Kentallenite (olivine-monzonite) in Bindal, Central Norwegian Caledonides

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A rock-type identified as kentallenite is reported from the southwestern part of the Helgeland Nappe Complex, Central Norway. The kentallenite is a hypabyssal rock and belongs to a suite of appinitic mafic dykes and small stocks which are spatially and temporally associated with calc-alkaline granitoids of the Bindal Batholith. The petrography of the rock is characteristic with phenocrysts of olivine and zoned clinopyroxene in a groundmass which usually consists of plagioclase, biotite, K-feldspar, clinopyroxene, orthopyroxene, ilmenite and apatite. A K-Ar whole-rock date of 399 ± 10 Ma can be interpreted either as a cooling age related to the emplacement of the rock, or it can be related to an Early Devonian thermal event.

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Introduction

Kentallenite (olivine-monzonite) intrudes granitoids of the Bindal Batholith (BB) in the southwestern part of the Helgeland Nappe Complex (HNC), which is the uppermost unit in the nappe pile of the Central Scandinavian Caledonides (Ramberg 1967, Gustavson 1978b, Gee et al. 1985). Teall (1888) described a similar rock from Kentallen Quarry, Scotland, as olivine-monzonite, and the rock from this locality was named kentallenite by Hill & Kynaston (1900); see also Bailey & Maufe (1960).

Kentallenites are usually considered to be part of the appinite group (Pitcher & Berger 1972, Wright & Bowes 1979), which may be regarded as the plutonic equivalent of the lamprophyres (Wright & Bowes 1979, Rock 1984, 1987, Barnes et al. 1986). Lamprophyres and appinites often occur in close association, and commonly in areas with extensive, calc-alkaline, granitoid plutonism.

In Bindal, the kentallenite cuts a large tonalite pluton, and rocks which have been described as medium- to coarse-grained appinites occur in the same area (Nordgulen 1984). Additionally, fine- to medium-grained, often amphibole-phyric 'lamprophyre' dykes and composite mafic to dioritic dykes are common. These rocks, including the kentallenite, are among the youngest igneous rocks in the area and may overlap in time with granitic, aplitic and pegmatitic dykes (Nordgulen 1984). Thus, the setting in which the kentallenite occurs resembles that described for rocks of similar aspect (see references above).

Regional context

Recent mapping in southwest Helgeland has demonstrated the presence of a composite nappe (HNC) where rocks of different provenance are stacked together. Presently at least two different tectonostratigraphic units are recognized. One of these is a basement-cover couple comprising a mafic/ultramafic basement unconformably overlain by a characteristic cover sequence consisting of mafic and calcareous conglomerates, psammites, schists and marbles (Husmo, pers comm. 1983, Bang 1985, Løseth 1985, Thorsnes 1985, Heldal 1987, Hjelmeland 1987). The other unit is less well defined and consists of partly migmatitic schists and gneisses, calc-silicate gneisses and banded marbles (Nordgulen 1984). A similar pattern has emerged further north in the HNC where Precambrian gneisses and seemingly younger cover sequences occur in separate provinces (Riis & Ramberg 1981, Tørudbakken & Mickelson 1986). For more detailed descriptions of various parts of the HNC, the reader is referred to Gustavson & Grønhaug (1960), Nissen (1965), Kollung

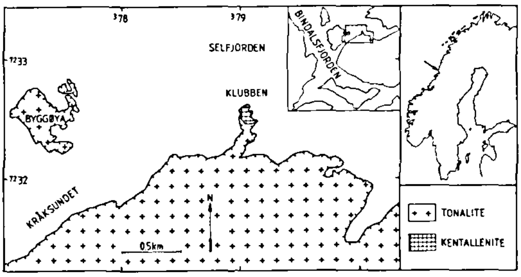

Fig 1. Location of kentallenite on the Klubben peninsula, Bindal, where it cuts tonalite of the Kråkfjellet Pluton. Coordinates as on map-sheet 1825-3, Terråk. Sample sites (see table 3): B174 (dated sample): 15 m from the contact with tonalite on the eastern part of peninsula; B442 and B443: Northeastern part of peninsula; N86-94, N86-95 and N87-102: Northwestern part of peninsula.

(1967), Myrland (1972) and Gustavson (1975, 1978a).

In the east and southeast the HNC lies structurally above low-grade rocks of the Köli Nappes (Lutro 1979, Dallmann 1986). The relationships are less clear in the west where the HNC is present above Precambrian orthogneisses and medium-grade supracrustals of unknown age (Kollung 1967, Schouenborg 1988). The base of the HNC has been mapped between Grong and Bindal (Roberts et al. 1983, Nordgulen & Bering 1987, Husmo in prep.). Further north, however, the continuation of the boundary has not yet been identified with certainty.

The Bindal Batholith (BB), which comprises the essentially calc-alkaline Caledonian plutonic rocks in the area between Namdalen in the south and Rana in the north (Nordgulen et al. 1988), occupies a major part of the HNC (Gustavson 1981). Medium- to coarse-grained and sometimes megacrystic granitoids, which occur as large plutons or smaller stocks and dykes, are the most common rock-types. However, the batholith composition ranges from mafic gabbro to leucogranite. Geochemical analyses of a wide range of granitoids show that the BB has many similarities with the Sunnhordland and Smøla-Hitra Batholiths (Gautneb 1987, Andersen & Jansen 1988, Nordgulen et al. 1988) as well as with the younger granitoids in Scotland (Stephens & Halliday, 1984). For a review of isotopic studies of the BB the reader is referred to Tørudbakken & Mickelson (1986) and Nissen (1986). The data published by these authors, by Priem et al. (1975) and Gustavson & Prestvik (1979) suggest Cambrian to Silurian ages for the BB.

Field relations

The kentallenite is dark grey to black with a spotted appearance enhanced by the weathering of olivine and clinopyroxene (cpx) phenocrysts. The groundmass minerals are normally very fine-grained, though locally there is a change towards a somewhat coarser variety where plagioclase and biotite can be readily distinguished. The transition between the textural varieties is gradational and typically takes place over a distance of about 10-20 cm.

Since the rock is only exposed on the end of a small peninsula (Fig 1, UTM 37900 - 723250), the true size of the intrusion cannot be assessed. The contact with the Kråkfjellet Pluton (KP) in the south has a steep attitude and curves gently across the peninsula. Generally the contact is sharp, and xenoliths of the KP occur near the contact. Chilling of the kentallenite towards the contact with the KP has not been noted. In some places, however, the contact appears to be gradational between the tonalite (KP) and the kentallenite. The transitional rock type has a dioritic groundmass and contains abundant, small, irregularly shaped fragments of: i) a greenish, altered, fine-grained rock which resembles the kentallenite; ii) dark, fine-grained dioritic material; iii) medium- to coarse-grained gabbro similar to xenoliths in the kentallenite.

The transitional rock-type also occurs in a 0.5 m thick steeply dipping lens about 3-4 m away from the contact. There are at least two possible explanations of these relationships: (i) The rock represents a partly assimilated material in the KP which has been cut by the kentallenite. (ii) Locally, partial melting and mobilization of the KP occurred during intrusion of the kentallenite. Subsequent mixing of the two partly solidified materials yielded the contact facies.

Support for the latter explanation derives from the presence of a xenolith of felsic granite in the kentallenite, which shows evidence of having been mobilized and having backveined its host. Furthermore, inclusions similar to the mixed rock-type have not been recorded elsewhere in the KP.

The kentallenite contains xenoliths of gabbro, granitoids and metasediments. Fig 2 shows a xenolith of coarse-grained gabbro which has been cut by a dyke and thin veinlets of kentallenite.

The latest magmatic activity in the area is represented by fine-grained granite dykes which cut the kentallenite (Nordgulen 1984).

Petrography and mineral chemistry

The common, fine-grained variety of the kentallenite has phenocrysts of olivine (<1.5 mm) and cpx (<4 mm) in a groundmass consisting of microphenocrystic laths of plagioclase and fine-grained orthoclase, biotite, cpx, ortopyroxene (opx), ilmenite and apatite (Fig 3).

Cpx is present as euhedral, fresh crystals which may display both normal and oscillatory zoning. Several smaller, anhedral grains may be clustered in glomeroporphyritic aggregates with interstitial plagioclase.

Analyses of zoned cpx phenocrysts were made along traverses from core to rim. Groundmass cpx was also analysed (one analysis included in Table 1). Generally, Mg and Cr are enriched in the core whilst Fe, Al and Ti increase towards the rim. The oscillatory nature of the zoning may cause some deviation from the overall trend, but this has not been studied in detail. Fig 4 shows that there is only a weak Fe enrichment in the cpx. This is typical of cpx in calc-alkaline and shoshonitic rocks as opposed to the rather marked trend towards a higher Fe-component during crystallization of tholeiitic magmas (e.g. Morrison 1980, Kay et al. 1983).

Olivine is less common than cpx and is present as anhedral crystals with rounded margins, usually partly or completely altered. Incipient alteration is manifested by a yellowish, fibrous serpentine mineral which grows along the margins and normal to fracture walls in the crystals. Where olivine has been totally replaced, its former presence is revealed by the alteration products; pale serpentine blackened by fine magnetite which in places is rimmed by biotite. In detail, magnetite commonly has the shape of thin, regular vermicules. Very rarely olivine is included in cpx. The olivine ranges in composition between $Fo_{84.5}$ and $Fo_{76.6}$ (Table 2). Although the partitioning of Fe2+ and Mg2+ in olivine may vary to some extent (Ford et al. 1983), the large variation in composition strongly suggests disequilibrium crystallization of the olivine phenocrysts. This is supported by the anhedral grain shape which indicates that resorption has occurred. It may thus be suggested that the olivine is in disequilibrium with the intermediate rock composition, and that rapid cooling, probably during intrusion, prevented it from reacting with the melt.

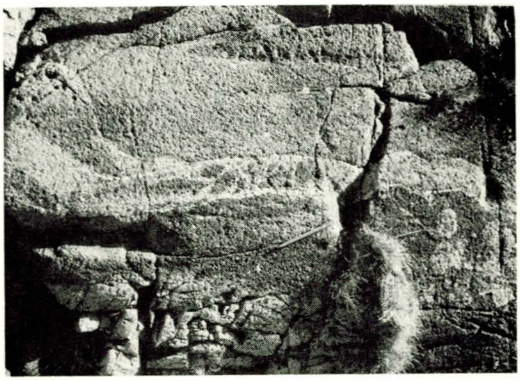

Fig 2. Xenolith of coarse-grained gabbro in the kentallenite. A dyke of the kentallenite has penetrated the gabbro and contains small inclusions of it. Locality: Close to the contact on the eastern side of Klubben.

Fig 3. Typical texture of the kentallenite. Partly altered irregular phenocryst of olivine (extinct crystal to the left of centre) is surrounded by numerous smaller crystals of cpx. Cpx occurs as phenocrysts of variable size and may show regular zoning revealed by small inclusions of biotite (right). Biotite is present as irregular grains which have grown along the margins of cpx or across groundmass minerals. In the groundmass, small laths of plagioclase have a distinct preferred orientation. Width of photo: 4 mm.

In the groundmass, small anhedral crystals of cpx and opx are present (microprobe analyses in Table 1). The small grain size makes optical discrimination impossible, and therefore their relative abundances are unknown. Biotite

Table 1. Microprobe analyses of pyroxenes.

	cpx1	cpx1	cpx1	cpx1	cpx2	cpx2	cpx2	cpx3	cpx3	cpx3	cpx4	cpx4	cpx4	cpx4	cpx5	cpx5	cpx6	cpx6	cpx6	cpx7	cpx7	groundmass	
	core			rim	core		rim	core		rim	core			rim	core	rim	core		rim		rim	cpx	opx
SiO_2	51.68	49.99	50.42	49.71	52.76	52.41	51.54	53.03	51.48	50.13	53.51	49.40	50.18	50.12	53.77	51.19	52.03	52.63	50.41	52.77	51.71	51.50	52.16
Al_2O_3	2.80	4.51	4.61	4.02	2.07	2.18	2.86	1.56	2.56	3.81	1.12	4.84	4.32	3.85	1.43	3.41	2.82	2.33	3.26	1.44	2.31	1.55	.82
TiO_2	.41	1.00	.68	1.04	.35	.33	.82	.27	.54	1.07	.08	.86	.80	1.01	.19	.60	.40	.33	1.02	.29	.38	.35	.12
Fe_2O_3	.20	.43	.00	1.25	.00	.48	.00	.00	.05	.76	.27	1.24	.03	1.41	.00	.00	.00	.00	.82	.24	1.37	.00	.00
MgO	16.28	14.28	15.30	14.05	16.34	17.17	14.91	16.52	15.27	14.09	17.34	13.72	14.30	13.91	17.17	14.08	15.57	16.26	14,39	16.42	15.42	12.21	18.73
FeO	5.52	7.67	7.57	7.06	5.14	4.72	7.81	3.75	6.38	7.79	4.52	6.54	6.98	6.89	3.75	8.29	7.32	5.61	7.44	4.01	5.98	11.40	25.83
MnO	.15	.19	.25	.17	.12	.16	.22	.19	.13	.20	.05	.21	.24	.20	.11	.23	.16	.15	.30	.10	.22	.32	.54
CaO	20.18	19.74	18.85	20.03	20.80	20.49	19.66	21.86	21.41	20.36	21.00	20.69	20.71	20.60	21.19	20.12	19.21	20.00	20.18	22.39	20.32	20.13	.95
Na_2O	.33	.44	.31	.52	.37	.26	.41	.30	.19	.37	.29	.42	.30	.52	.41	.35	.49	.31	.42	.28	.53	.48	.00
Cr_2O_3	.40	.06	.00	.07	.22	.32	.18	.75	.04	.08	.30	.12	.27	.20	.45	.20	.10	.39	.06	.47	.19	.00	.01
TOTAL	97.95	98.31	98.08	97.92	98.17	98.52	98.41	98.23	98.05	98.66	98.48	98.04	98.12	98.72	98.47	98.47	98.10	98.01	98.30	98.41	98.43	97.94	99.16
Structural formula based on 4 cations																							
Si	1.931	1.881	1.892	1.881	1.965	1.941	1.936	1.972	1.934	1.887	1.978	1.865	1.889	1.883	1.986	1.929	1.950	1.967	1.901	1.960	1.935	1.977	2.002
Al(IV)	.069	.119	.108	.119	.035	.059	.064	.028	.066	.113	.022	.135	.111	.117	.014	.071	.050	.033	.099	.040	.065	.023	.000
Al(VI)	.054	.081	.096	.061	.056	.037	.063	.040	.047	.056	.027	.081	.080	.054	.049	.080	.075	.070	.046	.023	.037	.047	.037
Ti	.012	.028	.019	.030	.010	.009	.023	.008	.015	.030	.002	.024	.023	.029	.005	.017	.011	.009	.029	.008	.011	.010	.003
Fe3+	.006	.012	.000	.035	.000	.013	.000	.000	.001	.021	.008	.035	.001	.040	.000	.000	.000	.000	.023	.007	.039	.000	.000
Mg	.907	.801	.856	.793	.907	.948	.835	.915	.855	.790	.955	.772	.802	.779	.945	.791	.870	.906	.809	.909	.860	.699	1.071
Fe2+	.173	.241	.238	.223	.160	.146	.245	.117	.201	.245	.140	.206	.220	.216	.116	.261	.229	.175	.235	.125	.187	.366	.829
Mn	.005	.006	.008	.005	.004	.005	.007	.006	.004	.006	.002	.007	.008	.006	.003	.007	.005	.005	.010	.003	.007	.010	.018
Ca	.808	.796	.758	.812	.830	.813	.791	.871	.862	.821	.832	.837	.835	.829	.839	.812	.771	.801	.816	.891	.815	.828	.039
Na	.024	.032	.023	.038	.027	.019	.030	.022	.014	.027	.021	.031	.022	.038	.029	.026	.036	.022	.031	.020	.038	.036	.000
Cr	.012	.002	.003	.002	.006	.009	.005	.022	.001	.002	.009	.004	.008	.006	.013	.006	.003	.012	.002	.014	.006	.000	.000
Mg	47.78	43.14	46.03	42.40	47.72	49.23	44.44	47.96	44.46	41.95	49.35	41.56	43.01	41.63	49.67	42.25	46.37	48.01	42.76	46.99	45.09	36.71	54.75
Fe	9.64	13.99	13.21	14.14	8.62	8.55	13.43	6.42	10.72	14.49	7.68	13.38	12.22	14.06	6.27	14.35	12.50	9.55	14.14	6.95	12.20	19.78	43.26
Ca	42.58	42.87	40.76	43.45	43.66	42.23	42.12	45.62	44.81	43.57	42.96	45.06	44.77	44.31	44.06	43.40	41.13	42.25	43.10	46.06	42.71	43.51	2.00

(‹0.5 mm) occurs as dark brown, irregular grains. Commonly small flakes are present within cpx or as rims around cpx and altered olivine. The major part of the biotite grows as small grains across the groundmass minerals including plagioclase (Fig 3). Plagioclase (0.2-0.5 mm) is present as twinned, lath-shaped, euhedral to subhedral crystals in the finer-grained (0.01-0.1 mm) groundmass. There is a strong normal zoning with variation from An_{52} in the central part to An_{30} near the margin of a grain. The plagioclase crystals commonly display a well developed preferred orientation which in detail is controlled by the shape of olivine and cpx phenocrysts (Fig 3). This mineral orientation is probably due to flow when the rock was partially crystallized. K-feldspar appears to be interstitial with respect to plagioclase. The analyses indicate 5-15 % Ab in the K-feldspar. Also present in the groundmass are small, equant grains of ilmenite in addition to pale, tiny, needle-shaped crystals of apatite.

Locally the groundmass is coarser; plagioclase laths are typically 0.5-1.0 mm, biotite (0.5-2.0 mm) is more abundant, and several separate biotite crystals may be in optical continuity over a small area. Biotite grows across other minerals and sometimes occurs as elongate grains (‹3 mm) made up of a few small crystals with the same orientation. The groundmass contains little or no pyroxene and ilmenite, and apatite is present as euhedral crystals enclosed in cpx, biotite and plagioclase. Some crystals of K-feldspar may show the characteristic microcline twinning. Fresh olivine is no longer present, and most of the cpx is mantled by green hornblende, or completely altered to hornblende and pale amphibole speckled with small blebs of exsolved opaques. Some tiny crystals of titanite, epidote and calcite are considered to be of secondary origin.

Table 2. Selected microprobe analyses of olivine.

	1	2	3	4	5	6
SiO2,	39.34	39.41	38.93	39.32	39.12	39.93
FeO	14.93	19.21	20.51	20.09	21.52	14.73
MgO	44.58	41.62	39.78	40.78	39.22	44.72
MnO	.24	.27	.38	.37	.32	.25
NiO	.15	.11	.13	.13	.12	.15
TOTAL	99.87	100.65	99.85	100.73	100.35	99.95
Structural formula based on 4 oxygens						
Si	.999	1.018	1.000	1.024	1.017	1.002
Fe	.311	.409	.440	.436	.467	.308
Mg	1.672	1.612	1.537	1.592	1.530	1.683
Mn	.005	.006	.008	.009	.007	.006
Ni	.003	.002	.003	.003	.003	.003
100Mg/Mg+Fe	84.3	79.8	77.8	78.5	76.6	84.5

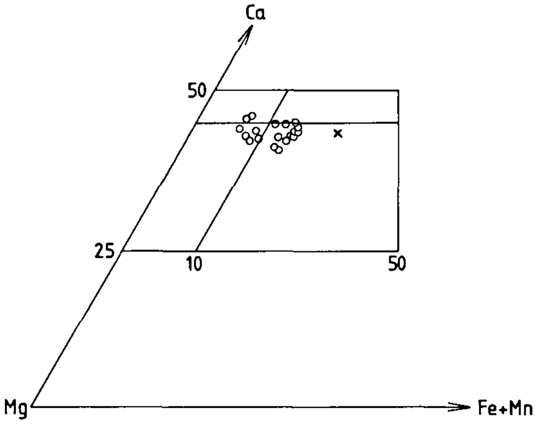

Fig 4. Part of a Ca-Mg-Fe + Mn diagram showing the clinopyroxenes listed in Table 1. One analysis of groundmass cpx (X) has distinctly higher Fe than the tightly clustered phenocryst compositions. The cores of the analysed crystals always have a low Fe-content (see Table 1).

As will be shown below, the two textural varieties are not geochemically distinguishable, and it is thought that they crystallized from practically identical magmas. The variation in grain size may therefore be due to variable nucleation density and/or slightly slower solidification of the coarser rock-type. An extended period of solidification and cooling would also explain the clearly more extensive breakdown of primary phases (cpx and olivine) to minerals which are stable at lower temperatures.

Similarities to the type kentallenite (Teall 1888, Hill & Kynaston 1900) include the porphyritic nature, the typical appearance of anhedral olivine and euhedral cpx, inclusions of olivine in cpx, brown biotite with separate crystals having uniform orientation, and euhedral and zoned plagioclase with interstitial K-feldspar. There is also an obvious resemblance between the rock from Bindal and kentallenite illustrated in McKenzie et al. (1982); however, olivine is less abundant in the former. As far as the fine-grained variety is concerned, it was pointed out by Hill & Kynaston (1900) that rocks with fine-grained groundmass and small biotite flakes are also present among the kentallenites. Based on these arguments and the proximity to appinitic rocks in the area (Nordgulen 1984), the application of the term kentallenite to the Bindal occurrence seems fully justified. Following the classification of Streckeisen (1976), the rock should be termed dark olivine-monzonite. However, in this paper we will use the term kentallenite.

Geochemistry

Major and trace element analyses from six fresh 0.5 - 1.0 kg samples collected at different places (Fig 1) show that the kentallenite is very homogeneous (Table 3). Note that the three samples with a comparatively coarse groundmass (N86-94, N86-95 and N87-102) are not significantly different from the common fine-grained variety. The kentallenite is silica-saturated (1.4 - 6.5 % normative quartz) and straddles the boundary between the alkaline and sub-alkaline fields of Irvine & Baragar (1971).

Table 3. Whole-rock analyses

	B174	B442	B443	N86-94	N86-95	N87-102
SiO_2	56.04	57.05	56.06	55.52	55.75	54.71
TiO_2	.72	.76	.76	.90	.89	.89
Al_2O_3	13.84	13.63	13.55	14.28	14.16	14.66
Fe_2O_3	6.47	7.49	7.83	8.01	7.90	7.87
MgO	7.16	6.89	7.53	7.02	7.03	6.74
CaO	7.05	7.14	7.47	7.15	7.01	6.93
Na_2O	2.81	3.28	3.41	2.74	2.62	2.82
K_2O	3.39	3.53	3.57	3.08	3.31	3.22
MnO	.12	.13	.13	.14	.13	.12
P_2O_5	.27	.27	.34	.29	.27	.28
LOI	.17	.85	.80	.53	.79	.80
TOTAL	98.04	101.02	101.45	99.66	99.86	99.04
Ba	nd	nd	nd	830	786	758
Ce	71	77	73	75	84	74
Co	39	41	41	29	27	29
Cr	300	302	326	366	381	345
Ga	nd	nd	nd	17	18	17
La	26	35	38	30	25	39
Nb	12	13	13	10	10	9
Nd	36	41	48	37	31	42
Ni	67	69	77	83	81	85
Pb	nd	nd	nd	23	23	20
Rb	103	101	98	102	109	107
Sc	nd	nd	nd	23	23	18
Sr	513	507	518	623	574	581
Th	nd	nd	nd	10	15	17
U	nd	nd	nd	3	4	2
V	137	140	145	151	147	156
Y	20	20	20	27	27	28
Zn	76	77	77	88	82	77
Zr	139	196	194	174	156	152

nd: not determined.

K-Ar analytical data:

K_2O = 3.51 ± 0.01
Radiogenic ^{40}Ar = (5.05 ± 0.06) * 10^{-2} mm^{3}gm^{-1}
% atmospheric ^{40}Ar = 2.4

Apparent age = 399 +/+ 10 Ma

Wright & Bowes (1979) pointed out that the appinitic rocks are geochemically dissimilar from the more common basaltic and andesitic rocks. K_2O is much higher than in calc-alkaline and tholeiitic rocks of similar bulk composition, and the rocks also have characteristic trace element signatures. Fig 5 shows the MORB-normalised pattern for the Bindal kentallenite. For comparison, Fig 5a also shows the trace element contents of Caledonian lamprophyres from northern England (MacDonald et al. 1985) and southern Scotland (MacDonald et al. 1986). In Fig 5b, analyses of a mafic kentallenite (MS 143, Thompson et al. 1984) and a typical shoshonitic volcanic arc basalt (Pearce 1982, table 1) are included. Finally, the mean chemical analyses of appinitic rocks from Scotland (Wright & Bowes 1979, table 1) have been plotted in Fig 5b. Note that for this group the lowest values for P and Ti are from the extremely mafic (biotite pyroxenites, hornblendites and cortlandites) and the most strongly evolved (intermediate granodiorites and feldspathic appinites) rocks, respectively.

It is clear from Fig 5 that the trace element pattern for the kentallenite from Bindal is similar to patterns from the rocks with which it is compared. It also strongly resembles the spidergrams for lamprophyres and appinites in southern Scotland (Barnes et al. 1986, fig 5; Rock et al. 1986, fig 4b). This also applies to the compatible elements (Ni and Cr) which are not plotted in Fig 5. The spidergrams are characterised by strong enrichment of large ion lithophile elements, a pronounced trough at Nb and lesser enrichment of the highly charged cations, including the LREE (Table 1). These general features were also pointed out by Wright & Bowes (1979). MacDonald et al. (1985, 1986) provided a more detailed treatment and discussed the possible sources, and processes governing the petrogenesis of such rocks, based on models developed by Saunders et al. (1980), Pearce (1982), Saunders & Tarney (1984) and Pearce et al. (1984) for magma genesis related to destructive plate boundaries. Inherent in the models are various metasomatic processes causing selective enrichment of most incompatible elements in a sub-crustal source region (see discussion in MacDonald et al. 1985; for a different view, see Thompson et al. 1984). Such models are interesting since the overall trace element enrichment of kentallenites, appinites and lamprophyres is very similar to that of high-K

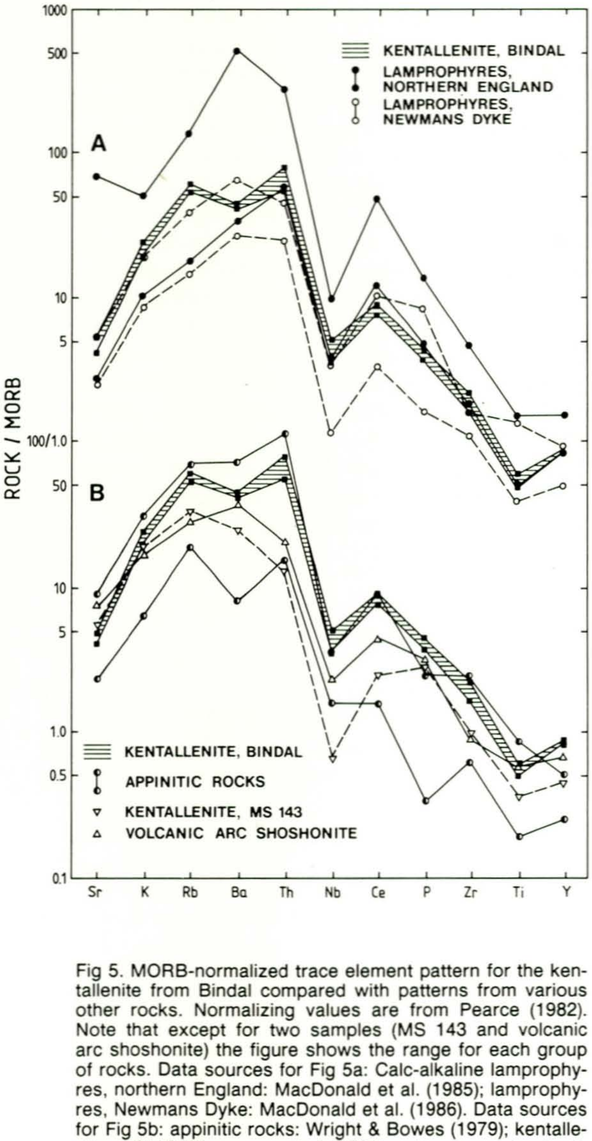

Fig 5. MORB-normalized trace element pattern for the kentallenite from Bindal compared with patterns from various other rocks. Normalizing values are from Pearce (1982). Note that except for two samples (MS 143 and volcanic arc shoshonite) the figure shows the range for each group of rocks. Data sources for Fig 5a: Calc-alkaline lamprophyres, northern England: MacDonald et al. (1985); lamprophyres, Newmans Dyke: MacDonald et al. (1986). Data sources for Fig 5b: appinitic rocks: Wright & Bowes (1979); kentallenite, MS143: Thompson et al. (1984); volcanic arc shoshonite: Pearce (1982).

volcanic arc basalts. This could indicate that the petrogenesis of these hydrated basic magmas is related to processes near a destructive plate boundary. Support for this view can be found in Thompson et al. (1984) who maintained that kentallenites can be regarded as 'subduction-related shoshonitic picrites', whereas ultra-potassic magmas such as minettes must be considered post-collisional. In general, however, it seems that lamprophyres and related ultra-potassic rocks may have a variety of essentially sub-crustal sources, and that they need not be directly related to active subduction processes (Rock et al. 1986, Nelson et al. 1986).

Based on the similarities with the rocks discussed above we conclude that the kentallenite and related rocks in Bindal most probably have a sub-crustal source. However, since isotopic data are not available, the possibility of some crustal involvement, particularly at lower crustal levels, cannot be ruled out.

K-Ar dating

A whole-rock sample (B174, Table 3) of the kentallenite has been dated using the techniques described by Mitchell (1972), yielding an apparent age of 399 +/- 10 Ma (decay constants of Steiger & Jæger 1977, see Table 3). The dated sample belongs to the fine-grained variety, and apart from some alteration of olivine it is completely fresh. Of the several requirements which must be satisfied if an apparent age is to be accorded geological significance (see Faure 1977 for detailed discussion), age perturbation due to incorporation of argon derived from the xenolithic material is regarded as potentially the most significant. It is, however, impossible to quantify this possible effect on the basis of a single sample analysis. A further uncertainty implicit in determining K-Ar ages of hypabyssal rocks arises from the protracted time scale of intrusion, solidification and cooling to below the blocking temperature for argon diffusion. Only in the case of rapid (by comparison with the geological age) uplift, immediately following intrusion, would the apparent age represent the age of emplacement.

In the Bindal area there are very few age constraints on the timing of plutonic and metamorphic events. Even though rapid cooling to subsolidus temperatures can be suggested on the basis of e.g. olivine disequilibrium, continued intrusive activity and/or regional metamorphism could clearly have delayed argon retention for a considerable period of time after intrusion. Equally, these processes could have 're-opened' the K-Ar isotopic system at a time substantially after the initial cooling. Evidence for such a thermal event in the Early Devonian has been reported from immediately below the southwestern boundary of the

HNC where a pegmatite has yielded a U-Pb age of 401 +/- 3 Ma (Schouenborg 1988.)

Similar observations have been made in the Western Gneiss Region by Tucker et al. (1987) who reported medium- to high-grade metamorphism at 395 +/- 2 Ma in the area southwest of Trondheim. Further southwest in the Western Gneiss Region, isotope data indicate uplift and cooling in the period 410-370 Ma (Lux, 1985). The detailed relationship of these results to age data obtained from the HNC remains an open question that must be kept in mind during future research in the area.

When viewed in the context of these thermal events with which it is coincident, the age obtained here for the kentallenite must be interpreted as providing only a minimum estimate for the time of intrusion.

Conclusions

Mafic dykes and stocks including kentallenite, appinite and lamprophyre are spatially and temporally related to calc-alkaline granitoids of the Bindal Batholith. This would appear to be the first kentallenite that has been identified in association with Caledonian granitoids in Scandinavia. The kentallenite represents an essentially sub-crustal magma emplaced at hypabyssal levels in the waning stages of intrusive activity in the area. An Early Devonian K-Ar (whole-rock) apparent age of 399 +/- 10 Ma has been obtained from a single sample of the kentallenite. Similar isotopic ages obtained from adjacent areas are believed to be a consequence of an Early Devonian thermal event. On this basis the apparent age must be regarded only as a minimum estimate of the time of emplacement of the kentallenite. In Scotland and NW Ireland, mafic rocks including appinites occur together with calc-alkaline granitoids which at least partly are similar to those of the Bindal Batholith. These common features suggest that comparable, though not necessarily time-equivalent, tectonomagmatic processes prevailed in the northern British Isles and the Uppermost Allochthon of Norway during the evolution of the Caledonides.

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