Strontium isotope composition of the Bindal Batholith, Central Norwegian Caledonides

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A strontium isotope study of the Bindal Batholith has been carried out. The data generally do not permit precise and accurate age calculations; however, good estimates for initial Sr ratios are commonly obtained. Low initial ratios (c. 0.704-0.705) with little internal variation are present in granitoids in the southeastern part of the batholith. Rocks with intermediate initial ratios (0.705-0.710) predominate and are present throughout most of the batholith, whereas very high ratios (>0.715) are found in tourmaline granites and anatectic granitoids in the west. Considering a subduction related setting for the plutonism, the geographical distribution of Sr initial ratios would be consistent with a westward-dipping subduction zone.

Contamination of the magmas at the level of emplacement is thought to be of minor importance, and disturbance of the isotope system by secondary alteration appears to be relatively uncommon. Considerable isotopic variation within plutons are probably a result of isotopic heterogeneity in the source materials which has not been obliterated by magmatic processes. The range in Sr initial ratios in the Bindal Batholith reflects that the granitoids were derived in variable proportions from relatively non-radiogenic upper mantle to lower crust as well as isotopically heterogeneous crustal rocks.

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Introduction

The Caledonian Bindal Batholith, which is located in the Helgeland Nappe Complex in north-central Norway, consists of a variety of rock types ranging in composition from mafic olivine gabbro to leucogranite. In this paper, we report the results of a Sr isotope investigation of the batholith. At present, a total of c. 250 analyses are available, including 45 samples analysed by Priem et al. (1975), Nissen (1986, 1988) and Tørudbakken & Mickelson (1986). Partly as a consequence of the overall low Rb/Sr-ratios, acceptable isochrons and age determinations are rarely obtained. However, the analyses allow reasonably precise estimates to be made for the initial $^{87}Sr/^{86}Sr$ ratios (SrI) for most plutons and rock types. The results are therefore of considerable interest for classification and comparative studies, and are useful when trying to constrain possible source regions for the granitoids.

Isotope analyses are not available from the northwestern part of the batholith, i.e. the area between Vefsnfjord and Ranafjord, and from rocks along the eastern boundary of the Helgeland Nappe Complex (Fig. 1).

Regional context

The Bindal Batholith (BB) occurs in the Helgeland Nappe Complex (HNC), which belongs to the Uppermost Allochthon in the Scandinavian Caledonides (Gee et al. 1985). As outlined by Thorsnes (1987), Nordgulen & Schouenborg (1990) and Thorsnes & Løseth (1991), two series of metasupracrustal rocks are intruded by the granitoids. One of these consists of migmatitic gneisses, calc-silicate rocks and marbles. Earlier work in the northern parts of the HNC suggests that these rocks are Precambrian in age (Riis & Ramberg 1981, Tørudbakken & Ramberg 1982, Brattli et al. 1982). The other metasupracrustal series, which comprises mafic and calcareous conglomerates, calc-silicate rocks, marbles, psammites and schists, is thought to represent a cover sequence to ophiolite fragments in the HNC (Bang 1985, Løseth 1985, Thorsnes 1985, Heldal 1987). Correlating the ophiolite fragments in the HNC with the Early Ordovician Leka Ophiolite Complex, it is inferred that the cover sequences must be Early Ordovician or younger in age (Nordgulen & Schouenborg 1990, Thorsnes & Løseth 1991). The ophiolite

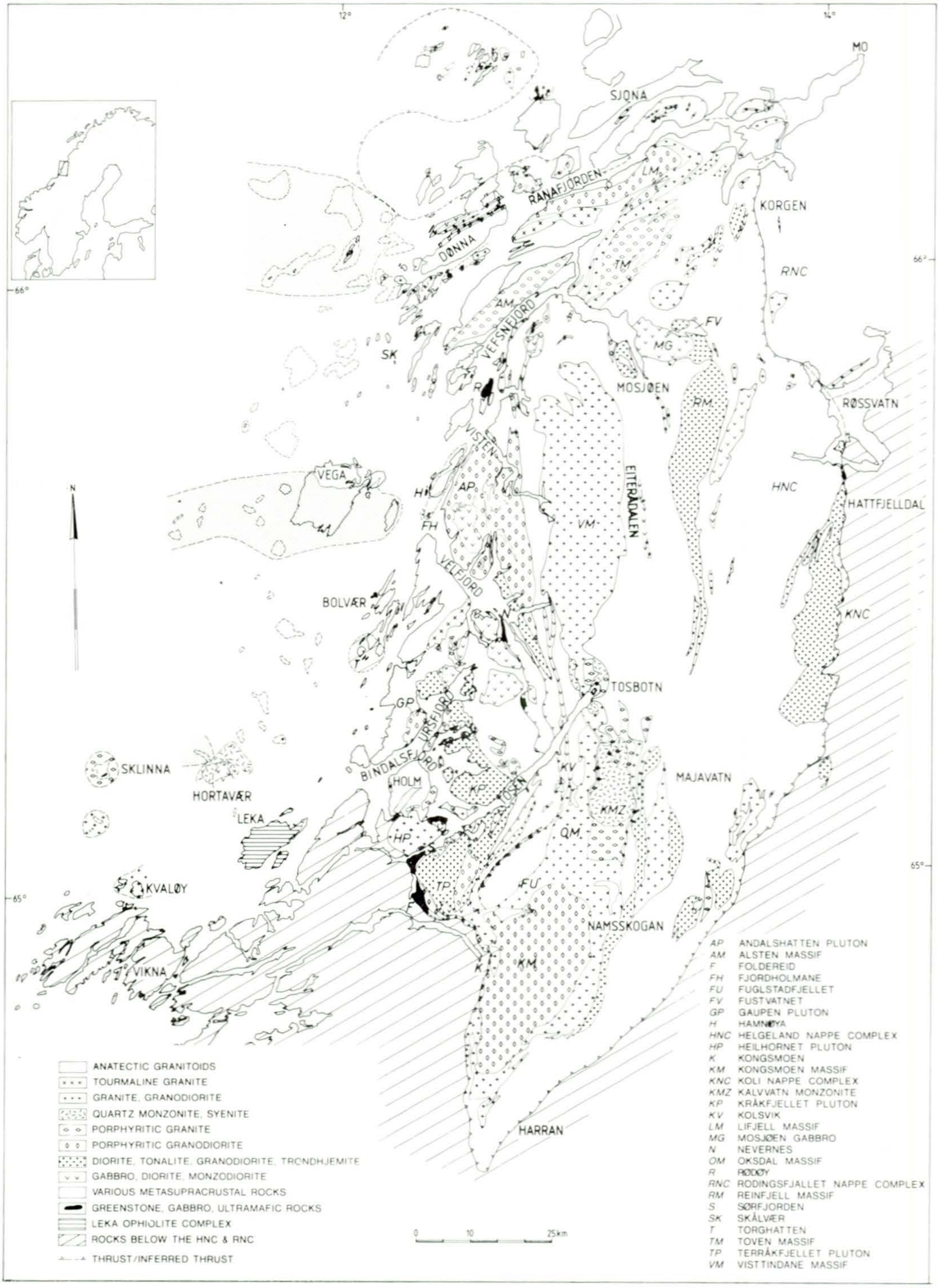


Fig. 1. Geological map of the Bindal Batholith.

fragments as well as their cover rocks were deformed and metamorphosed prior to being cut by Late Ordovician granitoids. Juxtaposition of the ophiolite related rocks with the older metasupracrustals must also have occurred in the Ordovician.

The Bindal Batholith consists of more than 50 plutons and occupies a substantial part of the HNC (Fig. 1). Descriptions of parts of the batholith were provided by Kollung (1967), Myrland (1972), Nordgulen (1984), Theissen (1986), Gustavson (1988), Nordgulen & Mitchell (1988) and Nordgulen & Schouenborg (1990).

The rocks are generally equigranular or porphyritic, medium- or medium- to coarse-grained and predominantly granodioritic to granitic in composition. A few plutons are tonalitic, and gabbros, diorites and monzonitic rocks are present in some areas. Tourmaline granites and anatectic granites are fairly abundant in the western part of the batholith (Fig. 1). Petrographic and chemical data show that the majority of the rocks are I-type according to the classification of Chappell & White (1974). However, some plutons show transitional behaviour towards A-type granites, and the anatectic rocks in the west may be regarded as S-type granites (Nordgulen et al. 1988).

Only a limited number of age determinations are available from the BB. Rb-Sr whole-rock and mineral data indicate a fairly wide age span ranging from the Late Cambrian to the Middle Silurian (Priem et al. 1975, Gustavson & Prestvik 1979, Nissen 1986, 1988, Tørudbakken & Mickelson 1986). Recently, a number of U-Pb age determinations on zircons have yielded Late Ordovician to Early to Middle Silurian ages for different rock types in the batholith (Nordgulen & Schouenborg 1990, Nordgulen et al., in prep). The U-Pb data thus suggests a relatively narrow age range for the plutonism and indicates that the dates obtained by the Rb-Sr method must be confirmed by more precise dating techniques.

Analytical methods

All sample preparations and chemical preparations were performed at the NGU-laboratories. Rb/Sr ratios were generally determined by XRF-spectroscopy; samples having low (<60 ppm) Rb or Sr, however, were subjected to isotope dilution (ID) determination. Sr isotope ratios and ID-determinations by mass-spectroscopy, and Rb/Sr ratio determination by XRF-spectroscopy were carried out at the Laboratory for geochronology and isotope geology at the Mineralogical-Geological Museum, University of Oslo. The analytical procedures used have been published elsewhere (Jacobsen & Heier 1978). For some samples, Rb/Sr ratios were determined by XRF-spectroscopy at the NGU-laboratories (Table 1). The mass-spectrometer, a VG 354 five-collector instrument, yielded a value for the NBS 987 Sr standard of 0.71025 ± 3 during the period of analysis. The error of the XRF-determinations were estimated to $\leqq$ 1%, and that of the ID-method $\leqq$ .5%.

All isochron calculations and age data quoted have been performed or recalculated using the decay constants recommended by Steiger & Jäger (1977). All errors are quoted at the 2σ level. Elemental and isotopic data are listed in Table 1 together with $(^{87}Sr/^{86}Sr)_0$ ratios calculated with respect to an age of 440 Ma. For samples with $^{87}Rb/^{86}Sr$ ratios less than 1, a 20 Ma shift in the assumed age will cause a very small change (<0.0003) in the calculated initial ratio, whereas samples with $^{87}Rb/^{86}Sr$ ratios of c. 10 will have a change of c. 0.003 in the initial ratio.

Strontium isotope data

The southwestern part of the batholith

Introduction

Several large to intermediate size plutons spanning a wide compositional range are present in this area. Analyses are available for the Kråkfjellet, Terråkfjellet and Heilhornet Plutons in Bindal, and the porphyritic Sklinna Pluton, which is located southwest of Leka (Fig. 1). From the Holm peninsula, north of the Heilhornet Pluton, data are presented from tourmaline granite, anatectic granite and a deformed megacrystic granite west of Bindalsfjord. Included with the data for the tourmaline granites are two analyses of chemically and

Table 1. Elemental and isotopic data. Rb- and Sr-values in ppm. $^{87}Sr/^{86}Sr$ is given with standard error. $(^{87}Sr/^{86}Sr)_0$ is calculated assuming an age of 440 Ma.

[#] Rb, Sr and Rb/Sr determined by isotope dilution technique.
[1] Rb and Sr analysed by XRF-spectroscopy at NGU, otherwise at Min. Geol. Museum, Oslo.

Kråkfjellet Pluton, Bindal

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$
B520	18253	37555	723065	74.1	462.9	.463	.70859 ± 2	.7057
B523	18253	37635	723325	64.7	808.9	.231	.70698 ± 2	.7055
B526	18253	37510	723790	55.3	924.5	.173	.70662 ± 2	.7055
B529	18253	37780	723640	79.3	879.6	.261	.70720 ± 2	.7056
B538	18253	38500	722795	83.8	553.3	.438	.70883 ± 2	.7061
B551	18253	38125	723400	53.3	1116.0	.138	.70638 ± 2	.7055
B552	18253	38230	723215	50.2	1075.5	.135	.70645 ± 2	.7056
B557	18253	37760	722755	62.2	485.4	.371	.70837 ± 2	.7060
B729	18253	38070	721820	70.7	817.5	.250	.70742 ± 2	.7059
UR13	18254	38100	725015	65.0	733.7	.256	.70748 ± 2	.7059
UR21	18254	37260	724405	45.1	946.8	.138	.70655 ± 2	.7057

Terråkfjellet Pluton, Bindal

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$
B762	18253	37235	721645	134.4	590.3	.659	.71261 ± 2	.7085
B764	18253	37055	721235	106.0	690.0	.445	.71052 ± 2	.7077
B769	18253	37620	721510	142.1	573.0	.718	.71287 ± 2	.7084
B772	18253	36950	721525	125.2	681.4	.532	.71123 ± 2	.7079
B786	18244	37435	720780	89.5	874.4	.296	.70961 ± 2	.7078
B797	18253	37855	721880	140.4	659.6	.616	.71296 ± 2	.7091
B806	18253	37920	721560	102.8	811.6	.367	.71139 ± 2	.7091
B808	18244	37710	721035	120.7	720.7	.485	.70863 ± 2	.7056

Tourmaline-granite, Holm peninsula and Velfjord

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$
HH330	17252	36495	723204	215.0	107.0	5.842	.75620 ± 4	.7196
HH331	17252	36495	723204	207.6	93.8	6.438	.76057 ± 4	.7202
HH332	17252	36495	723075	257.1	78.3	9.565	.77920 ± 4	.7193
HH333	17252	36495	723065	274.0	73.4	10.890	.78913 ± 4	.7209
HH334	17252	36500	723005	293.0	65.2	13.123	.80567 ± 4	.7234
HH335	17252	36500	723045	290.6	64.5	13.164	.80606 ± 4	.7236
HH336	17252	36510	722900	224.3	72.6	9.011	.78712 ± 4	.7306
HH337	17252	36505	722885	214.2	45.5	13.762	.81747 ± 4	.7312
HH344	17252	36910	723015	243.9	74.3	9.556	.77493 ± 3	.7150
VF60	18254	36120	726100	222.0	87.0	7.425	.76068 ± 3	.7141
N88-108	18254	38120	726185	270.8	54.6	14.513	.81719 ± 3	.7262

Anatectic granites, Holm peninsula

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$
HH341	17252	36890	722935	136.5	153.4	2.580	.73398 ± 3	.7178
HH342	17252	36890	722935	163.6	206.0	2.303	.73166 ± 3	.7172
HH346	17252	36615	722530	141.2	258.6	1.583	.72898 ± 3	.7191
HH348	17252	36595	722535	187.4	222.2	2.445	.73452 ± 3	.7192

Porphyritic granite, Sklinna

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
S120A	16252	59370	723300	292.2	203.1	4.172	.73436 ± 3	.7082
S120B	16252	59370	723300	297.8	41.8	20.849	.82253 ± 3	.6919
S120C	16252	59370	723300	333.2	41.2	23.699	.84857 ± 3	.7000
S122	16252	59220	723250	275.3	109.5	7.307	.75162 ± 3	.7058
S124	16252	39235	723315	257.4	129.4	5.778	.74379 ± 3	.7076
S130	16252	39135	723390	213.4	217.6	2.843	.72644 ± 3	.7086

Porphyroclastic granite, Bindalseid, Holm peninsula

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N88-73	18253	37320	723020	215.6	73.4	8.559	.77089 ± 3	.7173
N88-74	18253	37365	722950	307.3	55.5	16.197	.82082 ± 3	.7193

Andalshatten Pluton, Vevelstad

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
VS12	18263	39180	728665	160.8	536.4	.868	.71447 ± 3	.7090
VS16	18263	38850	729135	105.6	746.6	.410	.71101 ± 3	.7084
VS18	18263	38510	729245	175.3	364.7	1.392	.71717 ± 3	.7085
VF22	18263	37945	727355	158.9	307.3	1.498	.71753 ± 3	.7081
VF24	18263	38207	727025	179.3	264.4	1.965	.72104 ± 3	.7087
N88-01	18263	38490	727940	149.3	300.9	1.437	.71656 ± 3	.7076
N88-02	18263	38420	727925	174.0	352.3	1.430	.71636 ± 3	.7074
N88-03	18263	39150	727840	141.4	505.3	.810	.71402 ± 3	.7089
N88-05	18263	38720	727690	175.1	365.0	1.390	.71854 ± 3	.7098

Gaupen Pluton, Ursfjord

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
UR02	18253	37310	723920	174.0	470.0	1.072	.71337 ± 3	.7067
UR03	18254	37550	724205	160.6	405.9	1.146	.71487 ± 3	.7077
UR18	18254	37275	724370	154.2	474.5	.941	.71427 ± 3	.7084
N86-90	17252	36920	723855	175.2	423.8	1.197	.71520 ± 3	.7077

Porphyritic granites associated with the Velfjord plutons

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
VF47	18254	38705	725830	157.6	201.6	2.265	.72033 ± 3	.7061
VF52	18252	39105	725120	158.7	231.0	1.993	.73062 ± 3	.7181
VF58	18254	39085	725225	168.9	193.1	2.537	.72847 ± 3	.7126

Porphyritic granites southwest of Velfjord[1]

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N87-42	18254	37790	726135	239	171	4.057	.74242 ± 3	.7170
N87-49	18254	37930	725625	170	108	4.572	.74886 ± 3	.7202
N87-52	18254	37950	725565	154	188	2.376	.73271 ± 3	.7178
N87-58	18254	37840	725475	247	412	1.738	.73143 ± 3	.7203

Mafic to intermediate plutons in Velfjord and Ursfjord[1]

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
VF41	18254	38340	726175	79	1057	.216	.70807 ± 3	.7067
VF42	18254	38320	726010	74	972	.220	.70761 ± 3	.7062
VF43	18254	38400	725905	76	716	.307	.70801 ± 3	.7061
VF45	18254	38560	726060	97	838	.335	.70894 ± 3	.7068
VF50	18254	38150	725735	64	333	.556	.71167 ± 3	.7082
VF53	18254	39075	725120	78	567	.398	.70834 ± 3	.7059
VF55	18254	38880	724570	40	276	.419	.70972 ± 3	.7071
VF59	18254	38765	725515	74	717	.299	.70823 ± 3	.7064
N87-26	18254	38620	725325	60	936	.185	.70696 ± 3	.7058
N87-48	18254	37795	725745	15	309	.140	.70960 ± 3	.7087
N87-50	18254	37900	725575	82	334	.710	.71275 ± 3	.7083
N87-53	18254	37950	725565	111	256	1.256	.71612 ± 3	.7083
N87-54	18254	37950	725565	77	261	.854	.71546 ± 3	.7101
N87-56	18254	38010	725370	21	464	.131	.70652 ± 3	.7057
N87-173	18254	37835	724990	38	770	.143	.70751 ± 3	.7066

Anatectic granitoids at Vega[1]

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
VG01	17262	62925	728750	161	120	3.902	.76069 ± 3	.7362
VG08	17262	36315	728630	214	216	2.874	.73553 ± 3	.7175
VG09	17262	36300	728680	113	361	.907	.72321 ± 3	.7175
VG13	17262	63040	729780	161	136	3.440	.75323 ± 3	.7317
VG17	17262	63410	727905	202	199	2.946	.73831 ± 3	.7199
VG18	17262	63400	729720	175	139	3.660	.75762 ± 3	.7347
VG20	17262	63620	728690	101	146	2.009	.74595 ± 3	.7334
VG21	17262	63775	728280	140	226	1.797	.73646 ± 3	.7252
VG23	17262	63630	728690	126	183	1.996	.72878 ± 3	.7163
VG24	17262	63630	728690	138	298	1.342	.72193 ± 3	.7135
VG25	17262	63695	728615	119	190	1.816	.73084 ± 3	.7195
VG10*	17262	63680	728740	36	150	.695	.71529 ± 3	.7109

* Mafic diorite

Granites in the Visten-Lomsdal area

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
VS01	18262	40600	728245	159.9	476.1	.972	.71173 ± 3	.7056
VS03	18262	40535	728260	143.4	716.9	.579	.71075 ± 3	.7071
VS05	18262	40245	728180	130.6	716.2	.528	.71038 ± 3	.7071
VS08	18262	39875	728120	166.4	487.1	.989	.71207 ± 3	.7059
VF34	18251	40235	726145	176.3	486.3	1.049	.71389 ± 3	.7073
VF36	18251	40090	726070	125.1	710.1	.510	.71087 ± 3	.7077
VF37	18251	39980	725960	92.5	407.1	.658	.72022 ± 3	.7161
N88-37	18251	40215	725230	69.9	688.3	.294	.70760 ± 3	.7058
N88-38	18251	40145	725330	187.6	563.3	.967	.74627 ± 3	.7402

Granites in the area between Tosbotn and Kolsvik

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N86-58	18251	40345	724015	201.6	336.8	1.733	.71613 ± 3	.7053
N86-60	18251	40370	723870	182.0	409.2	1.287	.71306 ± 3	.7050
N86-62	18252	40490	723665	152.3	455.9	.967	.71100 ± 3	.7049
N86-64	18252	40240	723770	180.3	359.8	1.451	.71527 ± 3	.7062
N86-69	18252	40140	723540	154.0	434.7	1.025	.71246 ± 3	.7060
N86-87	18251	40240	724535	103.0	495.0	.602	.71174 ± 3	.7080
N86-89	18251	40160	724445	172.8	274.6	1.822	.71814 ± 3	.7067

Granites in the area Kolsvik-Fuglstadfjellet

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N86-31	18253	38880	721145	151.7	390.5	1.125	.71496 ± 3	.7079
N86-34	18244	38215	720570	253.2	387.9	1.890	.71952 ± 3	.7077
N86-36	18244	38105	720445	150.5	541.6	.804	.71189 ± 3	.7069
N86-39	18244	38070	720675	167.7	439.1	1.106	.71484 ± 3	.7079
N86-47	17241	39935	722585	181.8	260.9	2.018	.71963 ± 3	.7070
N86-70	18252	39485	721980	189.3	367.4	1.492	.71636 ± 3	.7070
N86-108	18253	37750	722405	111.2	517.2	.622	.71143 ± 3	.7075
N87-107	18252	39575	721425	126.2	530.3	.689	.71233 ± 5	.7080
N87-108	18252	39550	721415	190.4	436.8	1.262	.71477 ± 3	.7069
N87-110	18253	39130	721275	144.1	424.5	.982	.71378 ± 3	.7076
N87-115	18252	39540	722280	184.0	432.1	1.233	.71399 ± 3	.7063
N87-121	18252	39640	722635	87.1	458.2	.550	.70829 ± 3	.7048
N87-123	18252	39635	722780	167.1	477.5	1.013	.71265 ± 3	.7063
N87-127	18252	39680	722950	135.3	417.0	.938	.71097 ± 6	.7051

Tonalites (Fustvatnet Pluton and Reinfjellet Massif)

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N87-139#	19264	42990	730675	40.0	701.6	.165	.70613 ± 3	.7051
N87-140	19264	42465	731080	61.8	569.7	.314	.70338 ± 3	.7014
N87-141	19264	42595	731135	64.6	519.3	.360	.70759 ± 3	.7053
N87-144	19263	42500	727620	108.4	586.6	.535	.70958 ± 3	.7062

Granitoids south of Mosjøen

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N87-145	19263	42250	727740	180.1	327.4	1.593	.71925 ± 3	.7093
N87-146	19263	42250	727740	60.4	238.9	.732	.72368 ± 3	.7191
N87-147	19263	42075	727990	117.8	390.5	.874	.71399 ± 3	.7085

Granitoids in the Kalvvatnet area

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N88-46	18252	41035	723075	67.9	559.8	.351	.70906 ± 3	.7069
N88-47	18252	40965	723125	74.6	732.6	.295	.70807 ± 3	.7062
N88-56	18252	40335	722680	155.2	530.1	.848	.71483 ± 3	.7095

Two-mica granitoid dykes

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
VS11	18263	39230	728300	261.5	107.4	7.075	.75550 ± 3	.7112
VS13	18263	39180	728665	283.5	62.2	13.292	.79149 ± 3	.7082
VF31	18251	40515	726085	210.9	72.4	8.468	.76161 ± 3	.7085
VF38	18251	39860	726020	241.5	109.0	6.434	.74713 ± 3	.7068
B761	18253	37205	721615	118.1	391.3	.874	.71559 ± 3	.7101
B765	18253	37065	721235	125.1	446.4	.811	.71498 ± 3	.7099
B800	18253	37830	721645	142.8	176.8	2.341	.72469 ± 3	.7100
B805	18253	37890	721560	75.8	324.1	.677	.72092 ± 3	.7167
B809	18244	37710	721035	112.1	578.3	.561	.70940 ± 3	.7059
N87-36	18251	40100	724405	206.8	219.8	2.727	.72600 ± 3	.7089
N87-37	18251	40030	724315	180.6	166.5	3.144	.72958 ± 3	.7099
N87-122	18252	39600	722630	228.9	198.3	3.347	72997 ± 3	.7090
N87-124	18252	39640	722920	259.6	108.1	6.980	.75412 ± 3	.7104
N87-125	18252	39650	723000	244.9	96.8	7.358	.75554 ± 3	.7094
N88-77	18253	38875	721585	391.6	70.3	16.274	.80524 ± 3	.7032
N88-79	18253	38825	721560	230.5	65.1	10.303	.77114 ± 3	.7066
N88-110	18252	40540	722485	121.5	391.9	.897	.71362 ± 3	.7080
N88-111	18252	40540	722485	162.3	233.3	2.015	.71932 ± 3	.7070

Metasedimentary rocks, Helgeland Nappe Complex

SAMPLE	MAP	ECOORD	NCOORD	Rb	Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_0$
N88-54	19253	41775	721040	193.1	58.1	9.694	.78853 ± 3	.7278
N88-61	17252	36525	722565	110.1	118.9	2.692	.75651 ± 3	.7396
N88-62	17252	36525	722565	155.9	98.0	4.628	.76831 ± 3	.7393
N88-63	17252	36525	722565	177.0	110.8	4.650	.76787 ± 3	.7387
N88-64	17252	36525	722565	152.4	106.2	4.175	.76983 ± 3	.7437
N88-68	17252	36735	722555	54.3	218.8	.719	.72257 ± 3	.7181
N88-69	17252	36675	722520	179.4	129.0	4.036	.74481 ± 3	.7195
N88-71	17252	36325	722115	180.7	179.5	2.922	.74167 ± 3	.7234
N88-76	18253	38875	721585	109.8	156.8	2.030	.72564 ± 3	.7129
N88-78	18253	38825	721560	71.2	147.5	1.398	.72337 ± 3	.7146
N88-101	18253	38385	721520	110.0	164.2	1.942	.72620 ± 3	.7140
N88-103	18251	40090	724400	151.7	88.9	4.959	.75608 ± 3	.7250
N88-104	18251	39960	724280	93.2	104.6	2.582	.72798 ± 3	.7118
N88-106	18254	38965	725365	99.3	847.1	.339	.70823 ± 3	.7061
N88-109	18254	37865	726675	106.5	196.7	1.570	.73268 ± 3	.7228

isotopically similar rocks from a large body of tourmaline granite southwest of Velfjord.

Dykes of leucocratic 2-mica granites are common in the Bindal area. Isotope data for these rocks are presented together with those from other similar granites (see below).

The Kråkfjellet and Terråkfjellet Plutons

These plutons are chemically very similar, however, there are consistent small differences in both major and trace element contents (Nordgulen, in prep). There are marked contrasts in the abundance of Rb and Sr, and at similar levels of Si$_2$, the Kråkfjellet Pluton has higher Sr and lower Rb than the Terråkfjellet Pluton. On the isotope diagram (Fig. 2), the plutons plot in two distinct fields with the exception of one sample from the Terråkfjellet Pluton which plots on the trend defined by the Kråkfjellet Pluton.

The Sr data for the Kråkfjellet Pluton plot on a well defined trend (Fig. 2) with an initial ratio of c. 0.7055. Regression of all data do not yield a satisfactory isochron, however, a geologically reasonable date of 464 ± 30 Ma (SrI = 0.70549 ± 0.00005; MSWD = 3.74) was obtained for six samples in the central part of the pluton. This result is within error of a U-Pb zircon date of 443 ± 7 Ma for the pluton (Nordgulen et al., in prep).

The data from the Terråkfjellet Pluton have a comparatively large scatter which prevents the calculation of an isochron for the pluton. However, assuming an age of 440 Ma, the SrI values for the Terråkfjellet Pluton have an approximate range between 0.7075 and 0.709.

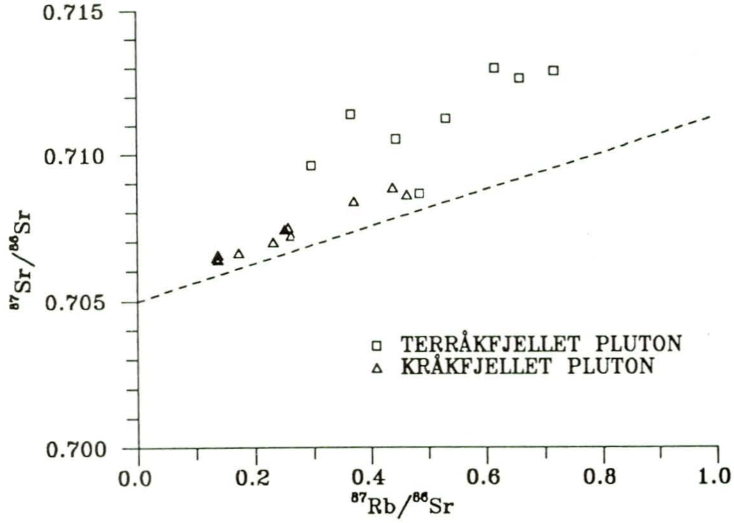
The Heilhornet Pluton

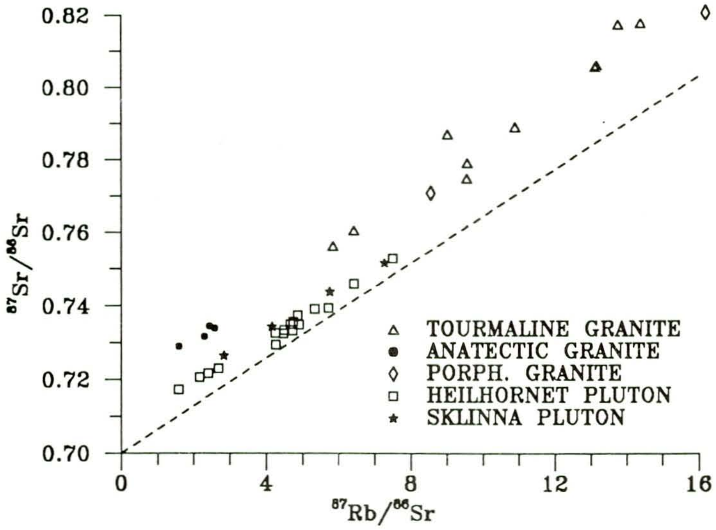
The results from the Heilhornet Pluton (Fig. 1) have been published by Nordgulen & Schouenborg (1990), but are shown in Fig. 3 for comparative purposes. In contrast to the Kråkfjellet and Terråkfjellet Plutons, the Heilhornet Pluton has a tendency towards alkaline compositions with higher alkali/lime and Fe/Mg ratios. Considering the trace elements, the Heilhornet Pluton has significantly higher abundances of LREE and HFSE, and also higher Rb/Sr ratios. Nordgulen & Schouenborg (1990) described the Sr isotope data and calculated an isochron for samples from the central part of the pluton. This gave a date of 428 ± 9 Ma (SrI = 0.70699 ± 0.00028; MSWD = 2.32), a result which overlaps with the U-Pb zircon date of 444 ± 11 Ma (Nordgulen & Schouenborg, 1990).

Tourmaline granite

Tourmaline granites occur as small stocks and dykes at the Holm peninsula north of the Heilhornet Pluton (Nordgulen & Bering 1987, Nordgulen et al. 1989). They cut marble, calc-silicate schist and semi-pelitic schist and are clearly younger than the strong S2 foliation in the host rocks. The tourmaline granites have high Rb/Sr ratios, and although there is considerable scatter in the Sr isotope ratios (Fig. 3), most of the samples define a trend indicating an initial ratio of c. 0.717. Assuming an age of 440 Ma, initial ratios are essentially between 0.715 and 0.725 with two samples showing values as high as 0.735. The granites at Holm contain abundant fractures and shear

Fig. 2. Isotope diagram for the Kråkfjellet and Terråkfjellet Plutons. The stippled reference line shown in Figs. 2-9 corresponds to an age of 440 Ma.





. 3. Isotope diagram for some itons in the southwestern part the Bindal Batholith.

zones, some of which have quartz and/or sulphide fillings. Therefore, secondary processes may have contributed to the spread in initial ratios.

A large body of tourmaline granite, which occurs southwest of Velfjord (Fig. 1), is represented by two samples in this study (VF60 and N88-108; Table 1). The granite is geochemically similar to and plots close to the most evolved tourmaline granites at Holm.

Anatectic granite

Anatectic granite occurs as an elongate NE-SW trending body at the Holm peninsula in Bindal (Fig. 1). The granite contains variable amounts of xenoliths of metasedimentary rocks. In places it has transitional contacts towards diatexitic metasedimentary rocks, which are also common at the Holm peninsula. The pluton consists of medium-grained granite and locally contains variable amounts of euhedral K-feldspar megacrysts. Four samples from the area immediately north of the Heilhornet Pluton have been analysed. Compared with the tourmaline granite, with which it is spatially associated, the anatectic granite has lower Rb/Sr ratios (^{87}Rb/^{86}Sr $<$ 3; Fig. 3). The data indicate an initial ratio of c. 0.718, which is close to the initial ratio for most of the tourmaline granites. This suggests that these rock types may have partly similar source regions.

The Sklinna Pluton

The Sklinna Pluton is located on a small group of islands c. 30 km northwest of Leka (Fig. 1). It consists of coarse-grained megacrystic granite with 70-74 % SiO_2. Four samples with a range in Rb/Sr between 1.0 and 2.5 have been analysed and define a trend with an initial ratio of 0.710 (Fig. 3). Two strongly fractionated samples of a fine-grained granite sheet in the pluton have very high Rb/Sr ratios (Table 1) and plot on the extension of the trend for the megacrystic granite (not shown on Fig. 3). The SrI values for S120A and S120B, with respect to 440 Ma, are very low (Table 1) and indicate isotopic heterogeneity and/or that the isotope system closed at a later stage. Regression of all the samples yields an apparent date of c. 396 Ma. This date is the youngest which have been found for any rock in the BB. However, textural evidence shows that the plagioclase of the Sklinna Pluton has partly suffered extensive sericitication which may have caused disturbance in the Rb-Sr isotope system. The indication of a Middle Devonian age obtained for the pluton therefore needs to be confirmed by more reliable data.

The Bindalseid Pluton

The Bindalseid Pluton is located immediately north of the Heilhornet Pluton (Fig. 1). It consists of strongly foliated granite (SiO_2 is c. 73%) with oriented microcline megacrysts in a medium-grained matrix. The two analysed samples have high Rb/Sr ratios, and the SrI values are 0.717-0.719, assuming an age of 440 Ma (Table 1).

Ursfjord, Velfjord, Visten and Vega

Introduction

Several different rock types from a number of plutons have been analysed. This includes mafic to intermediate intrusions in the Velfjord and Ursfjord district, the porphyritic Andalshatten Pluton, a porphyritic granodiorite in Ursfjord called the Gaupen Pluton, small bodies of porphyritic granite associated with the mafic plutons in the Velfjord-Ursfjord area, and anatectic granites from Vega (Fig. 1).

Mafic to intermediate intrusions in Velfjord and Ursfjord

The Sr data from these rocks are shown in Fig 4. For the majority of the samples, which have $^{87}Rb/^{86}Sr$ ratios < 0.5, the data plot in a narrow band with SrI values between 0.7057 and 0.7071. These samples include those from the three intrusions of the Velfjord Massif (Kollung 1967) and a mafic gabbro north of Ursfjord. Five samples from dioritic to gabbroic plutons in the area between Ursfjord and Velfjord have, with one exception, $^{87}Rb/^{86}Sr$ ratios > 0.5 with a range in SrI between 0.708 and 0.710. The plutons are spatially associated with anatectic metasedimentary rocks and porphyritic granites with high SrI values (see below). The common presence of pink garnet in some of the rocks would indicate that they may have experienced some contamination from metasedimentary rocks or that such rocks were present in the source region for the magmas. This could explain the elevated SrI values compared to other mafic intrusions in the Velfjord-Ursfjord area.

The Andalshatten Pluton

The megacrystic Andalshatten Pluton is a large intrusion located between Velfjord and Visten (Fig. 1). The pluton is characterised by euhedral megacrysts (2-5 cm) of greyish white microcline which occur in a medium- to coarse-grained granodioritic matrix. Mafic enclaves are common, and the granite is cut by a number of granitic and basic dykes. In the southwestern part of the pluton, medium- to fine-grained foliated dioritic rocks are enclosed in the pluton together with smaller bodies of peridotite and mafic gabbro. Xenoliths of migmatitic mica gneiss are present in the eastern part of the pluton, whereas in the west the xenoliths consist of banded calc-silicate rocks and polymict, calcareous conglomerates. Large rafts of banded marble and small bodies of serpentinite occur in the central part of the pluton.

The Andalshatten Pluton displays a considerable chemical variation (58-70 % SiO_2) which is reflected in a wide range in Rb/Sr ratios. Of the seven analysed samples, all but one (N88-05) plot on a fairly well defined trend (Fig. 4). Regression of six samples yields a

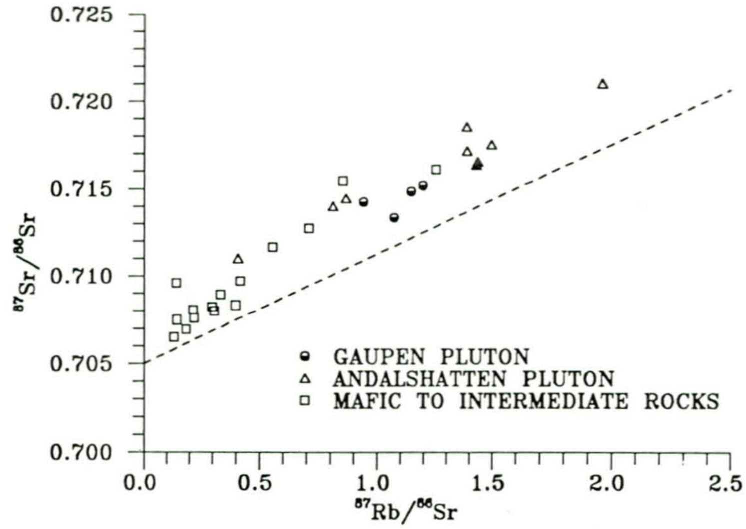


Fig. 4. Isotope diagram for the porphyritic granitoids of the Gaupen and Andalshatten Plutons and mafic to intermediate rocks in the Velfjord and Ursfjord area. Filled triangles represent microporphyritic dykes in the Andalshatten Pluton (N88-01 and N88-02 in Table 1).

date of 448 ± 48 Ma (SrI = 0.70855 ± 0.00031; MSWD = 29.52), which is in agreement with a date of 447 ± 7 Ma obtained by the U-Pb method on zircons (Nordgulen et al., in prep).

The megacrystic granite is cut by a set of fine-grained microporphyritic dykes which are chemically related to their host. Sr data for two of these are also shown on Fig. 4, and they plot slightly below the trend defined by the porphyritic granite.

The Gaupen Pluton

The Gaupen Pluton, which consists of megacrystic granodiorite, is located in Ursfjord north of Bindalsfjord (Fig. 1). It contains abundant mafic enclaves and is cut by a variety of mafic and acid dykes. The pluton is chemically and mineralogically quite similar to the Andalshatten Pluton. Four samples have been analysed and plot in a small cluster slightly below the trend defined by the Andalshatten Pluton (Fig. 4). The data indicate an initial ratio of c. 0.708 for the Gaupen Pluton.

Porphyritic granites

Several small bodies of porphyritic granite occur adjacent to the mafic to intermediate plutons of the Velfjord Massif (Myrland 1972). The granites are generally quite strongly foliated with white to grey porphyroclasts of microcline in a variably recrystallised matrix. Transitional contacts towards diatexitic, semi-pelitic rocks indicate that the granites were generated by in situ melting of metasedimentary rocks during emplacement of the Velfjord plutons (Barnes et al., 1992). The presence of garnet, muscovite, sillimanite and monazite is in accordance with this interpretation. Chemically, the rocks have alkaline affinity with high alkali/lime and Fe/Mg ratios, and high abundances of LREE and HFSE (Y, Nb, Zr). Sr isotope data are available for three samples. The results show a large scatter (Fig. 5), which may indicate highly heterogeneous crustal source regions for the rocks.

Porphyritic granites are also present as small, irregular bodies associated with mafic intrusions between Ursfjord and Velfjord. The rocks are texturally similar to those in Velfjord, however, they do not posess the alkaline chemical characteristics exhibited by the Velfjord samples. Assuming an age of 440 Ma, the SrI values are between 0.717 and 0.720, which is in accordance with a crustal origin for the rocks (Fig. 5; Table 1).

The Vega granite

The granitoids on Vega are grey, medium-grained and extremely heterogeneous rocks. They are rich in metasedimentary xenoliths and commonly contain mafic clots consisting essentially of biotite and garnet. The Sr data show a large scatter (Fig. 5; Table 1), and apart from a diorite (VG 10), the initial ratos are between 0.714 and 0.736 (based on 440 Ma). A heterogeneous metasedimentary sour-

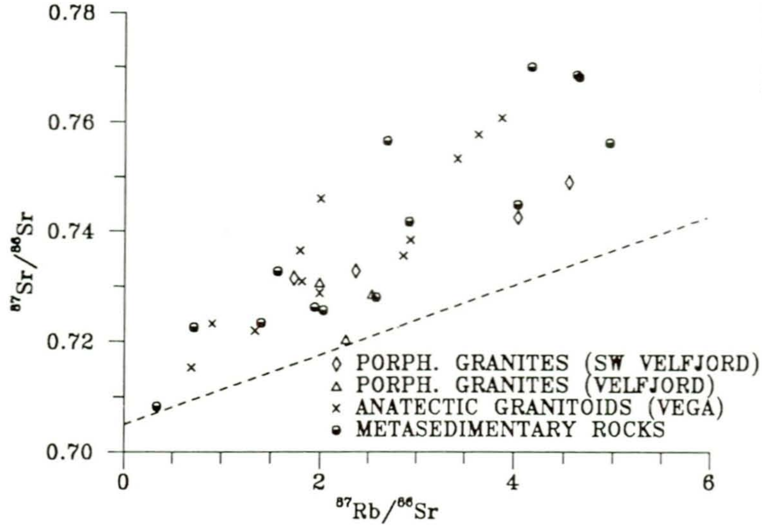


Fig. 5. Isotope diagram for porphyritic granites in the Velfjord region, anatectic granitoids at Vega, and various metasedimentary rocks in the Helgeland Nappe Complex.

ce, or possibly extreme contamination of an I-type magma, would be consistent with the Sr data.

Metasedimentary rocks

Sr isotope data for metasedimentary rocks collected in a number of localities in the southern parts of the HNC are also shown in Fig. 5. The isotope ratios, at an age of 440 Ma, are between 0.706 and 0.744 and scatter in a range similar to anatectic granitoids at Vega and in Bindal as well as the tourmaline granites and the porphyritic rocks associated with the mafic to intermediate rocks in Velfjord and Ursfjord. Judging from the Sr isotopes, the metasedimentary rocks would therefore provide a suitable crustal source for the granitoids with elevated initial ratios. This is in agreement with Nd- and Pb-isotope data (Birkeland et al., in press), which indicate a relatively strong upper crustal influence for these granitoids.

Granites in the central part of the Bindal Batholith

Introduction

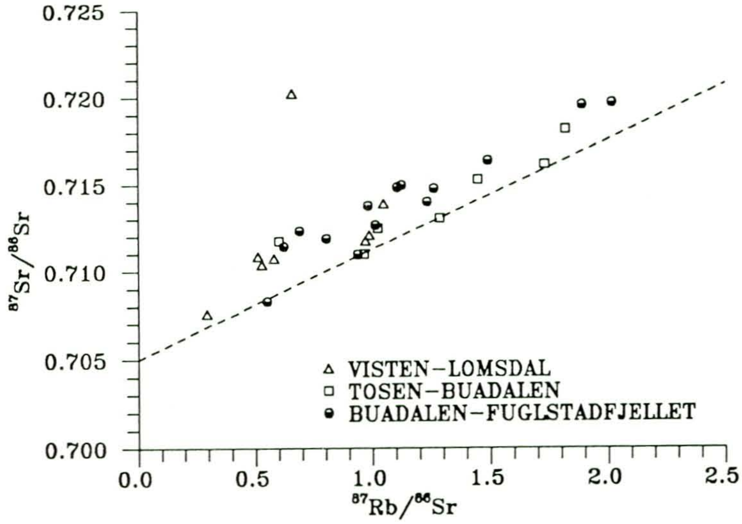
A belt of fine- to medium-grained 2-mica granite is present along a N-S trending zone close to the central axis of the BB (Fig. 1). North of Tosbotn a large body (c. 50 x 25 km) of this granite is located in the mountains between Visten and Velfjord in the west and Eiteràdalen in the east. In this area, the granites intrude migmatitic paragneisses. Near Tosbotn the granite also intrudes monzonitic and monzodioritic rocks, and east of Tosen it occurs between migmatitic gneisses in the west and the Kalvvatn Pluton (quartz monzonite) in the east. To the south, similar granites occur in the Oksdal Massif and at Fuglstadfjellet, and they also intrude porphyritic granodiorite northeast of Kongsmoen. Thus, the granites can be followed for at least 100 km along strike. A small granite pluton, which intrudes metasedimentary rocks on the island Øksninga south of the Kråkfjellet Pluton (Fig. 1), is also included in this group.

Although there is some variation in grain size and texture, the granites have been treated as one unit. They have c. 70 % SiO_2, and generally display little variation in chemistry although tonalitic to granitic rocks occur in the Oksdal Massif south of Kolsvik.

Isotope data

In Fig. 6 the Sr data for the granites have plotted with three different symbols representing different geographical areas. From north to south these are: 1. the Visten-Lomsdal area; 2. the Tosen-Buadalen (Kolsvik) area; and 3. the area south of Buadalen including a small granite pluton situated on the island Øksninga

Fig. 6. Isotope diagram for granitic rocks occurring along the N-S trending central part of the Bindal Batholith. N88-38 (Table 1) has a very high $^{87}Sr/^{86}Sr$ ratio and is not shown on the diagram.



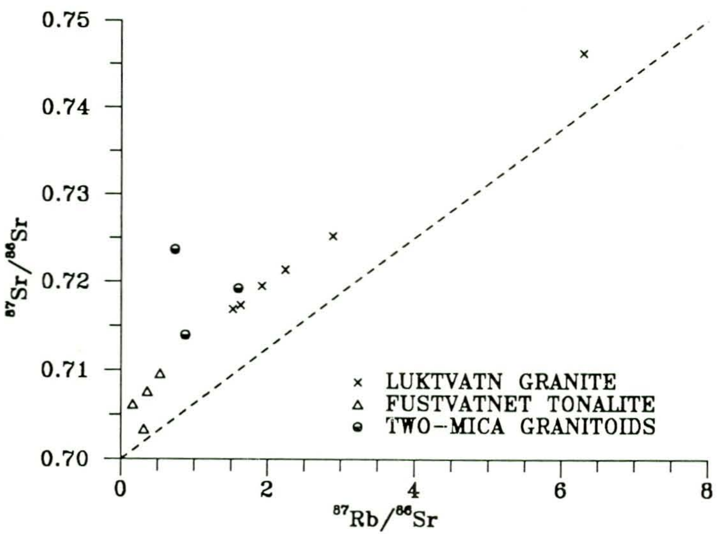


Fig. 7. Isotope diagram for rocks in the northern part of the batholith. Data for the Luktvatn Granite are from Tørudbakken & Mickelson (1986).

in Bindalsfjord, south of the Kråkfjellet Pluton (Fig. 1).

It is clear from Fig. 6 that the granites show a consistent isotopic pattern with $^{87}Rb/^{86}Sr$ ratios between 0.5 and 2.0. However, the scatter in $^{87}Sr/^{86}$ Sr ratios within the groups is substantial, and any calculation of isochrons would yield meaningless results. There is no obvious indication of secondary processes which would affect the isotope system, and the observed isotopic scatter probably reflects a primary feature of the rocks.

Rocks in the Visten-Lomsdal area have $^{87}Rb/^{86}Sr$ ratios less than 1, and initial ratios are generally between 0.7056 and 0.7077. Two samples have very high $^{87}Sr/^{86}Sr$ (VF37 and N88-38; Table 1) and are not part of the same magmatic unit. The rocks south of Tosbotn exhibit larger variation in $^{87}Rb/^{86}Sr$ ratios, and the SrI values are between 0.705 and 0.708. Two samples from near Kolsvik (N87-121 and N87-127; Table 1) are tonalitic in composition and have fairly low initial ratios of c. 0.705. Otherwise the rocks in the Oksdal Massif and at Fuglstadfjellet are granitic with initial ratios between 0.706 and 0.708.

The granites included in this group are probably somewhat varied expressions of the same

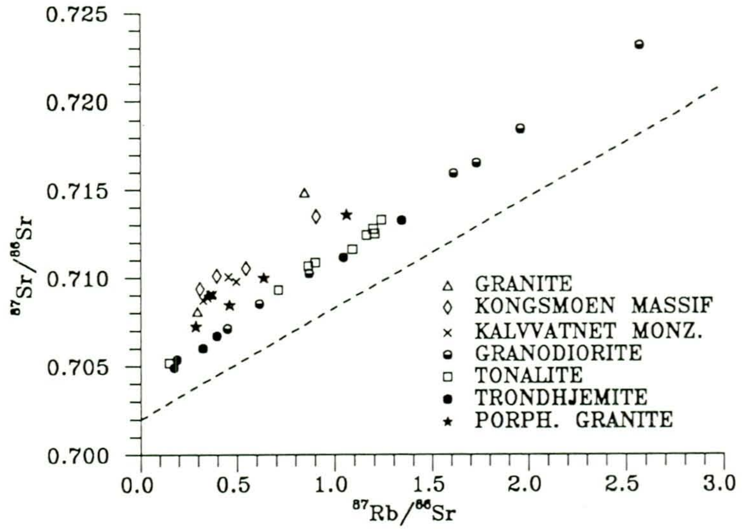


Fig. 8. Isotope diagram for rocks in the southeastern part of the batholith. Data for the Kalvvatnet Monzonite, granodiorite, tonalite, trondhjemite and porphyritic granite are from Nissen (1986, 1988); data for the Kongsmoen Massif from Priem et el. (1975); data for undifferentiated granite from this study.

magmatic event. In Tosen, a monzodiorite which has yielded a U-Pb zircon date of 428 ± 3 Ma (Nordgulen et al., in prep) is cut by the granite. Although there may be some variation in the age of the granites, this implies that a substantial part of the BB, including the granites described above, is Silurian in age.

The Mosjøen area

Isotope data

Only a few samples have been analysed from the plutons in this area (Fig. 7). Tørudbakken & Mickelson (1986) reported a Rb-Sr date of 433 ± 11 Ma (SrI = 0.7075 ± 0.0002; MSWD = 1.22) from a granite dyke north of Luktvatn. The data from that study are plotted in Fig. 7 together with data from a tonalite at Fustvatnet (northeast of Mosjøen), and granitoids sampled along the Vefsn valley south of Mosjøen (Table 1).

Although there are few data, some features can be pointed out. Two samples from the tonalite at Fustvatnet (N87-139 and N87-141) indicate an initial ratio of c. 0.705 for this pluton. Another sample from the same pluton (N87-140) has a very low $^{87}Sr/^{86}Sr$ ratio (Fig. 7) corresponding to an extremely low initial ratio (c. 0.701), which may be due to analytical error. A single sample of tonalite of the Reinfjellet Massif (N87-144) has an SrI value of c. 0.706, and three samples of foliated granite (N87-145, -146 and -147) collected along the western margin of the Reinfjell Massif display a wide scatter in isotope ratios (Fig. 7) with initial ratios between 0.709 and 0.719 (Table 1).

The southeastern part of the Bindal Batholith

Introduction

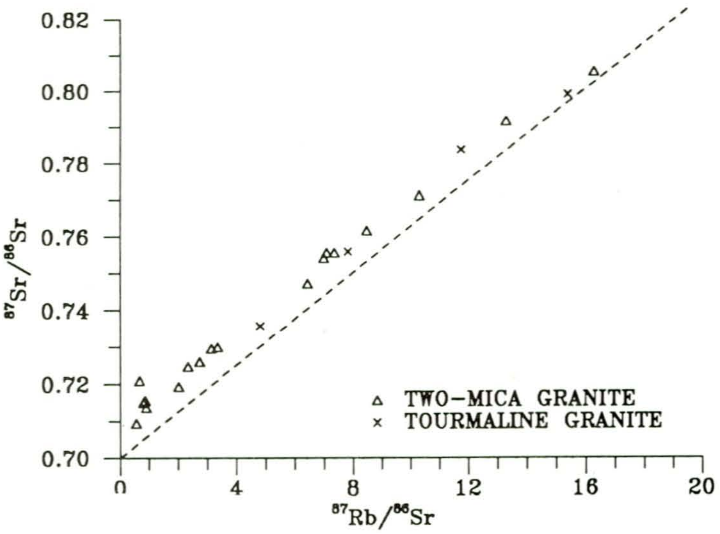
In the southeast part of the BB, there are various porphyritic rocks and a fairly large pluton of quartz monzonite (Fig. 1). The eastern part of the area, north of Namsskogan, is characterised by NE-SW trending, steeply dipping belts of variably foliated tonalites and granodiorites separated by zones of metasupracrustal rocks. Granite and aplite dykes are common locally.

Data from this area have previously been reported by Priem et al. (1975) and Nissen (1986, 1988). For comparison, the results from these studies are shown in Figs. 8 and 9 together with some new data.

Isotope data

Priem et al. (1975) analysed four samples of porphyritic granodiorite from the Kongsmoen Massif. Three samples referred to as aplites were also analysed, but there is no evidence that the aplites are related to the porphyritic granite. Data for a sample of granodiorite from

Fig. 9. Isotope diagram for two-mica granite (this study) and tourmaline granite in the southeastern part of the batholith (Nissen 1988).



Bindalseid was also published, however, the Rb and Sr contents as well as the isotope characteristics of this rock show that it belongs to the Heilhornet Pluton. Consequently, the date of 415 ± 15 Ma reported by Priem et al. (1975) is based on data from different plutons and must be regarded as incorrect.

In Fig. 8, the porphyritic granodiorite of the Kongsmoen Massif analysed by Priem et al. (1975) has been plotted. An initial ratio of c. 0.7075 is indicated by the data. The analyses published by Nissen (1986, 1988) have also been compiled and plotted on Fig. 8. The rocks termed granodiorite, tonalite and trondhjemite plot on a well defined trend with an initial ratio of c. 0.704, which is the lowest obtained for rocks in the BB. Trondhjemite and tonalite span a similar range in Rb/Sr values, whereas the granodiorites are generally more evolved. The porphyritic granite, which occurs south of the Kalvvatnet Monzonite (Fig. 1) has higher ^{87}Sr/^{86}Sr ratios and yield an initial ratio of c. 0.706. The Kalvvatnet Monzonite has even higher ^{87}Sr/^{86}Sr ratios with an initial ratio of c. 0.7065. Three samples of porphyritic to equigranular granites present adjacent to the Kalvvatnet Monzonite (data from this study) are also plotted on Fig. 8. Two of these plot close to the monzonitic rocks, whereas the third has higher ^{87}Sr/^{86}Sr ratios than other rocks in the area.

Nissen (1988) also published results for tourmaline granites (Fig. 9) which have substantially higher Rb/Sr ratios than other rocks in the area. On the isotope diagram they overlap with the rocks which in this study are referred to as 2-mica granite dykes (see below). The tourmaline granites from the western part of the BB have similar Rb/Sr ratios, but significantly higher ^{87}Sr/^{86}Sr ratios than those reported by Nissen (1988).

Age calculations performed by Nissen (1986, 1988) gave the following results:

	Age (Ma)	(^{87}Sr/^{86} Sr)$_0$	MSWD
Fine-gr. granodiorite	526 ± 10	.70374 ± .00016	.57
Tonalite	503 ± 23	.70416 ± .00028	3.93
Trondhjemite	493 ± 25	.70382 ± .00018	3.71
Porphyritic granite	568 ± 23	.70488 ± .00018	1.68
Tourmaline granite	449 ± 51	.70518 ± .00546	21.43

Field relations indicate that the tonalite is the older of these (Nissen 1986). A U-Pb zircon date of 437 ± 4 Ma for the tonalite (Nordgulen et al., in prep) probably represents the crystallization age of the rock. This result, and the substantial uncertainties for most of the Rb-Sr dates, show that precise U-Pb zircon dates are required to understand the plutonic history of the batholith.

Two-mica granite dykes

Introduction

These rocks are widespread in the BB and are generally among the youngest intrusive phase within any area. They usually occur as regular sheets, and the most prominent ones may be more than 100 metres wide. Locally, the dykes are very abundant, and in some small areas they are the dominant rock type. The granites clearly cut the strong fabrics related to D_2, as defined by Thorsnes & Løseth (1991), but some of the dykes are folded by open D_3 structures. Chemical data show that the dykes range in composition from tonalites and granodiorites with relatively low Rb and K_2O, to strongly evolved aplitic rocks with high Rb and K_2O (Nordgulen, in prep).

Isotope data

The rocks analysed in this study have been collected from widely separate areas, and the dykes intrude different types of plutonic and metasedimentary rocks. Dykes intruding the Terråkfjellet Pluton have the lowest Rb/Sr ratios, and these samples also show significant scatter in $^{87}Sr/^{86}Sr$ ratios (Fig. 9). One sample (B805; Table 1) clearly plots above the trend. The majority of the samples yield a surprisingly well defined trend on the isotope diagram (Fig. 9). The slope of a line drawn through the points would correspond to an age of c. 430 Ma with an initial ratio of c. 0.710. The granites have lower $^{87}Sr/^{86}Sr$ than other rocks with similar $^{87}Rb/^{86}Sr$ such as the tourmaline granites and the anatectic granites.

The relatively coherent isotopic pattern shown by rocks from widely scattered localities (Fig. 9) suggests that an event of widespread dyke intrusion took place at a comparatively late stage in the development of the BB. However, despite the evolved nature of the granites, there are differences in chemistry which indicate that the rocks represent the end products of more than one fractionation series. It must also be pointed out that small variations in age (e.g. 10-20 Ma) would cause relatively minor shifts in the $^{87}Sr/^{86}Sr$ ratios. Thus, there may be variations in age and/or initial ratio within the group, which are not possible to resolve by the isotope data.

Discussion

The source of the granitoids

The SrI values, which have been calculated or estimated for various rock types and plutons in the BB, are summarised in Fig. 10. A range of initial ratios within a pluton is a common feature of the batholith. This is common in granitoids and indicates that processes such as melt production, aggregation, transport, emplacement and solidification of the magma do not result in an isotopically homogeneous intrusion (Hill & Silver 1988). Each pluton may therefore preserve a record of initial $^{87}Sr/^{86}Sr$ variation in the source, and this may allow an assessment of the sources from which the melts were produced. Using this approach, various explanations have been proposed to explain isotopic heterogeneity in plutons. Mafic magmas from an upper mantle or lower crustal source may mix with melts from crustal rocks (e.g. DePaolo 1981, Kistler et al. 1986, Arakawa 1990). It is also plausible to explain the data as a result of magmas being produced from isotopically heterogeneous source rocks of crustal origin (e.g. Deniel et al. 1987, Hill & Silver 1988). In addition, high-level contamination from partially melted xenoliths as well as interaction with fluids during and/or after solidification of the pluton may disturb the isotope system.

A number of plutons in the BB contain metasedimentary xenoliths in variable amounts; however, with the exception of the anatectic granitoids, there is no field evidence to suggest significant contamination of intrusive rocks by melts derived from xenoliths. Generally, there appears to be no correlation between the amount of xenoliths and isotopic heterogeneity. The Kråkfjellet Pluton is an example of an intrusion which in large parts contains abundant metasedimentary xenoliths (Nordgulen 1984, Nordgulen et al. 1990). The relatively low and constant SrI values (Fig. 2), compared with the uniformly high $^{87}Sr/^{86}Sr$ ratios of the metasedimentary rocks, support the interpretation that the Sr isotope system has not been significantly disturbed by incorporation of wall-rock components in the magma.

Disturbance of the isotope system by secondary alteration is difficult to assess. However, the overall fairly fresh mineralogy of the granit-

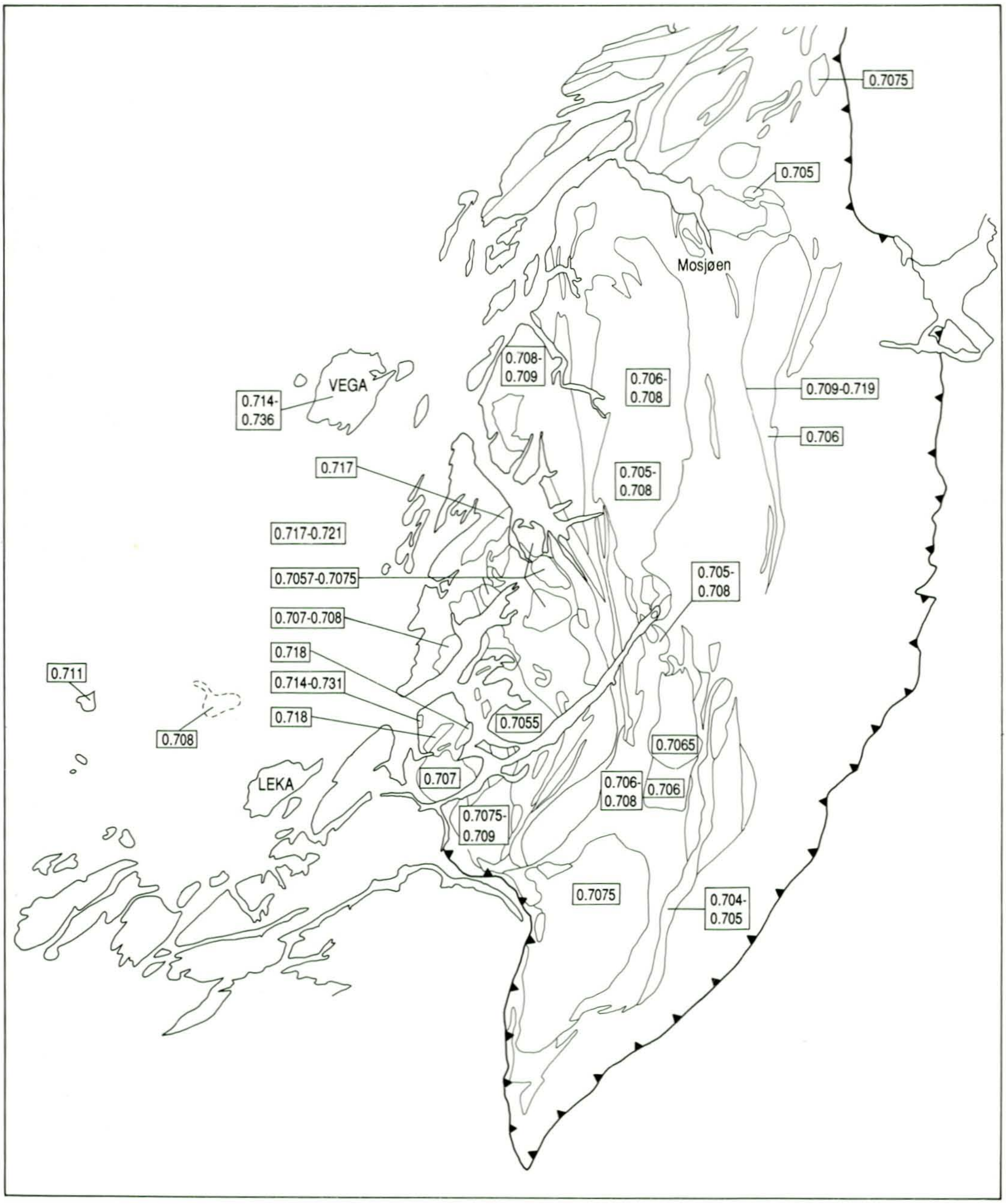


Fig. 10. Schematic outline of the Bindal Batholith (cf. Fig. 1) showing strontium initial ratios for plutons and rock types. For the Sklinna Pluton the initial ratio corresponds to an age of c. 395 Ma. Otherwise the initial ratios are calculated with respect to an age of 440 Ma.

oids does not suggest that such processes have been widespread. The Sklinna Pluton may provide an exception to this rule. Strong sericitisation in the pluton and the indication that the Sr isotope system closed after 400 Ma may indicate that the rocks have been subjected to some alteration at a late stage.

Low to intermediate initial ratios (0.704-0.710) predominate and are present in a wide variety of rock types throughout the batholith

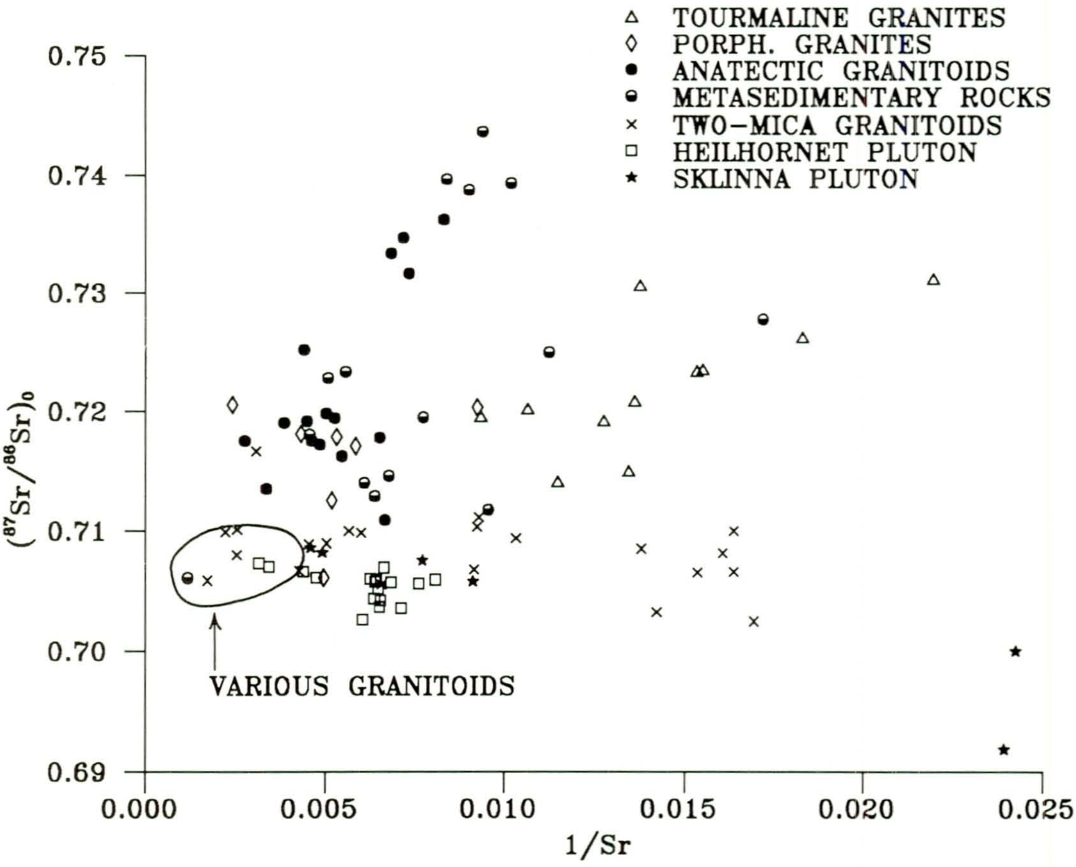


Fig. 11. Strontium intial ratios based on an age of 440 Ma plotted against 1/Sr. Samples from plutons and rock types which are not specified in the legend plot in the field labelled 'various granitoids'. This also includes the data published by Nissen (1986, 1988), but not those of Priem et al. (1975).

(Fig. 10). Most of these rocks have relatively high Sr contents, and they plot within a small field in Fig. 11. Within this group, some plutons have constant or narrow ranges in SrI values. These have comparatively low SrI (0. 704-0.705), and some of them exhibit considerable chemical and petrographic variation. The chemical and isotopic characteristics for the plutons would be compatible with differentiation of isotopically fairly homogeneous magmas derived from a mafic to intermediate upper mantle to lower crustal source.

The plutons with SrI values between 0.705 and 0.710 (Fig. 11) comprise several rock types which exhibit variable degrees of isotopic heterogeneity. Representative samples from a number of plutons have $\epsilon_{Nd} < -2$ and fairly radiogenic feldspar Pb (Birkeland et al., in press). The source regions for these rocks are difficult to assess and may include upper mantle and various crustals sources. Lower crustal materials with relatively short crustal residence times are also a potential source; therefore, an entirely crustal origin for the rocks cannot be ruled out. A similar argument can also be made for the tonalites and granodiorites that have low SrI values. However, a signficant sub-crustal input may appear more likely in such cases.

The gabbros and diorites in the Velfjord-Ursfjord area generally have low to intermediate SrI (0.7057 - 0.7071), whereas higher values (SrI > 0.708) are present in some rocks occurring west of Velfjord (Fig 4). Generally, the geochemistry of these rocks would require an upper mantle or lower crustal mafic source with a variable crustal contribution.

The late granitoid dykes constitute a diverse group of rocks with highly variable Rb/Sr ratios (Fig. 9). They intrude different types of granitoid and metasedimentary rocks, but, there is no clear relationship between the isotope composition of the dykes and their host. Thus, it would seem that the generation of these dykes is not generally related to the petrogenesis of the granitoid in which they occur. The dykes have clearly lower $^{87}Sr/^{86}Sr$ ratios than the metasedimentary rocks, and although other isotope data are not available there is no indication that they were generated by upper crustal melting. The sources for the rocks are probably varied and similar to those of other tonalitic to granitic rocks in the BB.

Relatively non-radiogenic sources are also suggested for the Heilhornet and Sklinna Plutons (Fig. 11). The apparent negative trend for the Sklinna Pluton indicates that the age used to calculate the initial ratios may be too young.

In the BB, a wide range in SrI is especially pronounced in the anatectic granitoids and the tourmaline granites (Fig 11). Field evidence suggests that at least some of the anatectic rocks are a result of local melting of metasedimentary rocks. The rocks have overall high SrI and low ϵ_{Nd} values which are consistent with a predominantly crustal origin (Birkeland et al. in press). In Fig. 11, variable mixing between two components with different initial ratios will produce linear trends between the end members. Anatectic granitoids overlap with most of the samples of metasedimentary rocks, suggesting that they were generated by mixing of components from a highly radiogenic crustal source and a less radiogenic, possibly lower crustal/mantle source (Fig. 11). Some samples of the metasedimentary rocks overlap with a broad array defined by the tourmaline granites. Again, the trend may be explained by mixing a radiogenic and a non-radiogenic source. The radiogenic end-member for the tourmaline granites, however, is distinct from and less radiogenic than that of the anatectic rocks. The porphyritic granites (Fig. 11), which occur together with mafic to intermediate plutons in the Velfjord district, also have a high SrI indicative of a strong influence from radiogenic sources. Metasedimentary rocks within the HNC, or equivalent rocks at depth, which have Rb/Sr and $^{87}Sr/^{86}Sr$ ratios similar to the granitoids, would provide a potential source lithology for the granitoids with high SrI.

Isotope data (Rb-Sr, Sm-Nd and Pb-Pb in feldspars) from a series of representative samples of the BB show that the rocks originated from multiple sources including fairly depleted mantle to lower crustal rocks, enriched upper crust, and two types of Th-enriched, probably lower crustal rocks (Birkeland et al., in press). The Sr isotope data presented here show that most of the batholith has SrI <0.71; however, a number of plutons have higher SrI values reflecting a strong influence from radiogenic crustal rocks. Of particular interest is the heterogeneous nature of the radiogenic source (Fig. 11). This feature was not apparent from the study by Birkeland et al. (in press). Thus, the comprehensive study of the Sr isotope variation has led to an improved understanding of the complexity involved in the petrogenesis of the BB.

To summarise, melting of heterogeneous source regions and/or mixing of melts derived in variable proportions from isotopically different crustal and sub-crustal sources may account for the variability in Sr isotopes of the BB. Contamination at the level of emplacement as well as secondary alteration appears to be of limited importance, and isotopic heterogeneity within and between plutons and rock types is thought to reflect the varied nature of the source rocks.

Geographic variation in initial $^{87}Sr/^{86}Sr$ ratios

Most of the granitoids in the Bindal Batholith have Rb/Sr ratios < 1.0. The exceptions are the tourmaline-granites in Bindal, the Sklinna Pluton, most of the Heilhornet Pluton, and the majority of the 2-mica granite dykes. Most of these also have high or fairly high initial Sr ratios. The anatectic granites may have Rb/Sr < 1.0 though the initial ratios are high. Some intrusions (e.g. the Kråkfjellet Pluton) have very low Rb/Sr ratios, but most of the rocks have ratios in the range 0.2 - 1.0.

Fig. 10 shows how variation in SrI values relate to geographic position. Most of the rocks with low SrI (< 0.705) occur in the eastern part of the batholith. Rocks with intermediate initial ratios (0.705 - 0.708) are common throughout the batholith and include the mafic to intermediate plutons in the Velfjord and Ursfjord areas. The highest values (SrI > 0.715) are represented by tourmaline-granites and anatectic granites in the west.

These results may constrain the models for Caledonian magmatism in Norway. Isotopic polarity is a feature of some, but not all examples of documented Phanerozoic subduction/volcanic arc related plutonism. Where polarity exists, it generally shows an increase from low values at the continental margin to higher values in the continental hinterland (Kistler & Peterman 1973, Farmer & DePaolo 1983, Liew & Hofmann 1988, Arakawa 1990). Assuming a destructive plate margin setting, the pattern of initial Sr values now established for the BB would indicate that the continental hinterland lay to the west at the time of plutonism.

Conclusions

The strontium isotope chemistry of the Bindal Batholith has been investigated. The mafic intrusions must have a mafic source in the upper mantle to lower crust, although the initial ratios of the investigated rocks (0.705-0.707) indicate significant influence from isotopically evolved material in the source region. For some plutons having more evolved compositions and fairly low initial $^{87}Sr/^{86}Sr$ ratios (c. 0.704), the upper mantle to lower crust would be the most likely source region. Granitoids with higher initial ratios (0.705-0.710) would require an increasingly stronger crustal influence. The tourmaline granites and anatectic granites with high or very high initial ratios ($>$ 0.715) may be of entirely crustal origin, and the data suggest that two types of radiogenic crustal rocks contributed to the magmas. There is little evidence of high-level contamination, and significant secondary alteration of the granitoids is observed in very few cases. The varied nature of the Sr isotope data are generally interpreted to reflect differences in relative input from source rocks with variable Rb/Sr-ratios and isotope composition.

Due to the isotopic heterogeneity generally observed in the BB, it is virtually impossible to obtain meaningful dates using Rb-Sr whole-rock isochrons. This emphasizes the need for precise U-Pb dates in the study of the granitoids.

Intrusions in the southeastern part of the batholith have constant or narrow ranges of generally low initial $^{87}Sr/^{86}Sr$ ratios. Intermediate and variable initial ratios are present in several plutons occurring in most parts of the batholith. Tourmaline granites and anatectic granites with the highest initial ratios are located in the western part of the batholith. Interpreting the data in terms of a subduction related setting, the geographic distribution of initial $^{87}Sr/^{86}Sr$ ratios would indicate that the continent lay to the west during the time of plutonism.

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