (Mørk & Stabel 1988, 1990 (this issue)), and was followed by post-metamorphic cooling dated to ca. 490 Ma (Dallmeyer 1988). However, as nepheline syenite dikes probably coeval with those dated at 520–530 Ma (Pedersen et al. 1989) clearly post-date the main gneiss foliation in the area, this foliation must be older than ca. 530 Ma. The age of ca. 611 Ma (Brueckner 1973) on apparently undeformed and unmetamorphosed syenitic perthosites with intrusive relationships to the enclosing gabbro-gneiss further indicates that the main foliation/metamorphism in the area occurred before or at ca. 610 Ma. One possible explanation is that the perthosites may represent partial fusion of the host rock at the temperature maximum during late stages of the main metamorphic event, as their initial $^{87}Sr/^{86}Sr$ ratio (0.7031) is identical with the average $^{87}Sr/^{86}Sr$ ratio at 611 Ma of the analysed gabbro-monzonite samples given in this paper. This is also constrained by the occurrence of migmatite domains with perthositic neosomes within the gabbro-monzonite gneisses. The similar ages (612 ± 33 Ma and 604 ± 44 Ma) on the Storvik and Kvalfjord gabbros, respectively, have been interpreted to represent the intrusion age of these layered bodies (Daly et al. 1990). The Storvik gabbro on Øksfjordhalvøya is, however, strongly foliated and recrystallized to a two-pyroxene granulite, the foliation being parallel with the foliation observed in the adjacent gabbro-monzonitic gneiss dated here. The metamorphic nature of this rock is also confirmed by Mørk & Stabel (1990, this issue), and Aitcheson (1989, Fig. 18), who presents a microphoto of the dated rock showing total recrystallization. The Kvalfjord gabbro seems, however, to be rather undisturbed (Aitcheson 1989, Fig. 17). A plausible interpretation is that these layered gabbros intruded syn- to late during the deformation episode giving rise to the main foliation in the area. The main foliation and metamorphism of the area thus seem to pre-date the intrusion of the ultramafic rocks. This further makes the Sm/Nd mineral–whole-rock age of 502 ± 28 Ma of Mørk & Stabel (1988, 1990 (this issue)) difficult to interpret. One possibility is that this age may represent the timing of the later event of higher-pressure shear-zone formation as discussed above.

As there is an apparent increase in pressure (from ca. 6 to >8 kbar) at constant temperature (ca. 640°C) from the main deformational/metamorphic event to the shear deformation (Elvevold 1990, in prep.), this suggests that the whole province has been at considerable depth also during the intrusion of the late alkaline rocks, in contrast to the interpretation of Pedersen et al. (1989).

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