Geochemistry of the Skålvær greenstone, and a geotectonic model for the Caledonides of Helgeland, north Norway

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Some 30 specimens from five profiles through the Skålvær greenstone, south Helgeland, have been analysed for major and trace elements. Variations in the chemical compositions have been found to relate mostly to primary fractionation processes, but variations in Sr content are probably due to secondary alteration. Both major and trace element chemistry indicate that the Skålvær greenstone is an ocean-floor type basalt, in most respects similar to the abyssal tholeiites of mid-oceanic ridges. Consideration of the volcanic and sedimentary characteristics and the regional geology, however, has led to the conclusion that the basalt was most probably formed in a marginal, back-arc basin. Based on this conclusion and on the regional geological development, a geotectonic model for the area is briefly outlined.

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The main lithotectonic units of the Helgeland area of central Norway and of adjoining areas of the Swedish Caledonides are shown in Fig. 1. Precambrian basement is exposed east and south of the Caledonian nappes and in a number of tectonic windows within the nappe areas.

The rock sequence of the Skålvær area (Fig. 2) has been described as part of the Helgeland Nappe Complex (Gustavson 1975). This is the major Caledonian nappe unit in south Helgeland and borders on greenschist facies Köli rocks of the Seve-Köli Nappe Complex to the east. The Helgeland Nappe Complex is composed of amphibolite facies metasedimentary rocks as well as granitoid and mafic intrusives, but the rocks of the Skålvær area are in a considerably lower degree of metamorphism than the rest of the nappe complex. The structural interpretation of the area indicates that the greenstones are the lowermost and oldest formation in the local stratigraphy, which is as follows:

Quartz keratophyre
Dark phyllite and mica schist
Dolomite conglomerate and metagreywacke
Dark, dolomitic crystalline limestone and
    calcite marble
Greenstone.

Regional considerations and lithostratigraphic correlations led to the conclusion that the green-stone-bearing sequence is most probably of Middle to Upper Ordovician age. An important conclusion in this previous paper (Gustavson 1975) is that the Helgeland Nappe Complex and the Seve-Köli Nappe Complex are to some extent composed of the same formations, although these are usually in a higher metamorphic state in the Helgeland Nappe Complex than in the latter.

Major and trace element data from three specimens of the Skålvær greenstones (Gustavson 1975) indicated that two different magma types might be represented. As the greenstones seem to belong to one and the same horizon, 40 to 60 metres thick, it was decided to collect a larger number of samples in order to find the range and character of chemical variation. If variations were of the magnitude indicated by the first analyses it would be of importance to find their causes as well as to indicate their possible significance for the use of geochemical data in general in discussions of geotectonic models.

In the account which follows, the new data are presented and briefly discussed. Combined with the stratigraphic and structural evidence from this region they provide a basis for the proposal of a generalized model for the geotectonic evolution of the Helgeland area.
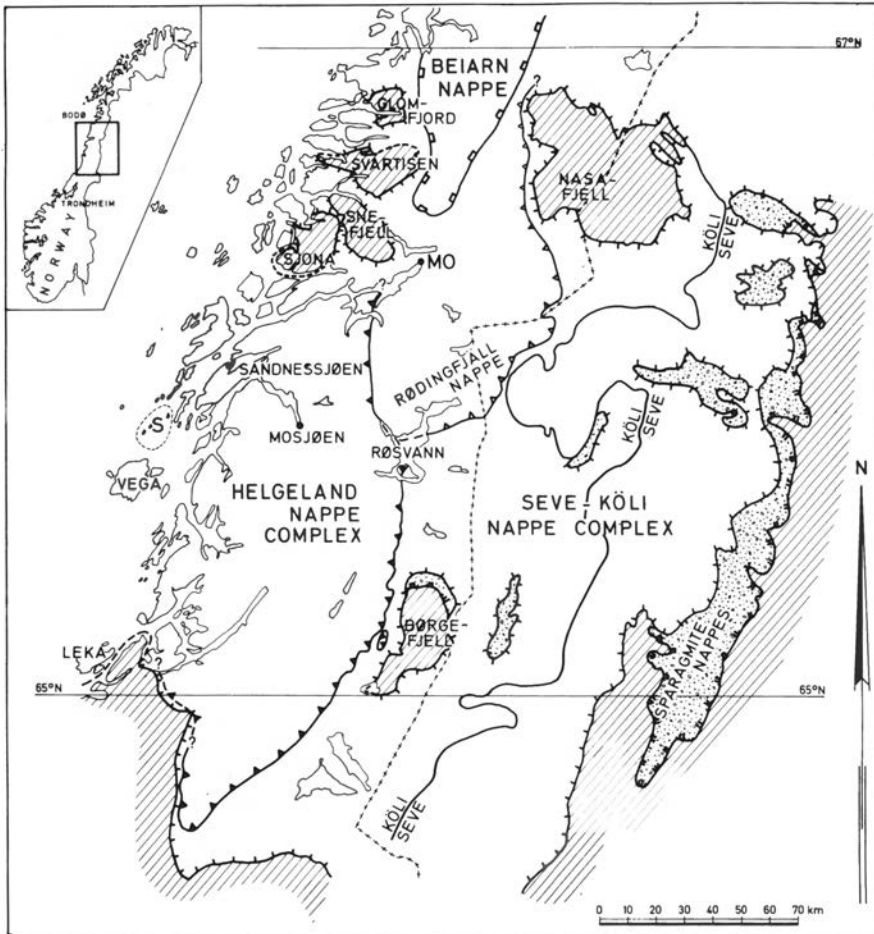
Fig. 1. Sketch map of the main litho-tectonic units of Helgeland and ajoining areas in Sweden. Hatched areas: Precambrian basement. Dotted: Sparagmitic allochthonous rocks. Name of Caledonian nappe complexes shown on respective areas on the map. S: Skålvær area.

The geochemistry of the Skålvær greenstone

Petrography

Well-preserved pillow structure at Grundværsnavaren (Fig. 2) testifies to the effusive submarine origin of the greenstones. Less well-defined fragmental forms may be explained as hyaloclastic breccia structures. Most greenstone variants are megascopically massive, but schistose types also occur.

All the greenstone localities described in this account lie within the chlorite and biotite zones of metamorphism (usually quartz-albite-muscovite-chlorite subfacies). Most prominent among the metamorphic minerals are pale green to colourless actinolite and albite. Epidote (clinozoisite) and chlorite and minor amounts of ore minerals, sphene, and calcite are present in most thin-sections; biotite is only occasionally present.

Texturally most thin-sections show irregularly arranged actinolite prisms in a mosaic of the other minerals. In some specimens the minerals,

Fig. 2. Geological map of the Skålvær area. (S. on key map). Sampling localities: Lille Ørnøy, Lamskinnet, Flatskjær, Ovnskjær, Grundværsnavaren.
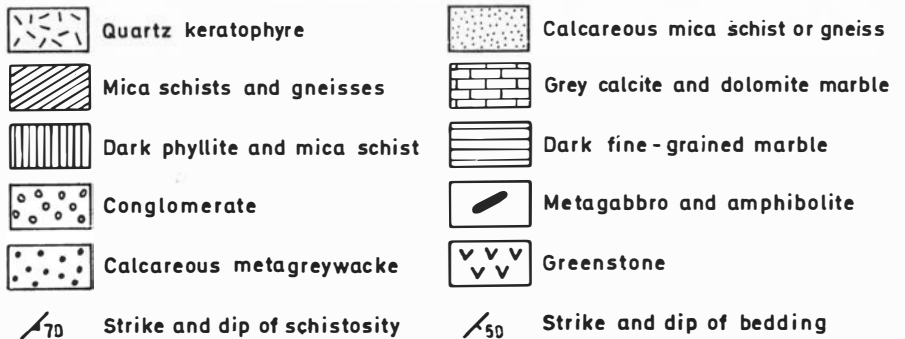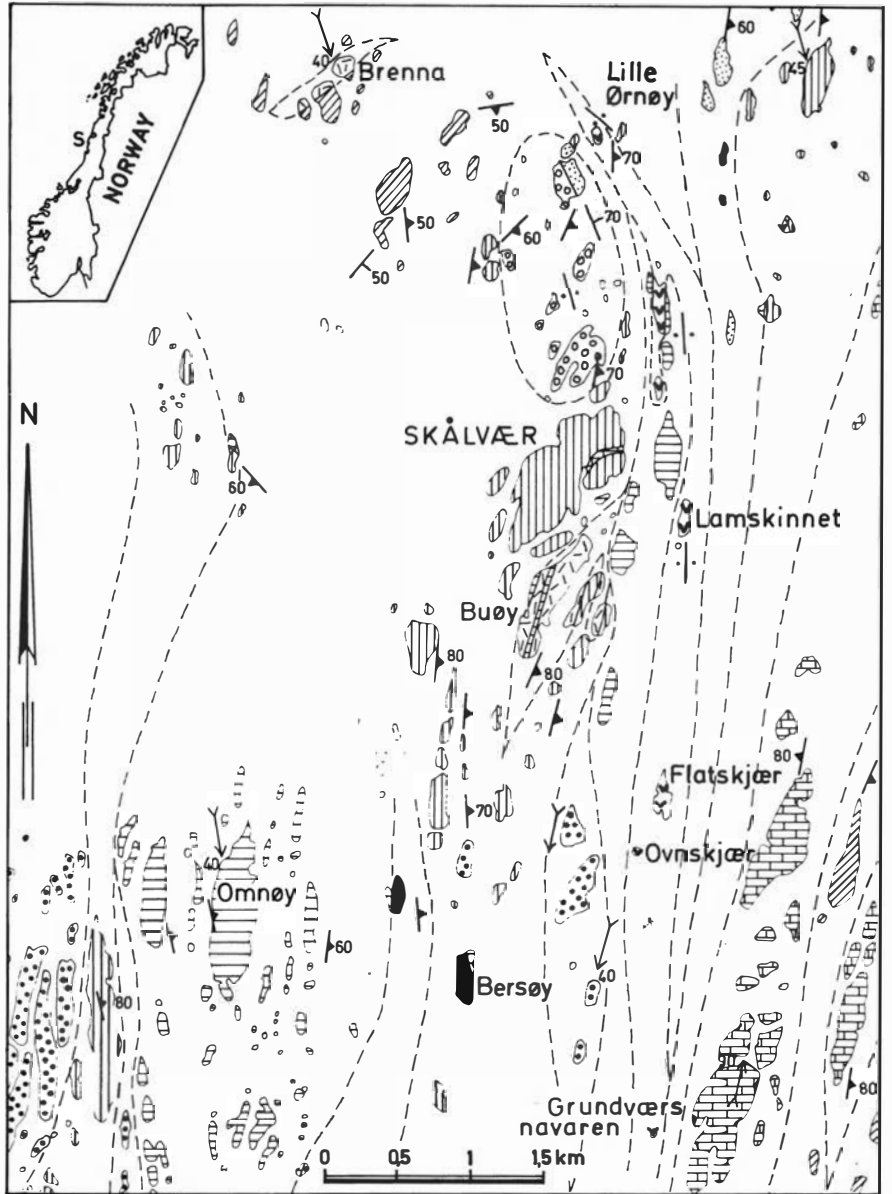
Table 1. Chemical compositions of the Skålvær greenstones from Lille Ørnøy and Lamskinnet.

wt %	Ø1	Ø2	Ø3	Ø4	Ø5	Ø6	Ø7	Ø8	L1	L2	L3	L4
SiO_2	51.24	49.16	50.07	42.80	50.13	46.18	49.88	47.12	48.29	48.18	49.94	47.44
TiO_2	1.56	1.71	1.72	1.38	1.96	1.85	1.64	1.35	1.81	1.68	1.70	2.13
Al_2O_3	15.69	13.02	14.53	15.15	14.46	16.16	15.46	16.82	14.09	14.80	15.12	16.04
Fe_2O_3	0.46	1.88	1.02	0.83	0.68	1.48	0.85	0.52	1.09	0.84	0.97	0.53
FeO	8.95	10.46	9.67	7.19	10.04	9.82	9.68	9.18	10.88	10.13	10.76	11.85
MnO	0.20	0.23	0.23	0.29	0.20	0.24	0.21	0.24	0.23	0.23	0.21	0.21
MgO	8.23	7.84	7.74	7.09	7.82	7.78	7.87	8.91	8.83	7.51	6.83	7.02
CaO	8.51	10.48	8.61	17.78	9.83	11.79	9.38	9.91	7.36	10.11	8.55	9.83
Na_2O	3.16	3.00	3.69	1.57	3.01	2.48	3.20	2.88	3.88	3.64	3.85	2.99
K_2O	0.13	0.18	0.25	0.10	0.16	0.13	0.13	0.14	0.71	0.20	0.18	0.17
H_2O-	0.08	0.05	–	0.11	0.10	0.06	0.07	0.04	0.04	0.10	0.08	0.07
H_2O+	1.93	1.69	1.74	2.39	1.58	1.74	1.65	2.40	1.76	1.76	1.60	1.63
CO_2	0.08	0.10	0.06	3.48	0.05	0.13	0.06	0.27	0.79	1.11	0.18	0.18
P_2O_5	0.09	0.12	0.12	0.09	0.10	0.10	0.09	0.09	0.11	0.11	0.09	0.10
Total	100.31	99.92	99.45	100.25	100.12	99.94	100.17	99.87	99.87	100.40	100.06	100.19
ppm												
Zr	102	119	117	89	122	127	108	95	110	104	101	127
Y	33	40	37	29	40	37	34	30	37	36	39	44
Sr	99	160	123	231	124	181	164	134	130	233	248	209
Rb	n.f.*	n.f.	17	n.f.	n.f.	n.f.	n.f.	n.f.	36	n.f.	n.f.	n.f.
Zn	79	97	93	70	97	95	98	84	117	106	99	114
Cu	n.f.	31	2	27	10	n.f.	n.f.	n.f.	n.f.	1	43	22
Ni	97	83	99	84	63	92	84	157	59	63	64	53
Cr	363	339	344	322	332	151	334	354	143	155	156	177
Ba	n.f.	n.f.	165	n.f.	57	28	n.f.	21	99	n.f.	46	n.f.
V**	350	370	400	300	440	390	340	340	470	440	410	530

* n.f. = not found. Measured intensity is less than background intensity.
** Semi-quantitative determination.
Analysts: Major elements, P.-R. Graff, Norges geologiske undersøkelse.
   Trace elements, G. C. Faye and M. Ødegård, Norges geologiske undersøkelse.

especially longitudinal actinolite prisms, are subparallel-orientated and define a fairly penetrative schistosity. Primary textures appear to be absent; nothing reminiscent of a porphyric or ophitic texture has been detected. A spotty arrangement of light and dark minerals in some thin-sections may reflect a primary distribution, but irregular boundaries between the present aggregates of greenschist facies minerals show that direct pseudomorphic recrystallization did not occur.

Actinolite prisms are 1–2 mm long, slender, slightly green-coloured, and pleochroic. The albite grains are irregularly shaped and twinning is usually absent. Clinozoisite or epidote grains are colourless. Larger amounts of this mineral in a few specimens correlate with high CaO and low Na_2O and SiO_2 contents in the respective analyses. Opaque grains are generally of pyrite. Biotite is found in small amounts as light brown

flakes in two analysed specimens containing more than 0.25 wt % K_2O. Colourless or very pale green chlorite is present in most thin-sections, rarely more than a few percent.

Sampling procedure and analytical techniques

Thirty samples were collected from the following five islands (Fig. 2), with the number of samples shown in parentheses: Lille Ørnøy (8), Lamskinnet (4), Flatskjær (6), Ovnskjær (5), and Grundværsnavaren (7). The distance between the islands is 2 to 3 kilometres with the exception of Flatskjær and Ovnskjær which are fairly close together. At each locality samples were taken at 5 m to 15 m intervals in profiles normal to the strike. In each section approximately the same spacing was used for all samples except where weathering or visible signs of secondary altera-

Table 2. Chemical compositions of the Skålvær greenstones from Flatskjær and Ovnskjær.

wt %	F1	F2	F3	F4	F5	F6	O1	O2	O3	O4	O5
SiO_2	48.06	49.98	48.62	47.24	48.90	47.42	49.52	44.79	49.44	49.45	48.65
TiO_2	2.01	1.26	1.72	1.63	1.66	1.65	0.64	1.53	1.45	1.56	1.52
Al_2O_3	14.37	16.78	14.66	14.34	16.02	14.68	16.54	14.80	14.00	14.28	15.63
Fe_2O_3	1.13	0.24	0.10	0.68	1.31	0.93	0.51	2.83	1.33	1.36	1.79
FeO	11.45	8.28	9.76	11.79	8.33	10.13	7.83	7.45	9.39	9.64	8.70
MnO	0.28	0.17	0.20	0.21	0.17	0.17	0.17	0.16	0.18	0.13	0.14
MgO	6.97	8.24	10.39	9.47	7.37	7.23	8.48	8.18	7.96	8.51	7.90
CaO	10.45	8.98	8.20	9.63	9.32	12.22	10.06	16.73	10.33	9.20	10.13
Na_2O	2.90	3.39	2.97	2.18	3.67	2.36	3.26	0.69	3.03	3.67	3.62
K_2O	0.12	0.14	0.10	0.13	0.11	0.15	0.12	0.09	0.25	0.17	0.15
H_2O-	0.01	0.02	0.04	0.03	0.04	0.05	0.03	0.02	0.05	0.02	0.06
H_2O+	1.39	2.10	2.42	2.53	2.04	1.94	2.17	1.96	1.45	1.66	0.72
CO_2	0.24	0.02	0.24	0.24	0.07	1.15	0.43	0.60	0.48	0.10	0.05
P_2O_5	0.12	0.08	0.10	0.08	0.09	0.08	0.05	0.08	0.08	0.10	0.09
Total	99.50	99.68	99.52	100.18	100.00	100.34	99.81	99.91	99.42	99.80	99.15
ppm											
Zr	120	90	104	105	112	102	34	93	74	97	92
Y	45	34	35	34	16	49	18	39	34	39	37
Sr	164	262	153	115	189	154	122	84	106	71	88
Rb	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.
Zn	118	77	102	117	95	135	71	99	94	96	101
Cu	13	n.f.	n.f.	n.f.	n.f.	n.f.	21	n.f.	20	19	3
Ni	35	121	49	50	85	55	107	74	57	60	51
Cr	25	372	170	141	274	127	419	291	192	209	245
Ba	n.f.	10	n.f.	n.f.	17	6	51	n.f.	n.f.	n.f.	n.f.
V	510	290	400	400	400	400	250	370	450	350	500

For abbreviations, see Table 1.

tion made variations necessary. A sample size of about 1000 grams was considered sufficient in view of the fairly homogeneous appearance of the greenstone.

Pillow structure is especially well developed in the southernmost locality of Grundværsnavaren. The first four samples in this locality were taken from massive greenstone containing diffuse fragments (Gustavson 1975 Fig. 3), the other three from the central parts of large pillows.

The sampling procedure adopted is considered suitable for revealing possible variations along the strike, and it also covers the eventuality that any one horizon might be composed of more than one lava flow.

The major elements were determined by wet chemical methods by Per-Reidar Graff, Norges geologiske undersøkelse, and the trace elements by X-ray fluorescence methods according to Faye & Ødegård (1975).

Chemical composition of the greenstones

Major and trace elements of all 30 samples of the Skålvær greenstone, together with the calculated average for all analyses, are shown in Tables 1, 2, and 3. The major oxides show relatively small variations, the most evident being the high CaO contents combined with low Na_2O and SiO_2 in specimens Ø4 and O2. Microscope work has shown this to relate to an unusually high content of epidote minerals combined with very little albite. Apart from this there is obviously a two-fold grouping in the TiO_2 values; most analyses show TiO_2 between 1.5% and 2%, while six of the seven specimens from the southernmost locality, Grundværsnavaren, together with specimen O1, have TiO_2 in the range 0.6% to 1.0%. Considerable variation in some of the trace elements can be read from the table.

Various methods have been tried in order to compare the major and trace element chemistry with established groupings of magma types. The major elements have been recalculated accor-

Table 3. Chemical compositions of the Skålvær greenstones from Grundværsnavaren.

wt %	G1	G2	G3	G4	G5	G6	G7	Average (all 30)
SiO_2	49.84	50.20	51.35	48.37	51.07	49.25	51.83	48.81
TiO_2	0.98	0.94	0.94	1.79	0.68	0.64	0.64	1.45
Al_2O_3	14.38	13.00	13.92	14.23	16.43	16.00	16.44	15.06
Fe_2O_3	1.29	1.29	0.99	1.12	0.36	0.54	0.52	0.98
FeO	10.60	11.58	10.21	10.76	7.72	7.24	7.04	9.55
MnO	0.30	0.69	0.21	0.21	0.16	0.24	0.15	0.22
MgO	7.70	7.85	7.84	7.70	7.96	7.81	7.47	7.95
CaO	9.16	9.51	9.38	11.28	10.44	11.57	9.10	10.26
Na_2O	3.76	3.41	3.43	2.86	3.60	3.70	4.18	3.13
K_2O	0.15	0.18	0.20	0.14	0.19	0.21	0.26	0.17
H_2O-	0.08	0.05	0.03	0.08	0.04	0.04	0.01	0.05
H_2O+	1.52	1.61	1.69	1.80	1.28	1.52	1.63	1.77
CO_2	0.05	–	–	0.39	0.06	1.47	0.39	0.41
P_2O_5	0.10	0.12	0.11	0.10	0.05	0.09	0.05	0.09
Total	99.91	100.43	100.20	100.83	100.04	100.32	99.71	99.90
ppm								
Zr	120	117	114	112	32	26	30	96
Y	44	36	37	39	18	17	14	34
Sr	59	56	42	62	131	151	188	141
Rb	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	3	–
Zn	114	124	105	113	66	65	59	103
Cu	n.f.	38	n.f.	n.f.	109	41	117	–
Ni	52	44	51	48	111	107	112	76
Cr	138	131	121	139	458	411	411	248
Ba	1	8	n.f.	n.f.	n.f.	n.f.	18	–
V	440	400	440	440	280	240	260	387

For abbreviations, see Table 1.

ding to a statistical method described by Pearce (1976). Eight of the major oxides, SiO_2, TiO_2, Al_2O_3, FeO (total iron), CaO, MgO, Na_2O and K_2O, were used in calculating the following three parameters or factors:

$$F_1 = + 0.0088 \ SiO_2 - 0.0774 \ TiO_2 + 0.0102 \ Al_2O_3 \\ + 0.0066 \ FeO - 0.0017 \ MgO - 0.0143 \ CaO \\ - 0.0155 \ Na_2O - 0.0007 \ K_2O.$$

$$F_2 = - 0.0130 \ SiO_2 - 0.0185 \ TiO_2 - 0.0129 \ Al_2O_3 \\ - 0.0134 \ FeO - 0.0300 \ MgO - 0.0204 \ CaO \\ - 0.0481 \ Na_2O + 0.0715 \ K_2O.$$

$$F_3 = - 0.0221 \ SiO_2 - 0.0532 \ TiO_2 - 0.0361 \ Al_2O_3 \\ - 0.0016 \ FeO - 0.0310 \ MgO - 0.0237 \ CaO \\ - 0.0614 \ Na_2O - 0.0289 \ K_2O.$$

which were then plotted in two diagrams where the boundaries between ocean-floor basalts (OFB), low-potassium tholeiites (LKT), calc-alkali basalts (CAB), and shoshonites (SHO) have been empirically determined. The calculated values for F_1, F_2 and F_3 are given in Table 4. Only

the averages (one set of values) from each of the five localities and the average for all 30 are shown in Table 4 and plotted in the diagrams in Fig. 3. The reason for not using the individual analyses is that most of them plot too close together to be distinguishable in the diagrams. All values plot within the fields of OFB although the analyses from the southernmost locality (average of G1 to G7) lie close to the boundary with the CAB + LKT field in the F_1/F_2 diagram. Based on major elements and using the above plots the Skålvær greenstones would therefore appear to be classified as ocean-floor basalts.

Such a conclusion is not so equally obvious when considering the trace elements: Ti-Zr, Ti-Zr-Sr, and Ti-Zr-Y diagrams (Pearce & Cann 1973) are shown in Fig. 4 where all 30 analyses have been plotted. In the Ti-Zr diagram (Fig. 4a) 23 analyses fall within the field of ocean-floor basalts. Four analyses plot in the LKT field (A) or on the boundary of this field, while the three remaning analyses plot well with-
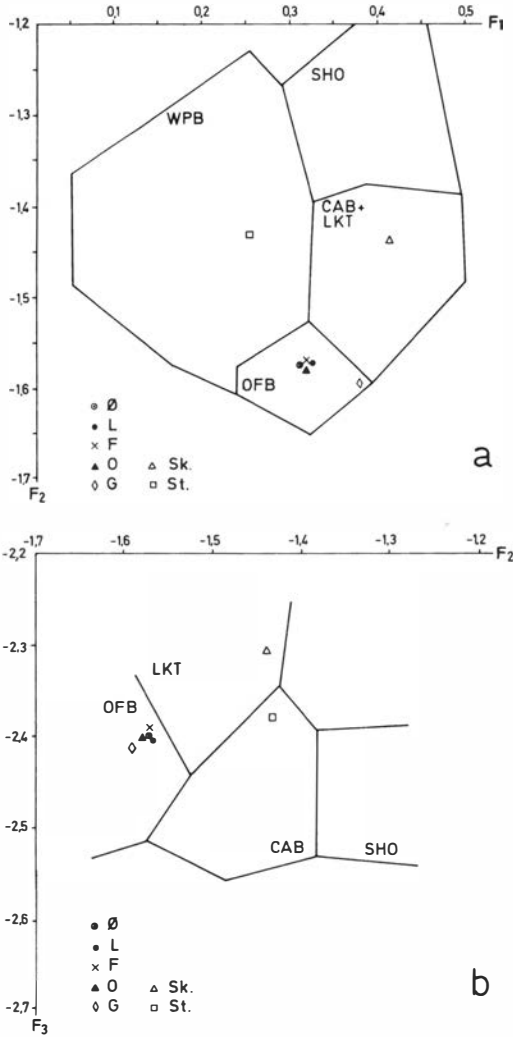
Fig. 3. F_1/F_2 and F_2/F_3 plot according to Pearce (1976). $\varnothing$, L, F, O, G: Average of the five localities, Skålvær area, from north to south, see Fig. 2. Sk: Average for Skei greenstone, Leka. St: Average for Storøya greenstone, Leka.
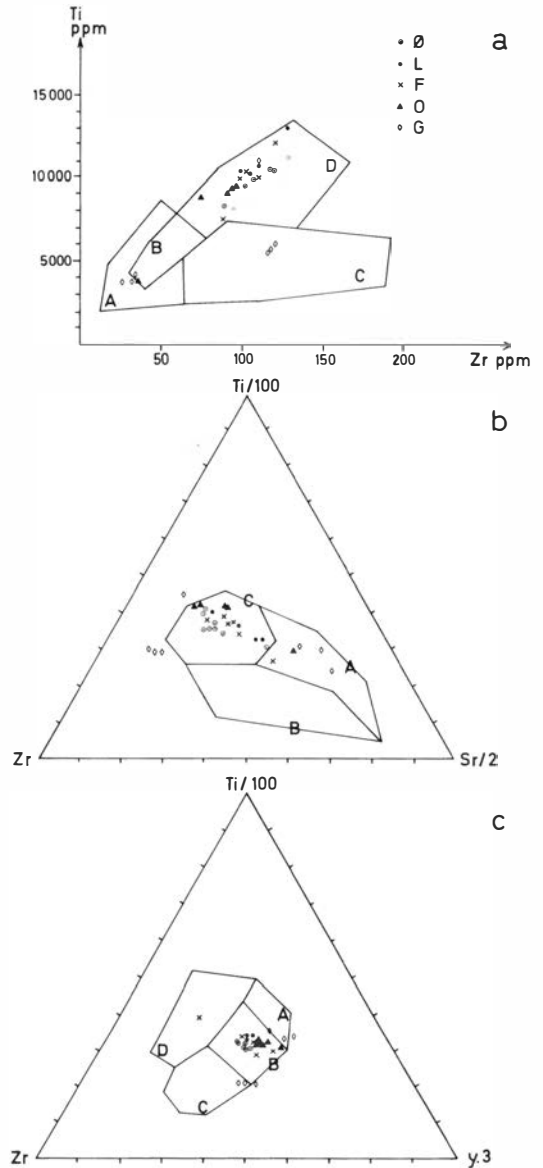

Fig. 4. Trace element plots of Skålvær greenstones in Pearce & Cann (1973) diagrams. Symbols for the localities as in Fig. 3.

Table 4. Discriminant factors for major element averages from the five Skålvær localities.

Locality	F_1	F_2	F_3
Lille Ørnøy	0.3075	−1.5766	−2.4004
Lamskinnet	0.3182	−1.5728	−2.4045
Flatskjær	0.3226	−1.5744	−2.3928
Ovnskjær	0.3120	−1.5834	−2.4003
Grundværsnavaren	0.3760	−1.5940	−2.4180
Average	0.3309	−1.5816	−2.4030

in the CAB field. In the Ti-Zr-Sr triangle (Fig. 4b) 21 analyses are within the OFB field, five plot in the LKT field, and four are outside and to the left of the OFB field. The Ti-Zr-Y diagram (Fig. 4c) shows 23 analyses within the field for OFB + LKT + CAB basalts, three analyses in the CAB field (C) or close to it, three within the LKT field or near its boundaries, and one single analysis within the WPB field. The averages for

Table 5. Trace element averages from Lille Ørnøy (Ø), Lamskinnet (L), Flatskjær (F), Ovnskjær (O), and Grundværsnavaren (G) and for all Skålvær analyses compared with OFB, LKT, CAB and OIB basalts*.

	Ø	L	F	O	G	Average	OFB	LKT	CAB	OIB
Zr	109.9	110.5	105.5	78.0	78.7	96.5	<u>92</u>	52	106	215
Y	35.0	39.0	35.5	33.4	29.3	34.0	<u>30</u>	19	23	29
Sr	152.0	205.0	172.8	94.2	98.4	141.1	<u>131</u>	207	375	438
Cr	317.4	156.5	184.8	271.2	258.4	248.0	310	160	130	<u>280</u>
Zn	89.1	109.0	137.2	92.2	92.3	102.6	–	–	–	–
Ni	94.9	59.8	65.8	69.8	75.0	75.6	–	–	–	–
V	366	463	400	384	357	387	–	–	–	–

* According to Pearce & Cann (1973).
The figure for each element fitting best with the Skålvær average is underlined.

the five localities as well as the average for all 30 specimens are well within the respective OFB fields in all three diagrams. A plot (not shown here) of Ti versus Cr according to a diagram by Pearce (1975) shows 26 of the 30 analyses to lie on the OFB side of the proposed OFB/LKT dividing line. Of the four analyses on the LKT side three are from the southernmost locality (G 1–3, together with F 1).

Fig. 4 shows that it is mainly the seven analyses from the southernmost locality (G) that deviate from the bulk of analyses, but also that specimens from other localities show similar deviations.

Table 5 shows trace element averages and compares the Zr, Y, Sr and Cr values with mean values for these elements in ocean-floor basalts, low potassium tholeiites, calc-alkali basalts, and ocean island basalts as given by Pearce & Cann (1973). The value which corresponds best with the average for the Skålvær greenstone is underlined for each element. It is seen that the averages for Zr, Y, and Sr are closest to those of the OFB while for Cr the average value corresponds best with that of OIB basalts, although for this element there is also a reasonably good correspondence with the mean value for the ocean floor basalts. This table might tend to indicate that this method of comparing the trace element values with OFB, LKT, CAB, or OIB averages is somewhat doubtful, and a comparison of the locality averages with the Pearce & Cann figures serves to demonstrate this. A rapid inspection of the table shows that the conclusion about magma type would be different from one element to another and also different from one locality to the next. Consideration of the average for all 30

specimens in this way is therefore misleading, as it tends to mask the variations evident from place to place. It seems possible that the total average correspondence with the OFB trace elements may therefore be mere coincidence.

Major and trace elements have also been plotted according to Miyashiro (1975) and Miyashiro & Shido (1975), who use the FeO*/MgO ratio (FeO* is total iron as FeO), expressing the degree of fractional crystallization, as abscissa in relation to SiO_2, FeO*, TiO_2, Ni, Cr, and V. In the SiO_2 diagram (Fig. 5a), it is seen that the averages from the five localities lie well below the calc-alkali/tholeiite (CA/TH) line. At low FeO*/MgO ratios (< 2.0), however, the CA/TH line represents no definite boundary between calc-alkali and tholeiitic basalts (Miyashiro 1975: 252).

In the FeO* vs. FeO*/MgO diagram (Fig. 5b), the Skålvær greenstones plot to the left of the drawn CA/TH divide and within the field of abyssal tholeiites. The locality averages (and individual analyses, not plotted) seem to indicate a variation trend similar to that of the abyssal tholeiites.

TiO_2 and V are plotted on a logarithmic scale against FeO*/MgO (Fig. 5c) following Miyashiro & Shido (1975) and again the locality averages fall within the indicated fields for abyssal tholeiites.

Cr and Ni have also been plotted against FeO*/MgO (Fig. 5d). With Cr all the points are within the abyssal tholeiite field, whereas the Ni plot shows four of the averages to the left of the lower part of this field. The fifth Ni average is within the lower part of the same field. In this diagram it can be seen that there is an overlap
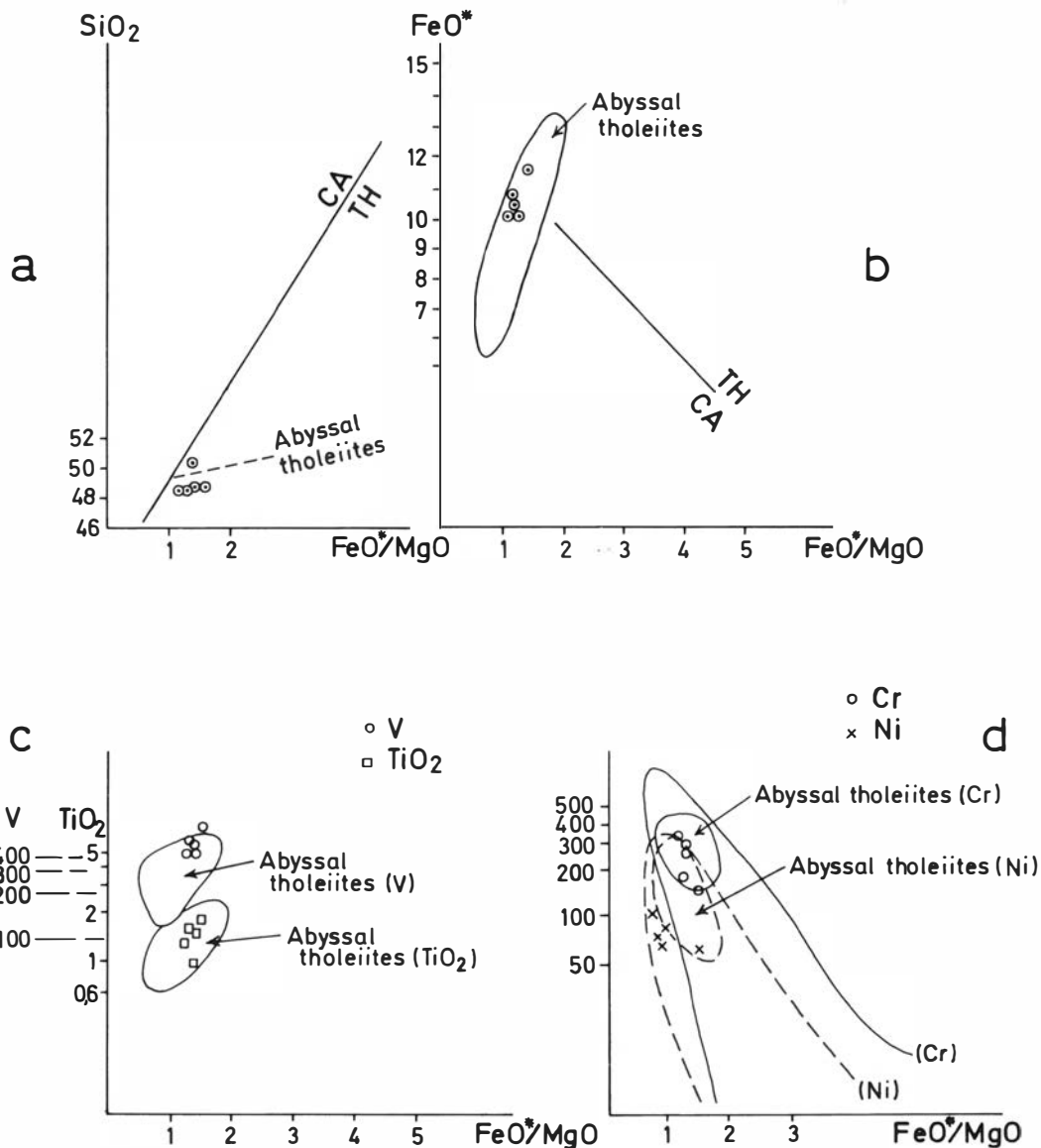
Fig. 5. Locality averages plotted in diagrams according to Miyashiro (1975) and Miyashiro & Shido (1975).

between the fields of abyssal tholeiites and the much larger fields for 'volcanic rocks of island arcs and continental margins'.

Following Miyashiro's (1975) definition, abyssal tholeiites are tholeiites of mid-oceanic ridges with low K_2O contents, generally below 0.4%. Such low K_2O contents are also a feature of the analysed specimens of the Skålvær greenstone with an average of 0.17%. Taking into consideration the possibility that metamorphic processes

may have altered the alkali contents to some degree, not too much stress should be laid on these low K_2O figures. For classification purposes it should be remembered that low K_2O contents also occur in basalts of tectonic environments other than those of mid-oceanic ridges. The Skålvær greenstone has FeO^*/MgO ratios between 1.20 and 1.55. These are typical values for abyssal tholeiites which generally have FeO^*/MgO below 1.70.

Table 6. Differences in chemical composition between two parts of the Grundværsnavaren greenstone.

	Specimens G1–G4	Specimens G5–G7	Average Skålvær greenstones
	(range)	(range)	
Zr	112–120	26–32	96
Y	36–44	14–18	34
Sr	42–62	131–188	141
Zn	105–124	59–66	103
Ni	44–52	107–112	76
Cr	121–139	411–458	248
FeO*	11.1–12.7	7.5–8.0	10.4
MgO	7.7–7.85	7.5–7.9	7.95
TiO$_2$	0.94–1.79	0.64–0.68	1.45

* Total iron as FeO

Discussion

Any conclusion about magma type drawn from the chemistry of metamorphosed basaltic rocks must be based on one of two assumptions; namely, that important secondary changes in composition did not occur, or that secondary alteration did take place and that the amount and character of such changes are known to a sufficient degree. In other words, what are primary and what are secondary chemical features? In recent literature this problem has not always received the serious discussion it deserves, but an increasing number of papers have been concerned with these questions for basalts of different metamorphic grade, especially basalts altered at low grade (zeolite facies to low greenschist facies) (e.g. Jolly & Smith 1972, Vallance 1974, Smith & Smith 1976).

That some redistribution of material has occurred in the Skålvær greenstone during metamorphism is indicated by veining and small concentrations of epidote minerals, but such features are considered to be relatively unimportant. It can be seen from Tables 1, 2, and 3 that variations in the major element compositions are small, particularly in the alkalies, which are important in this connection. Exceptions to this are seen in specimens no. Ø4, O2, and to some degree Ø6, which are rocks of relatively high epidote content, resulting in low alkali and SiO$_2$ contents and high CaO. The generally low Fe$_2$O$_3$ contents also indicate that weathering has not changed the compositions to any great extent.

All G specimens (Table 3) show relatively high Na$_2$O and SiO$_2$. This may be explained by relatively high modal contents of plagioclase in the analysed specimens. Petrographic studies show albite to be generally more abundant than in most other specimens. TiO$_2$ is low in the G specimens except in G4; this is probably a primary feature as TiO$_2$ is considered to be relatively immobile during metamorphism.

The trace element content variation from specimen to specimen calls for some further comments. As deviations from the majority of analyses are most pronounced in specimens G1 to G7, it is of interest to examine these a little closer. Table 6 and Fig. 4 show that the analyses from this locality fall into two groups, one comprising samples G1 to G4 and the other G5 to G7. It was noted earlier that the samples G1–G4 were taken from the massive greenstone with fragments while G5–G7 were taken from large pillows, and it may be recalled that this locality is the one with the most well-developed pillow structures. In G1–G4 Sr, Ni and Cr are considerably lower than the average, while Zr, Y, and Zn are about the average or slightly higher. G5–G7 show Zr, Y, and Zn contents far below the average value, while Ni and especially Cr are much higher than the average. These relations can probably be best explained by assuming different degrees of fractionation in G1–G4 and in G5–G7. An abundance of olivine would reduce the contents of Ti, Zr, Y, Sr, and Nb (Pearce & Cann 1973; 296) and increase Ni, Cr, and Mg. High primary contents of olivine could therefore help to explain the special trace element features of G5–G7, the pillow specimens (Considerable Ol is present in the CIPW norm of specimens G5–G7). As MgO content is about average while FeO is low in these analyses (Table 6), it is necessary to assume that high olivine contents were combined with relatively high plagioclase contents at the expense of clinopyroxenes. G1–G4 clearly represent a more advanced stage of differentiation. This is seen from the much higher FeO/MgO ratio, and the low Ni and Cr may indicate that primary olivine was absent in these specimens.

This discussion tends to show that most of the deviating chemical features of the Grundværsnavaren section can be explained by primary inhomogeneous chemical and mineral distribution within the locality and not to secondary alterations. Although Sr is here close to the average figure, the content of this element varies considerably throughout the whole area. Despite the relatively small range of CaO variation, a plot of Sr versus CaO reveals considerable scat-

ter. This random-looking variation must probably be explained by secondary processes. The variation trend in Fig. 4b is of the same type as that shown by Smith & Smith (1976), signifying the effects of low-grade alteration of basalt.

Chemical variations of the range and character present in the Skålvær greenstone are not unknown in fresh basalts from the Atlantic ocean-floor (e.g. Frey et al. 1974), but admittedly these recent basalt samples are in most cases from widely separated localities. The variations found within the Grundværsnavaren locality, thought to be of primary magmatic origin, may perhaps be explained by assuming the presence of two or more different lava flows. This is to some degree supported by the differences in the development of pillows or their absence, in the two parts of the section. However, there is no sharp boundary between the two types. Another objection is seen in the relatively constant values for Na_2O, SiO_2, and TiO_2 throughout the Grundværsnavaren section regardless of lava type.

From the foregoing comparison, and especially the calculations and plotting of major element discriminants according to Pearce (1976), it may be concluded that the Skålvær greenstone would appear to be a tholeiitic basalt of ocean-floor type. Plotting in Ti-Zr-Sr and Ti-Zr-Y diagrams generally points in the same direction, while classifications according to the principles described by Miyashiro (1975) and Miyashiro & Shido (1975) indicate that the greenstone belongs to the abyssal tholeiites of mid-oceanic ridges. The formation of tholeiitic basalts in other geotectonic environments is also possible, however. Recent investigations are showing that basalts from marginal seas behind island arcs have geochemical characteristics similar to those of abyssal tholeiites (Hart et al. 1972, Sclater et al. 1972, Pearce & Cann 1973). Geophysical and geochemical data indicate that such marginal or back-arc basins in the western Pacific have formed by crustal extension and dilation (Karig 1970, 1971). Similar tholeiitic magmas may also form in island arcs at the very earliest stages of arc development (Jakes & Gill 1970, Ringwood 1974). Based on chemistry alone, therefore, it cannot be decided whether the Skålvær greenstone has been formed in a mid-oceanic ridge, an incipient island arc, or within a marginal basin in an arc system. To solve this problem it is necessary to consider several criteria, especially the following:

Sedimentary characteristics of the area,

The character of igneous rocks in adjoining and more distant areas,

Regional stratigraphy and structural relations.

At the present state of knowledge of the Helgeland area it is premature to discuss these topics in any detail, but it is pertinent here to consider certain aspects of the regional geology and suggest the most likely geotectonic setting for the lavas.

A geotectonic model of the Caledonides of Helgeland

Although the boundary between the greenstone and the metasediments is exposed only in the northern part of the Skålvær area, it can be safely stated that there is no tectonic break between these units, and that the sedimentary sequence can thus be regarded as lying stratigraphically on top of the volcanic horizon. The sediment which lies directly above the greenstone is a dark, fine-grained, dolomitic crystalline limestone. This dolomitic rock as well as a bituminous mica schist higher up in the sequence, is suggestive of deposition in a basin with restricted circulation and ventilation. Between these two formations are calcareous metagreywackes with gradations into conglomerate, indicating relatively shallow-water conditions for these rocks and probably also for the underlying dolomitic limestone and the overlying pelite. A calcite marble in the eastern part of the area, which is considered to link up with the dolomitic limestone (Gustavson 1975), has been interpreted as deriving from calc-arenites. These sedimentary characteristics all seem to point to deposition in a relatively shallow basin where circulation was restricted, at least temporarily. This conclusion is hard to reconcile with deposition in the vicinity of a mid-oceanic ridge. On the other hand, as the amount of volcanic material in the metasediments is minimal, deposition obviously did not occur in the central parts of an island arc. The sedimentary characteristics of the area therefore seem to be best explained by assuming an origin for the greenstone and sediments within a marginal basin at some distance behind an island arc.

The scarcity of volcanics in the sequences of adjoining areas is another objection against formation within an island arc. It is not known what lies below the Skålvær greenstone, but it seems improbable that the greenstone could constitute the uppermost part of a thick and extensive vol-
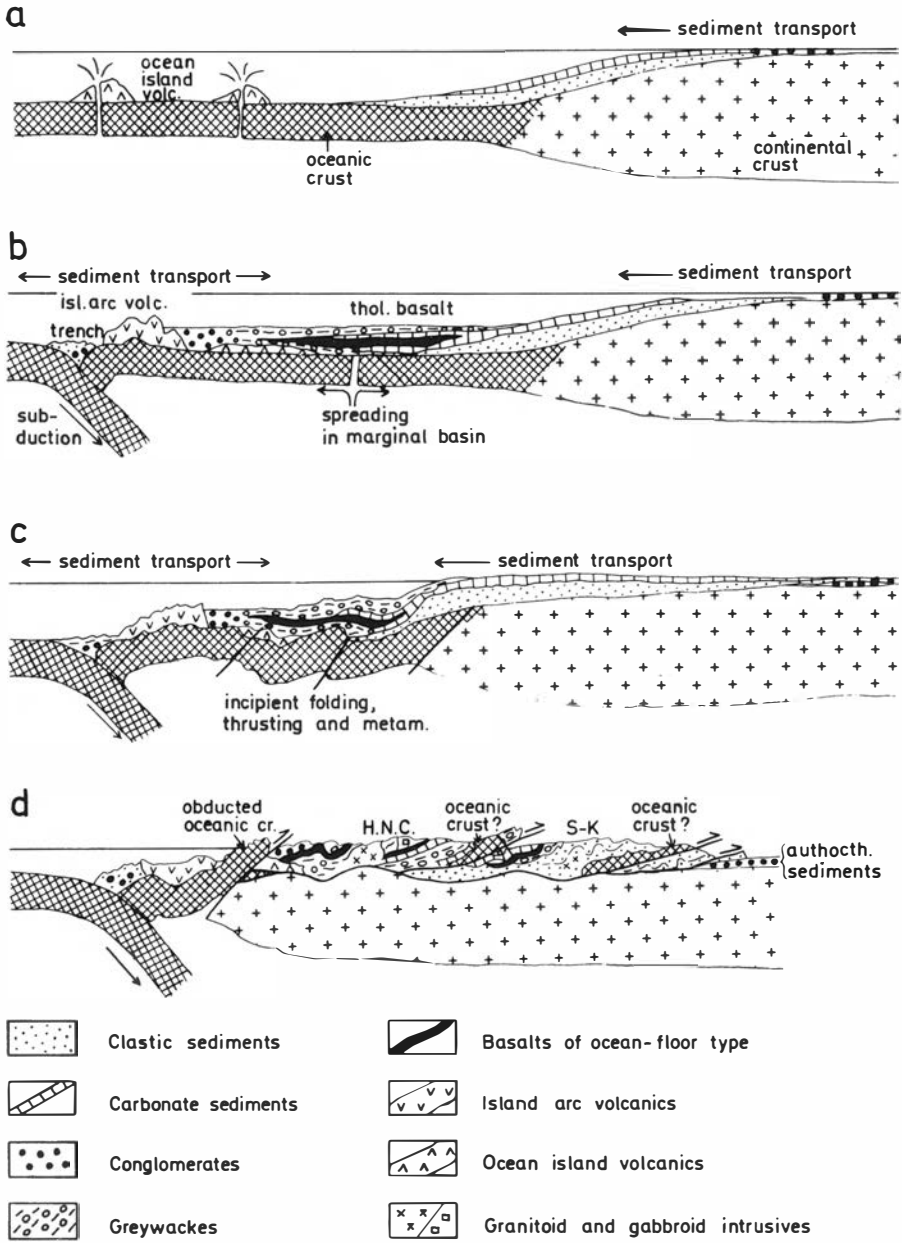
Fig. 6. Main stages in the geotectonic development of the Helgeland area.

a) Sedimentation in the boundary zone between continental and oceanic crust with deposition of terrigeneous material derived from eastern areas. Carbonate sedimentation in periods with limited supply of clastic debris. This sedimentation may have started in Late Precambrian time coeval with the initial rifting stage of the ocean, continuing into the Cambrian and Ordovician periods. Eruptions of ocean-island basalts may have occurred in western areas.

b) Subduction and formation of island arc volcanics. (This point is hypothetical as island arc volcanics have not been safely identified from the present area; see, however, the text on the Skei volcanics p. 173.) Ordovician to (?) Lower Silurian time. Spreading in back-arc basin with eruption of tholeiitic basalt of ocean-floor type (Skålvær greenstone). Sediments supplied both from eastern areas and probably as volcanic debris from an island arc to the west, in a basin of restricted circulation. Hypothetical trench sedimentation is also indicated.

c) Incipient folding, thrusting, and metamorphism in Silurian time of sedimentary and volcanic sequences. Sedimentation continuing, partly with erosion of early deposits.

canic pile. As already noted, tholeiitic basalts of ocean-floor type in an island arc tend to occur in the earliest extruded, lower parts of the volcanic sequence, being replaced at later stages by volcanics of calc-alkaline type.

Basaltic volcanic rocks have been described from the Leka area, some 90 km to the south (Prestvik 1972, 1974). In this area two distinctly different greenstone formations, the Storøya greenstone and the Skei greenstone, are present. Some acid volcanics (quartz keratophyres) are associated with the Skei metabasalt. Based on lithological similarities of the metasedimentary sequence above the uppermost greenstone (Skei) and that of the Skålvær area the present author (Gustavson 1975) proposed a correlation of the Skei and Skålvær greenstone. It must be admitted now that this correlation finds little support in the geochemistry of the volcanic rocks; as seen from Fig. 3a and 3b the Skei greenstones plot in the LKT + CAB and LKT fields, respectively, in contrast with plots of the Skålvær greenstone averages in the OFB fields. According to Prestvik (1974) the Skei greenstones have several chemical characteristics in common with island arc calc-alkaline rocks. Recent investigations of the REE, however, also indicate similarities with tholeiitic basalt types, OFB or LKT (T. Prestvik, pers. comm. 1977). This is in accordance with the plots in the LKT fields of the Pearce diagrams (Fig. 3a, b). Chemical composition together with sedimentary characteristics of the overlying sequence, therefore, may be indicative of an origin for the Skei greenstone in a marginal basin or in an island arc. The lower greenstone horizon, the Storøya greenstone (Prestvik 1974), has a composition typical of hawaiitic within-plate basalts, and is separated from the Skei greenstone by a sequence of shallow-water metasediments. The Storøya volcanics were possibly formed in oceanic islands at considerable distance from an island arc and before the initiation of arc volcanism. If the process of back-arc spreading led to the eruption of the Skei and the Skålvær greenstone, then the Storøya greenstone may originate from volcanic islands within this basin previous to the back-arc spreading.

Later folding and thrusting have greatly obscured primary relationships between various rock complexes of south Helgeland. Obduction of oceanic crust onto the southeastern continental margin of the Proto-Atlantic or Lapetus Ocean has been inferred from regional geochemical and structural patterns in south-central Norway by Gale & Roberts (1974), and this is also thought to be a likely explanation for the interrelations between the alpine-type mafic and ultramafic complex of Leka and the associated metavolcanic/metasedimentary rocks (Prestvik 1974). The results of the present investigation are also consistent with such an interpretation. This implies location of a subduction zone somewhere to the west of the boundary between continental and oceanic crust (Fig. 6). The Skålvær metabasalt and associated metasediments were deposited to the east of this subduction zone, but probably well within the oceanic part of the southeastern plate. Stratigraphical successions of the major nappe complexes of south Helgeland, the Helgeland Nappe Complex, and the Seve-Köli Nappe Complex, were probably also to a great extent deposited above oceanic crust. Their folding and final thrusting onto the continental crust margin occurred in Silurian time (Fig. 6). In some respects the history of the area also shows similarities to that described by Furnes et al. (1976) from parts of western Norway where sedimentary sequences and an Ordovician island arc complex, including early tholeiitic volcanicity, were formed upon oceanic crust above an eastward-dipping subduction zone. Later tholeiites of probable back-arc spreading origin are also reported from this district.

The main stages in the suggested development of the present area are shown in a simplified way in Fig. 6 a–d.

Conclusions

Variations in the major and trace element geochemistry of the Skålvær greenstone can mostly be ascribed to magmatic fractionation processes. Variations in the Sr contents, however, are probably due to secondary processes. Secondary alteration and local epidote veining has also re-

d) Continued compression and thrusting (Silurian and (?) Lower Devonian) of nappes (H.N.C. = Helgeland Nappe Complex, S–K = Seve Köli Nappe Complex) above eastern autochthon and continental crust. Metamorphism and intrusion of anatectic granitoids and some gabbros. The presence of oceanic crust within the nappe complexes is still hypothetical, but mafic and ultramafic bodies in the Seve-Köli and Helgeland Nappe Complexes may possibly originate from oceanic crust slices. In western areas obducted oceanic crust may be taken to represent the Leka alpine-type mafic and ultramafic rock complex.

sulted in variations in the contents of CaO, Na_2O, and SiO_2.

The major and trace element compositions show the greenstone to be of ocean-floor basalt type, and plotting according to principles described by Miyashiro (1975) points to strong similarities with abyssal tholeiites.

Consideration of the greenstone geochemistry and sedimentary characteristics of the area together with regional comparisons have led to the conclusion that the Skålvær greenstone was most probably formed in a marginal basin behind an island arc. Based on these preliminary results a geotectonic model for the area has been proposed (Fig. 6).

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