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Original paper

Preservation of magmatic signals in metavolcanics from Wedel Jarlsberg Land, SW Svalbard

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Abstract. The purpose of this study is to determine the role of metamorphism and thereby identify the preserved magmatic signature in metavolcanics from Wedel Jarlsberg Land in southwestern Svalbard. Samples have been collected from late Precambrian metavolcanics occurring within metasedimentary rocks of the Sofiebogen Group, as well as dikes cutting older metasedimentary rocks of the Deilegga Group. The volcanic rocks were metamorphosed under greenschist facies conditions during the Caledonian Orogeny. To investigate the role of metamorphism, we present petrography, major and trace element geochemistry, and use factor analysis as a tool to identify correlations that correspond to primary magmatic signals.

The metavolcanics are classified as subalkaline basalt to basaltic andesite and they contain relicts of primary clinopyroxene and plagioclase. The metamorphic minerals are actinolite, secondary plagioclase, chlorite and minerals belonging to the epidote group. Major element variations are highly scattered with no obvious trends observed. The HFSE and REE show strong trends attributed to fractional crystallization. The LILE, Th and La show elevated contents in some samples.

Factor analysis shows that the HFSE and REE are well correlated. The LILE form a separate well correlated group, while the major elements are not correlated, except for Na_2O, Fe_2O_3 and CaO. The lack of correlation for major elements, as well as the lack of observed fractional crystallization trends between these elements suggests that they were modified by metamorphism. The strong correlation of HFSE and REE reflects the original geochemical signal generated by magmatic processes. The correlation of the LILE is consistent with their elevated composition implying the influence of crustal contamination processes, and though some variability is likely superimposed due to metamorphism, the primary magmatic record is not completely destroyed. We conclude that the HFSE and REE are not influenced by metamorphic processes and therefore provide robust records of magmatic processes.

Key-words: Neoproterozic, Svalbard, metavolcanics, Factor Analysis

1. Introduction

The focus of this research is to distinguish the role of metamorphism from the magmatic processes involved in Late Neoproterozoic metavolcanics from Wedel Jarlsberg Land in southwestern Svalbard. These volcanics were metamorphosed during the Caledonian Orogeny under greenschist facies conditions, but still preserve their magmatic signatures. The aim of this study is to trace which elements were affected by metamorphism. The LILE are sensitive and mobile elements, hence metamorphism is expected to influence their composition. The continental crust is also enriched in LILE, relative enrichment might be explained by crustal contamination. To investigate the role of metamorphism, we use petrography, major and trace element geochemistry, preliminary isotope geochemistry and factor analysis to distinguish undisturbed magmatic signals from metamorphic changes.

2. Geological background

The Svalbard Archipelago, situated in the Barents Sea, north of Norway, is divided into Eastern, Northwestern and Southwestern basement provinces which differ from each other in age, metamorphic grade and lithology (Gee 1986; Gee, Page 1994; Gee, Tebenkov 2004), and are separated by major N-S trending transcurrent faulting (Fig. 1).

The main lithologies of the Southwestern Province are metasediments of the Deilegga and Sofiebogen groups. The northern part of this terrane is built of "exotic" rocks metamorphosed under blueschist to eclogite facies conditions (Otha 1979), named the Vestgötabreen Complex (Bernard-Griffiths et al. 1993). This exotic block is thrust on top of conglomerates and limestones of Ordovician age (Armstrong et al. 1986) and Silurian turbidites (Scrutton et al. 1976). Dallmeyer et al. (1990) determined an $^{40}Ar/^{39}Ar$ cooling age of 470 Ma for the Vestgötabreen Complex. In the southern part, Mesozoic and Neoproterozoic metamorphic basement of the Isbjørnhamna, Eimfjellet and Deilegga groups occur (Birkenmajer 1991). The latter is unconformably overlain by the Sofiebogen Group. The Deilegga and Sofiebogen groups are covered by Ediacaran tillites, known as the Kapp Lyell Formation (Bjørnerud 1990; Dallman et al. 1990; Harland et al. 1993). In Wedel Jarlsberg Land, high grade and low grade metamorphic rocks are juxtaposed by a sinistral strike-slip zone with WNW-ESE trend (Fig. 2), called the Vimsodden-Kosibapasset zone (VK zone) of Caledonian age (Czerny et al. 1993; Mazur et al. 2009). Higher grade amphibolite facies rocks outcrop in the southwestern part of Wedel Jarlsberg Land, while the northern part is metamorphosed only to greenschist facies.

The area south of the VK zone is built of thick sequences of metasediments (the Isbjørnhamna Group), metamorphosed under amphibolite facies conditions (Majka et al. 2010). This sequence is tectonically overthrust by the Eimfjellet Group, which is a complex of metamorphosed gabbros, granites and sandstones cut by mafic dikes (Larionov et al.

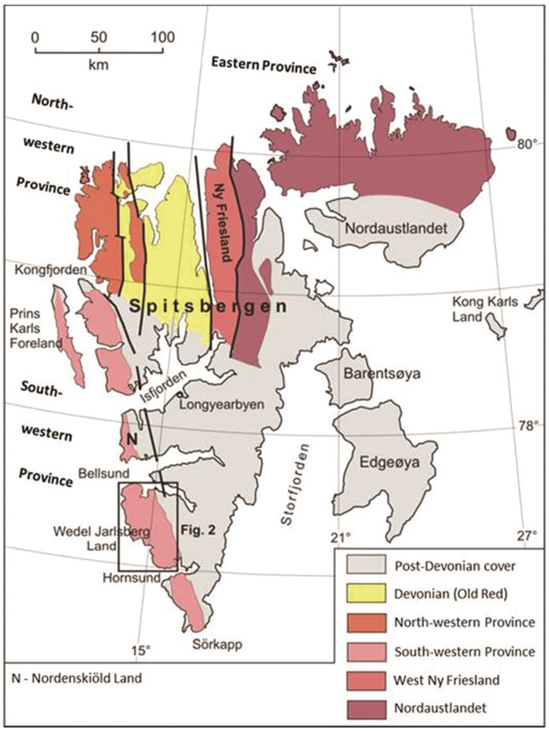

Fig. 1. Geological map of the Svalbard Archipelago (modified after Gee, Tebenkov 2004).

2010). Mafic and felsic tuff intercalations occur locally within these rocks. The age of the protoliths of the gabbros, granites and rhyolitic tuffs have been determined as 1.22-1.20 Ga (Balashov et al. 1995, 1996; Larionov et al. 2010). The geochemical character of these metaigneous rocks indicates a common origin associated with intracontinental rifting (Czerny 1999). All metasedimentary and metaigneous rocks from the Isbjørnhamna and Eimfjellet groups were metamorphosed in the late Neoproterozoic, as is confirmed by U-Th-total Pb dating of monazite (643±9 Ma; Majka et al. 2008) and $^{40}Ar/^{39}Ar$ dating of hornblende (ca 616 Ma; Manecki et al. 1998), respectively.

The area north of the VK zone, where samples for this study were collected, is dominated by thick sequences of the Deilegga- and Sofiebogen groups which are separated by a regional unconformity, the so-called Torellian Unconformity. The age of this unconformity is considered to be late Neoproterozoic, and post-dates the main metamorphic event in the southern tectonic block (Czerny et al. 2010). Both groups contain quartzites, phyllites and marbles. The Slyngfjellet metaconglomerate is a characteristic horizon, which separates the groups. Rocks of the Deilegga and Sofiebogen groups occur in northern Wedel Jarlsberg Land and extend to the Nordenskiøld Land, Oscar II Land and Prins Karls Forland. Samples for this research were collected from metalavas and metatuffs of the Sofiebogen Group and from dikes of metabasalt cutting metasedimentary rocks of the Deilegga Group. The term Jens Erikfjellet Formation, which is used throughout, is an informal name for metavolcanics belonging to the Sofiebogen Group and to the Deilegga

Group (Czerny 1999). Small amounts occur in the Slyngfjellet, Höferpynten and Elveflya formations and a thick sequence belongs to the Jens Erikfjellet Formation (all formations belong to the Sofiebogen Group).

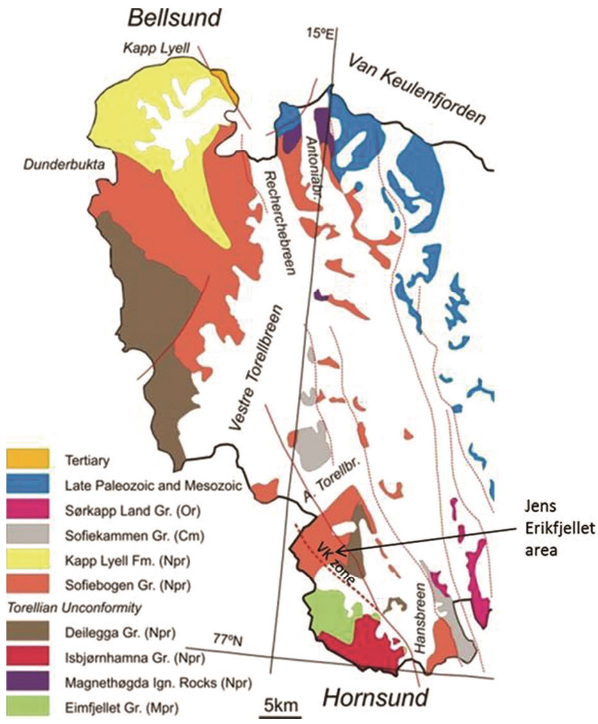

Fig. 2. Geological map of Wedel Jarlsberg Land (modified after Majka et al. 2012).

3. Analytical methods

16 samples of greenstones were collected during geological expeditions to Wedel Jarlsberg Land in 1985, 1986, 1988 (Czerny 1999). Samples were collected from three members of the Jens Erikfjellet Formation: Rundingen, Tonefjellbreen and Vimsa. In addition, samples were collected from the Slyngfjellet Formation (the Sofiebogen Group) and from dikes belonging to the Deilegga Group (Czerny 1999).

The analytical methods have been completely described by Czerny (1999). Briefly, the major elements were analyzed by X-ray fluorescence analysis (XRF) at the University of Oslo. Trace elements were determined using XRF (Ba, Rb, Sr, Zr, Nb, Y, Ga), neutron activation analysis (Co, Cr, Sc, Cs, Hf, Ta, Th, U, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Ag, Au, Sb, Cd, Mo) and atomic absorption spectroscopy (Mn, Ni, Zn, Cu, Ti). The results are presented in Table 1.

TABLE 1

Major (wt% oxide) and trace element abundances (ppm) of samples from the Jens Erikfjellet Formation.

Sample	Position in the lithostratigraphic profile	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
24/86C	Rundingen Mb	51.56	1.21	16.80	5.96	5.77	0.11	4.80	2.06	6.10	1.18	0.21	2.40	98.16
115/86A	Rundingen Mb	50.49	1.36	15.19	1.62	6.86	0.13	5.59	5.50	4.22	0.64	0.20	6.89	98.69
113/86A	Tonefjellbreen Mb	49.36	1.76	14.75	2.67	7.57	0.16	6.27	6.71	4.50	0.16	0.23	4.15	98.29
68/85A	Tonefjellbreen Mb	46.63	1.82	15.52	3.20	7.92	0.18	8.18	6.78	3.18	0.85	0.28	4.71	99.25
14/86A	Tonefjellbreen Mb	47.48	1.53	14.34	1.94	7.19	0.19	5.58	9.23	3.95	0.68	0.23	6.47	98.81
164/86C	Vimsa Mb	50.00	1.12	19.52	2.38	5.75	0.08	4.86	7.33	4.77	0.17	0.18	3.18	99.34
148/86C	Vimsa Mb	50.37	0.98	19.56	1.10	5.03	0.09	5.44	9.22	3.08	1.51	0.15	2.77	99.30
21/86A	Vimsa Mb	49.53	1.92	16.24	4.95	4.61	0.13	6.20	5.21	4.84	1.29	0.28	2.96	98.16
164/86A	Vimsa Mb	50.86	1.97	14.40	3.20	7.93	0.12	6.37	7.6	3.81	0.18	0.29	2.95	99.68
109/86A	Vimsa Mb	49.03	2.04	15.45	3.42	6.50	0.16	8.58	4.36	4.71	0.24	0.31	3.95	98.75
156/86B	Vimsa Mb	54.66	1.48	13.37	4.89	5.06	0.09	5.38	6.86	5.29	0.17	0.15	1.52	98.92
3/88A	Vimsa Mb	48.90	1.36	19.78	3.90	3.6	0.06	5.72	2.96	5.80	0.74	0.21	5.30	98.33
23/88A	Vimsa Mb	44.86	0.94	18.52	4.12	2.16	0.07	3.11	9.13	5.00	1.42	0.19	7.83	97.35
126/85	dike within Deilegga G	47.99	1.87	13.20	0.76	9.36	0.18	4.51	8.24	3.19	0.05	0.32	8.21	97.88
119/86	Slyngfjellet Fm.	41.16	3.45	13.03	2.54	12.25	0.17	4.53	8.01	2.23	<0.01	0.61	10.29	98.28
118/86A	Slyngfjellet Fm.	45.24	3.07	12.36	2.51	10.12	0.21	3.88	8.23	3.13	0.08	0.54	8.95	98.32

Sample	Position in the lithostratigraphic profile	Mn	Ni	Co	Cr	Sc	Ga	Zn	Cu	Cs	Rb	Ba	Sr	Zr	Nb
24/86C	Rundingen Mb	773.0	83.0	38.8	75.0	16.8	24.0	70.0	28.0	2.02	28.0	376.0	226.0	182.0	13.0
115/86A	Rundingen Mb	1083.0	79.0	33.0	120.0	24.9	16.0	70.0	48.0	2.13	28.0	443.0	167.0	206.0	15.0
113/86A	Tonefjellbreen Mb	1226.0	70.0	40.6	123.0	28.0	15.0	103.0	39.0	0.26	14.0	178.0	226.0	137.0	10.0
68/85A	Tonefjellbreen Mb	1397.0	78.0	46.9	123.0	43.1	15.0	83.0	59.0	0.37	35.0	236.0	242.0	131.0	12.0
14/86A	Tonefjellbreen Mb	1455.0	87.0	38.5	95.0	42.8	15.0	73.0	59.0	1.83	36.0	212.0	235.0	128.0	8.0
164/86C	Vimsa Mb	722.0	64.0	33.4	161.0	27.7	12.0	57.0	24.0	<0.22	15.0	169.0	322.0	100.0	8.0
148/86C	Vimsa Mb	830.0	60.0	26.3	123.0	29.3	12.0	51.0	25.0	0.45	35.0	1183.0	358.0	92.0	5.0
21/86A	Vimsa Mb	991.0	71.0	55.9	56.0	41.6	20.0	115.0	34.0	0.91	29.0	403.0	237.0	156.0	11.0
164/86A	Vimsa Mb	1010.0	62.0	45.7	33.9	37.9	12.0	105.0	120.0	<0.3	13.0	138.0	141.0	146.0	10.0
109/86A	Vimsa Mb	1183.0	52.0	48.0	20.2	32.7	18.0	114.0	356.0	0.72	14.0	159.0	49.0	159.0	14.0
156/86B	Vimsa Mb	667.0	55.0	25.1	136.0	29.7	11.0	52.0	22.0	<0.15	12.0	122.0	110.0	120.0	10.0
3/88A	Vimsa Mb	567.0	61.0	27.4	126.0	26.9	16.0	73.0	18.0	0.66	28.0	323.0	286.0	121.0	9.0
23/88A	Vimsa Mb	632.0	66.0	29.8	98.0	23.7	14.0	50.0	62.0	0.92	45.0	507.0	367.0	95.0	6.0
126/85	dike within Deilegga G	1408.0	66.0	27.2	74.0	24.4	17.0	79.0	26.0	0.91	17.0	210.0	287.0	190.0	15.0
119/86	Slyngfjellet Fm.	1296.0	45.0	39.9	16.2	33.8	20.0	149.0	25.0	<0.4	13.0	165.0	166.0	211.0	19.0
118/86A	Slyngfjellet Fm.	1647.0	42.0	41.7	12.0	30.7	19.0	101.0	40.0	4.46	15.0	231.0	246.0	229.0	21.0

Sample	Position in the lithostratigraphic profile	Hf	Th	U	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Ta	Y
24/86C	Rundingen Mb	4.7	13.0	n.d.	63.0	84.0	58.0	7.3	1.55	0.9	2.85	0.55	0.66	27.0
115/86A	Rundingen Mb	5.2	15.0	<2.1	25.4	61.0	35.0	7.8	1.21	1.08	2.96	0.46	0.97	28.0
113/86A	Tonefjellbreen Mb	3.18	5.8	n.d.	22.9	43.0	43.0	4.5	1.47	0.68	2.32	0.32	0.53	22.0
68/85A	Tonefjellbreen Mb	2.83	5.0	<5.0	22.3	43.0	29.7	4.7	1.3	0.88	2.22	0.42	0.7	27.0
14/86A	Tonefjellbreen Mb	3.08	7.0	<1.7	27.5	47.0	37.0	5.0	1.51	0.94	2.56	0.42	0.55	25.0
164/86C	Vimsa Mb	2.31	3.9	<1.5	17.6	30.1	19.9	3.5	0.96	0.62	2.06	0.33	0.37	19.0
148/86C	Vimsa Mb	1.89	3.4	<3.0	13.3	27.7	22.1	2.89	0.99	0.5	1.47	0.27	0.43	15.0
21/86A	Vimsa Mb	4.7	6.7	<1.7	24.6	60.0	24.7	4.6	2.14	1.28	3.24	0.39	0.75	32.0
164/86A	Vimsa Mb	3.53	6.5	<1.6	17.7	45.0	<39.0	5.2	1.43	1.17	2.57	0.31	0.58	22.0
109/86A	Vimsa Mb	3.5	6.3	<1.3	33.3	54.0	44.0	4.7	1.6	0.86	2.63	0.5	0.73	29.0
156/86B	Vimsa Mb	2.37	3.8	<1.6	29.1	41.0	22.7	5.8	1.1	0.69	2.09	0.48	0.46	22.0
3/88A	Vimsa Mb	2.39	4.0	<2.9	18.5	41.0	20.0	3.31	1.11	0.68	1.54	0.22	0.42	17.0
23/88A	Vimsa Mb	1.93	3.2	1.81	26.2	39.0	27.1	3.9	1.22	0.62	1.95	0.27	0.38	15.0
126/85	dike within Deilegga G	3.8	8.7	<1.7	36.0	62.0	48.0	6.0	1.43	0.83	2.55	0.43	0.88	28.0
119/86	Slyngfjellet Fm.	5.3	7.8	1.7	41.4	90.0	51.0	11.5	2.49	1.8	3.92	0.49	1.24	33.0
118/86A	Slyngfjellet Fm.	6.6	9.1	<1.7	52.0	95.0	71.0	8.9	2.49	1.41	4.3	0.73	1.47	35.0

Samples for Sr and Nd isotopes were separated and measured in the Isotope Geochemistry Laboratory in the Institute of Geological Sciences Polish Academy of Science, Krakow. Analyses were performed using a Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) Neptune. The samples were digested in three steps: first with HF:HNO_3, secondly with HNO_3 and finally with HCl and HF, following the procedure described by Anczkiewicz et al. (2004) and Anczkiewicz and Thirlwall (2003). The samples were then dissolved in HCl for loading on cation exchange columns with AG50Wx8 resin (Anczkiewicz et al. 2004). Final separation of Sr was performed by Sr-spec resin (Peryt et al. 2010) and Nd by Ln-spec resin (Anczkiewicz, Thirlwall 2003). Nd isotopes were normalized to $^{146}Nd/^{144}Nd$ = 0.7219 to correct for mass bias. Reproducibility of Nd standards over the period of analyses was $^{143}Nd/^{144}Nd$ = 0.512101±8 (2 s.d. n=3). Sr isotopes were normalized to $^{86}Sr/^{88}Sr$ = 0.1194 to correct for mass bias. Reproducibility of Sr standards over the period of analyses was $^{87}Sr/^{86}Sr$ = 0.710261±8 (2 s.d. n=3).

The aim was to test for the influence of metamorphism on the geochemistry and identify the undisturbed magmatic signatures. To achieve this aim, we use Factor Analysis, a statistical method to detect correlations in a data set. Factor Analysis is based on the variance between major and trace elements and similarity between samples (Miller et al. 1962; Davies 1986; Reimann et al. 2002). The data set is represented by 16 samples as observations and 11 elements as variables (Zr, Hf, Th, Nd, La, Na_2O, Fe_2O_3, CaO, Rb, Ba, Sr). In Factor Analysis, the number of variables should be less than the number of samples (Reimann et al. 2002), to provide a high level of confidence. The elements were chosen as representative for REE, HFSE, LILE and major element groups. To run the analysis, a Principal Component method was chosen with a correlation matrix. Based on a scree plot, we decided to extract 3 factors as an optimal solution. We selected Varimax as a factor rotation; this is orthogonal, meaning that rotated factors are not correlated (Reimann et al. 2002). The calculations were done using SPSS software.

4. Results

Field observations of the Jens Erikfjellet Formation reveal the occurrence of metavolcanics in three different members: Rundingen, Tonefjellbreen and Vimsa (Czerny 1999). Metavolcanics of the Rundingen Member, which occurs at the base of the Jens Erikfjellet Formation, are represented mainly by massive lavas and tufogenic rocks. These metabasalts are characterized by distinctive colors: green, bluish and black (from titanomagnetite). They mainly show aphanitic textures, in some cases, fine-porphyritic textures are observed. In the Tonefjellbreene Member mainly massive, green to dark green metabasalts with aphanitic texture occur. The Vimsa Member, occurring at the top of Jens Erikfjellet Formation, is represented by characteristic pale green plagiophyric greenstones and contains lenses of epidotites. The greenstones in this member have lamellae that are enriched in epidote and albite/chlorite. The greenstones in the Slyngfjellet Formation are dark- and grey-green carbonate bearing metabasalts occurring within metaconglomerate. Dark-green and light-green dikes occurring within the Deilegga Group are thin (up to a few meters thick) with mostly aphanitic textures and in some cases, porphyritic textures associated with phenocrysts of plagioclase. All of these rocks are affected by metamorphism under greenschist facies condition and in some, spilitization is observed.

Petrographic observation of the samples reveals that the rocks were metamorphosed under greenschist facies conditions. The metamorphic assemblage is dominated by albite (Czerny 1999) of variable size, in some cases, exceeding 2000 µm (Fig. 3a, b), and which commonly shows polysynthetic twinning and oscillatory zoning. Actinolite, chlorite and epidote also occur, with a greater abundance of epidote in some veins. Some of the samples are rich in carbonates. Rutile, titanite, quartz and opaque minerals occur as accessory minerals. Additionally, the metavolcanics contain relicts of clinopyroxene and primary plagioclase, the latter are commonly affected by sericitization (Fig. 3a) and replacement by clinozoisite. Textures range from aphanitic to porphyritic including plagiophyric, with relicts of plagioclase and large porphyroblasts of secondary plagioclase surrounded by a fine grained groundmass of plagioclase, chlorite, actinolite and epidote. In these same samples clusters of new secondary plagioclase are common. In the metamorphosed tufogenic samples, foliation formed mainly by the alignment of chlorite flakes is evident while, in metamorphosed lavas, granoblastic fabrics are more common.

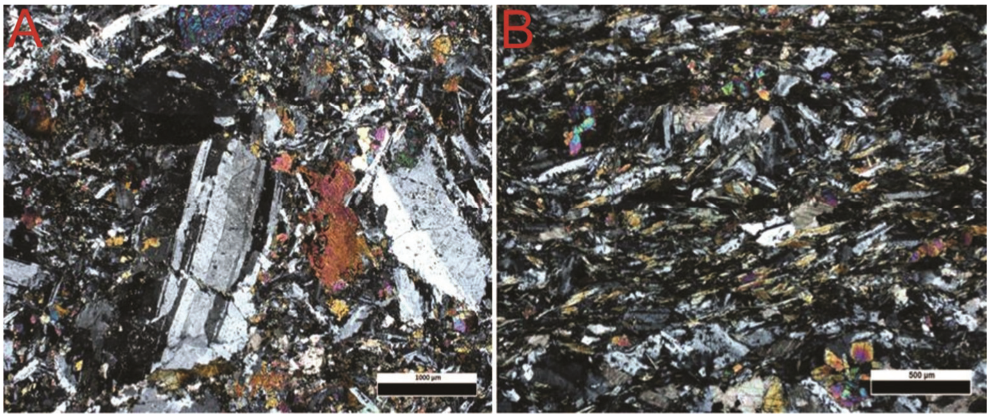

Fig. 3. Metavolcanics of the Jens Erikfjellet Formation metamorphosed under greenschist facies conditions. A – plagioclase affected by sericitization, B – metamorphic assemblage of plagioclase, actinolite, epidote.

The rocks from the Jens Erikfjellet area are classified as tholeiitic subalkaline basalt to basaltic andesite. The major elements show wide compositional ranges and no obvious trends are visible (Fig. 4). The HFSE and REE such as La, Sm, Nd, Nb, and Th show good trends reflecting fractional crystallization. The exceptions are samples from the Rundingen Member, which have elevated Th and La contents (Fig. 5). The LILE are elevated in some rocks, resulting in wide scattered ranges.

Preliminary Sr and Nd isotope data for 3 metavolcanics from the Jens Erikfjellet area reveal $^{143}Nd/^{144}Nd_{(i)}$ values ranging from 0.51217 to 0.51193 and values of $^{87}Sr/^{86}Sr_{(i)}$ from 0.70453 to 0.70990 (Fig. 6).

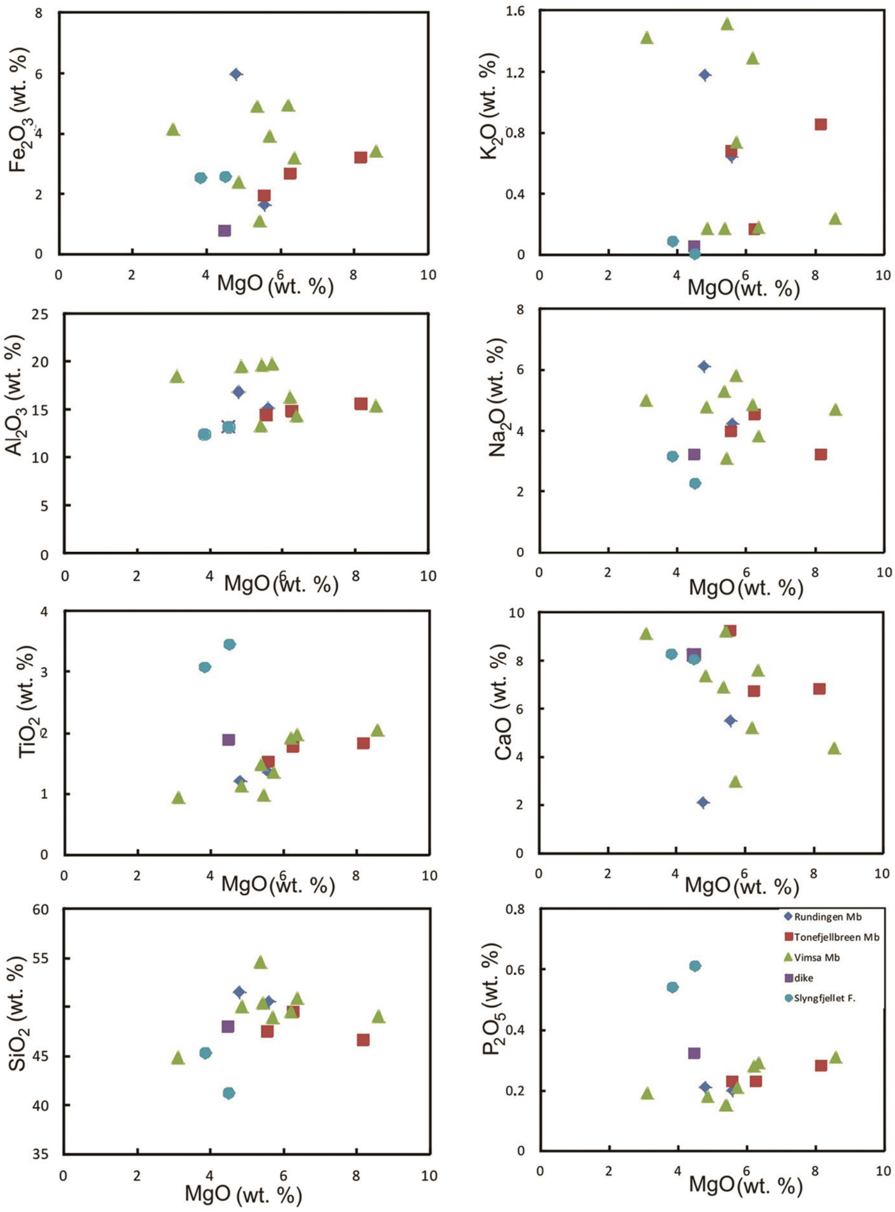

Fig. 4. Diagram of major elements vs. MgO showing wide compositional ranges.

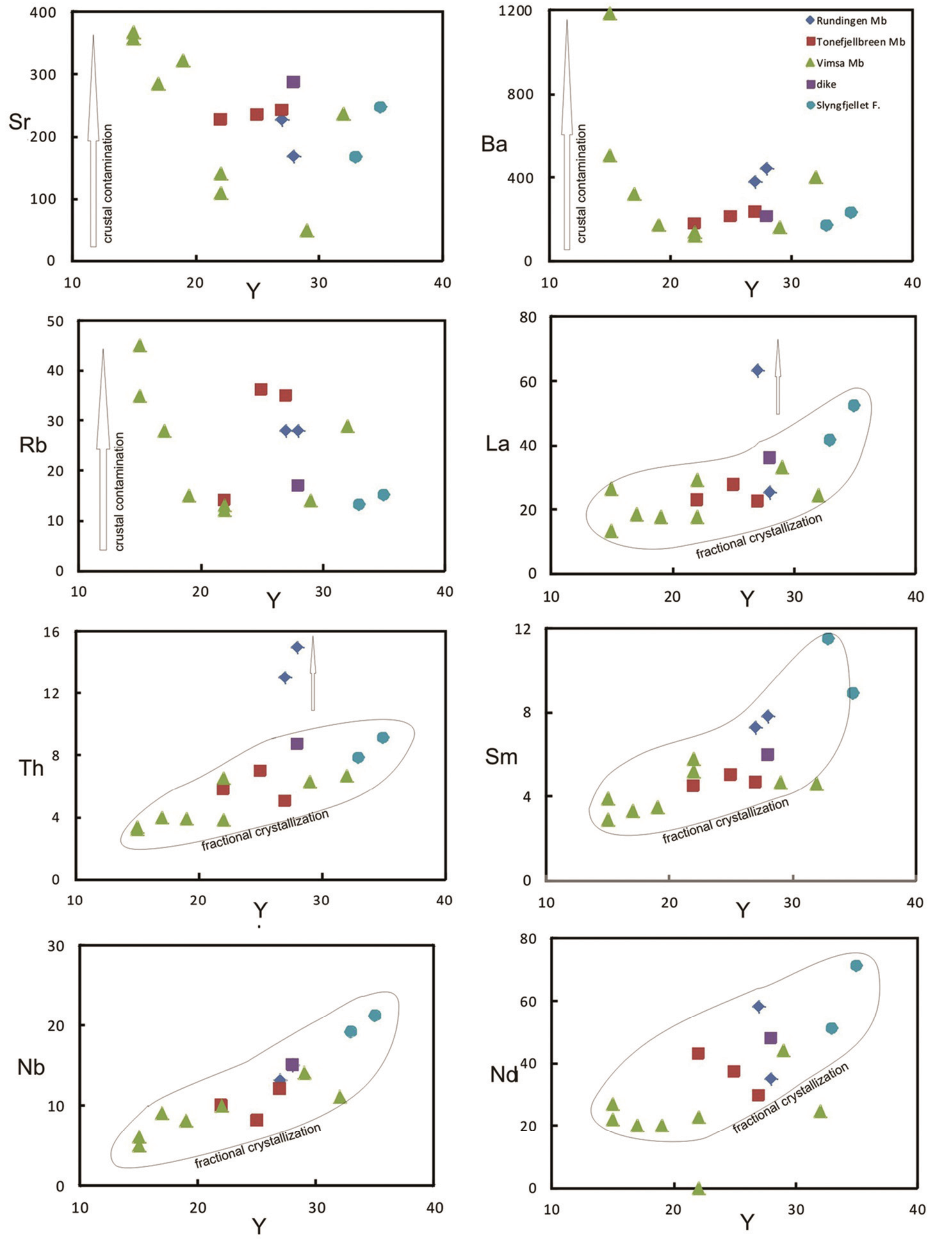

Fig. 5. Th, La, Sm, Nd and Nb vs. Y showing trends attributed to fractional crystallization whereas the LILE have widely scattered ranges and no obvious trends.

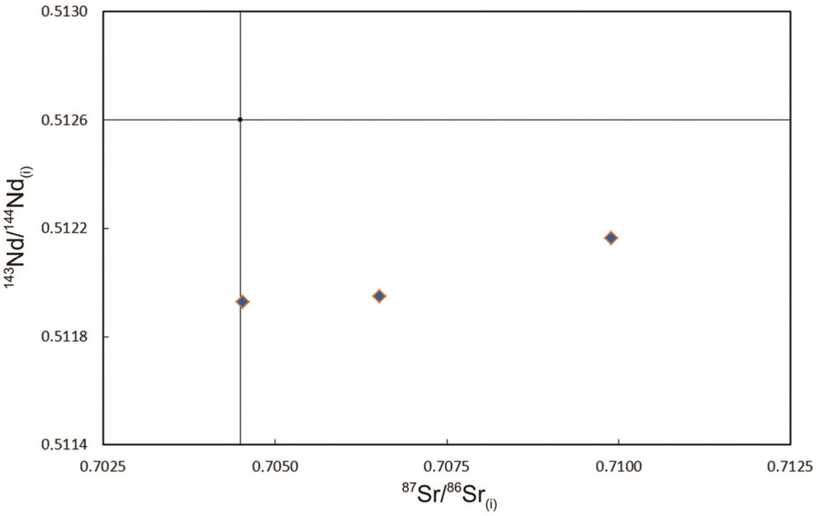

Fig. 6. Nd and Sr isotope data for the Jens Erikfjellet Formation indicate coupled enrichment. Age correction was applied for an initial age 600 Ma.

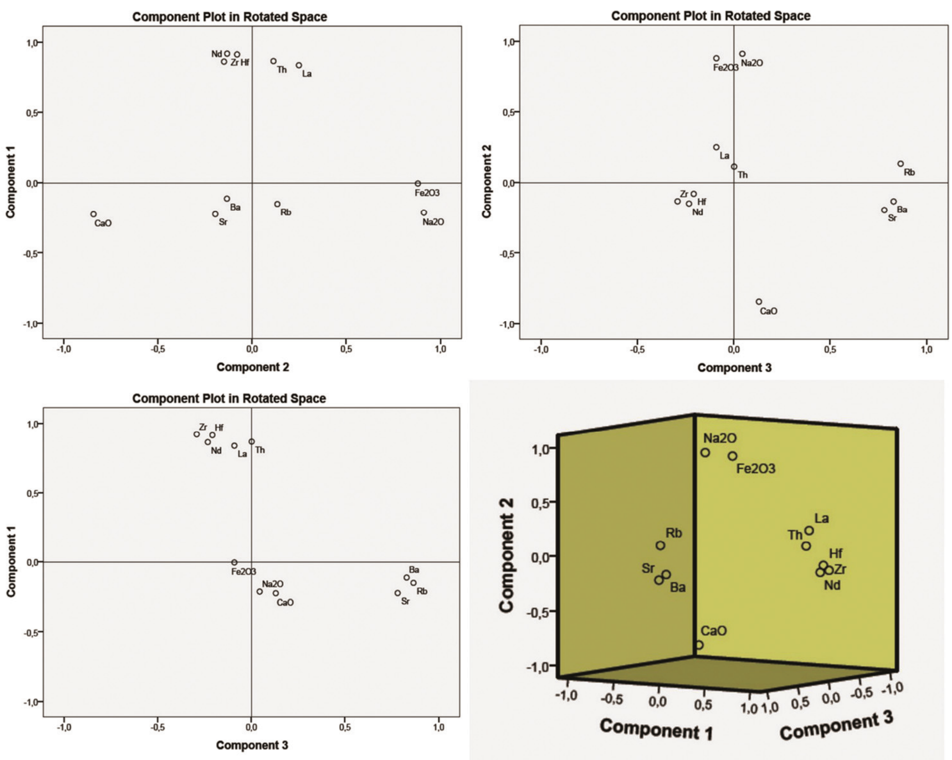

Fig. 7. 2D and 3D diagram shows high positive correlation for HFSE and REE, good positive correlation between LILE and high negative correlation between Na_2O, CaO, Fe_2O_3. 2D diagram shows that components are not correlated with each other.

The resulting Factor Analysis shows three components, which explain 80.3 % of the total variance of the rotation of sums of squared loadings of the data set. The first component, which explains 36.9% of the variance, contains the highly correlated (0.94-0.92) HFSE and REE elements Zr, Hf, Th, Nd and La (Fig. 7; Table 2). The second component, which explains 22.8% of the variance, contains the major elements Na_2O, Fe_2O_3 and CaO (Fig. 7; Table 2) with correlations from -0.843 to 0.91. The third component, explaining 20.6 % of the variance, contains the LILE elements Rb, Ba and Sr (Fig. 7; Table 2); correlations range from 0.781 to 0.866. The elements in components 1 and 3 are positively correlated, those in component 2 both positively and negatively (Table 2). The components are not correlated with each other (Fig. 7).

TABLE 2

Factor analysis shows three components after rotation (Varimax).

Rotated Component Matrix[a]			
	Component		
	1	2	3
Zr	.919		
Hf	.914		
Th	.866		
Nd	.863		
La	.837		
Na_2O		.912	
Fe_2O_3		.881	
CaO		-.843	
Rb			.866
Ba			.829
Sr			.781

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.[a]

a. Rotation converged in 4 iterations.

5. Discussion

Field observation reveals the influence, of both greenschist facies metamorphism and spilitization. In the Vimsa Member, enrichment in epidote and albite/chlorite could be a result of spilitization. The metavolcanics in the Jens Erikfjellet Formation contain albite, actinolite, chlorite and epidote, all characteristic for greenschist facies metamorphism and some samples are enriched in carbonates. These samples still preserve relicts of clinopyroxene and primary plagioclase. How much influence did the metamorphism have on these rocks and which elements were modified by the metamorphic event is the question.

The elements that are highly correlated are considered to be controlled by common processes and the three components that are not correlated with each other were controlled by different processes (Fig. 7). Component 1 in the factor analysis shows a high correlation (Table 2) between REE and HFSE, confirming that variations in the geochemical data show fractional crystallization (Fig. 5) we interpret this to represent the primary magmatic signature. The third component contains only LILE. As these elements are mobile and are enriched in the crust (Rudnick, Gao 2003), their controlling process could have been metamorphic or igneous processes that introduce variations such as crustal contamination. Both of these processes could be responsible for wide ranges such as that of e.g. Ba (Fig. 5). Component 2 is interesting as the negative correlation between Na_2O and CaO implies that the content of Na_2O increased while that of CaO decreased (Table 2).

In contrast, the major elements show wide ranges, and any correlation is very weak to non-existent (Fig. 4), which suggests that yet another process modified them. Two explanations for the LILE and major elements are considered: firstly, that the LILE are altered by metamorphism and secondly, by igneous processes. Chemical changes caused by veining can be excluded as the samples were collected far from veins. If metamorphism was the dominant process influencing the LILE, they might be expected to be correlated with the major elements.

The metamorphic processes

The mineral assemblage (albite, chlorite, epidote, actinolite) and the wide scatter of major elements, notably Fe_2O_3 and MgO, are associated with greenschist facies metamorphism. One possible metamorphic reaction is spilitization where fluids cause albitization of primary plagioclase and the simultaneous release of Ca, which can be incorporated into epidote and calcic amphibole, e.g., actinolite (Skelton et al. 2010; Arghe et al. 2011). Spilitization could also be responsible for changing the LILE (Ba, Rb and Sr), and sometimes the REE (Skelton et al. 2010). The mineral assemblage in the rocks (albite, epidote, chlorite, actinolite and calcite) supports this theory. However, as the REE are highly correlated with the HFSE, they probably remained unchanged by this process. Most of the samples are enriched in Na_2O and depleted in CaO (Fig. 8), indicating that spilitization has occurred. The most affected samples belong to the Vimsa Member where epidotite lenses are to be seen in outcrop. That spilitization occurred is supported by the factor analysis, which show negatively correlated Na_2O and CaO. However, as the LILE and Ca and Na are not correlated, they create two separate components, another explanation is needed to fully explain the variation in LILE.

Crustal contamination

Highly elevated concentrations of some trace elements (e.g. Th and La), and highly variable concentrations of LILE (e.g. Ba; Fig. 5) could have been modified by a process other than metamorphism. These elements (LILE and Th, La) are commonly enriched in continental crust (Rudnick, Gao 2003).

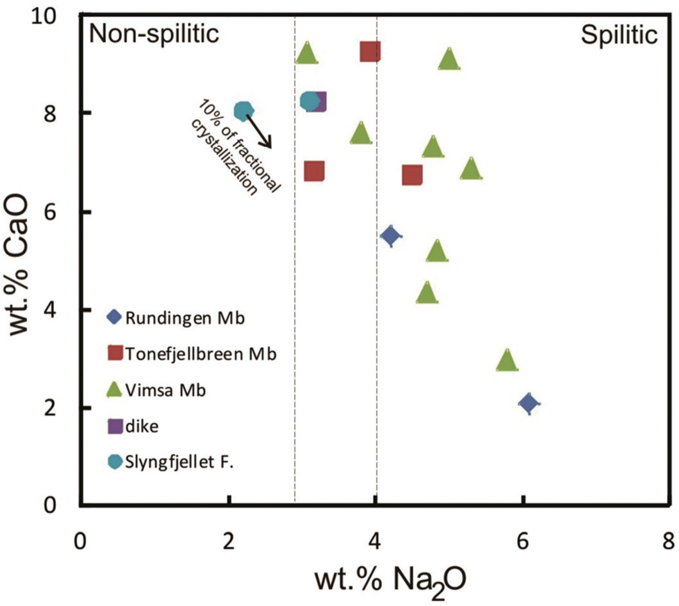

Fig. 8. Diagram of CaO to Na_2O shows spilitization of metavolcanic. The boundary between spilitic and non-spilitic rocks following Skelton et al. (2010) is 3-4 wt% Na_2O. Samples with > 4 wt% Na_2O are strongly spilitic, between 3-4 wt% Na_2O are weakly spilitic and samples with < 3 wt% Na_2O are not spilitic. The vector for 10% fractional crystallization shows that the data trend is consistent with spilitization. Sources for partition coefficients for plagioclase are Higuchi and Nagasawa (1969), for olivine are Leeman and Scheidegger (1977) and for pyroxene are Onuma et al. (1968) and Jones and Layne (1997). Calculation involved Rayleigh fractional crystallization with an assemblage of 40% plagioclase, 40% pyroxene and 20% olivine.

The high contents of elements such as Th, La and LILE, especially for samples from the Rundingen Member and the Slyngfjellet Formation, indicate the influence of continental crust. The samples with elevated Th and La also have elevated LILE, despite the fact that Th and La were unlikely to have been modified by metamorphism. This pattern is interpreted as having been caused by crustal contamination. Additionally, Th/Yb vs. Nb/Yb (Fig.9; Pearce 2008), all samples lie above the MORB – OIB array indicating crustal contamination (Fig. 9). A good indicator of contamination by crust is depletion in Nb (Frey et al, 2002); the samples being discussed here are all characterized by $(La/Nb)_{PM} >> 1$ and $(Th/Nb)_{PM} > 1.2$ (Fig. 10), therefore crustal contamination is indicated.

Furthermore, the coupled enrichment shown by low $^{144}Nd/^{143}Nd_{(i)}$ and elevated $^{87}Sr/^{86}Sr_{(i)}$ is consistent with enrichment by a common process, consistent with modification by crustal contamination.

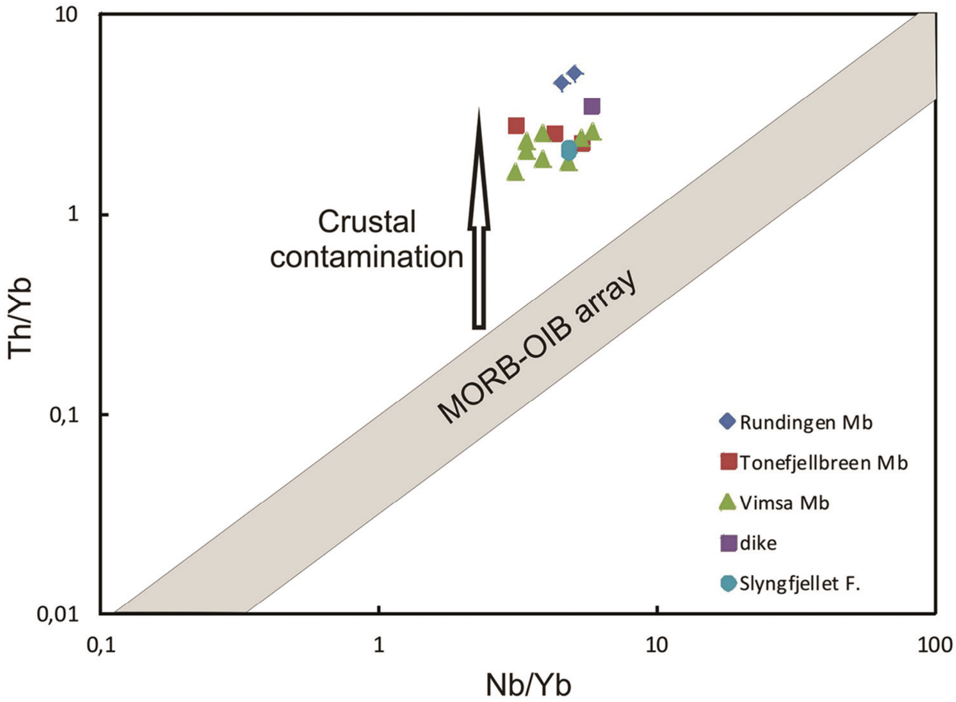

Fig. 9. Nb/Yb – Th/Yb indicate crustal contamination for all samples of Jens Erikfjellet Formation.

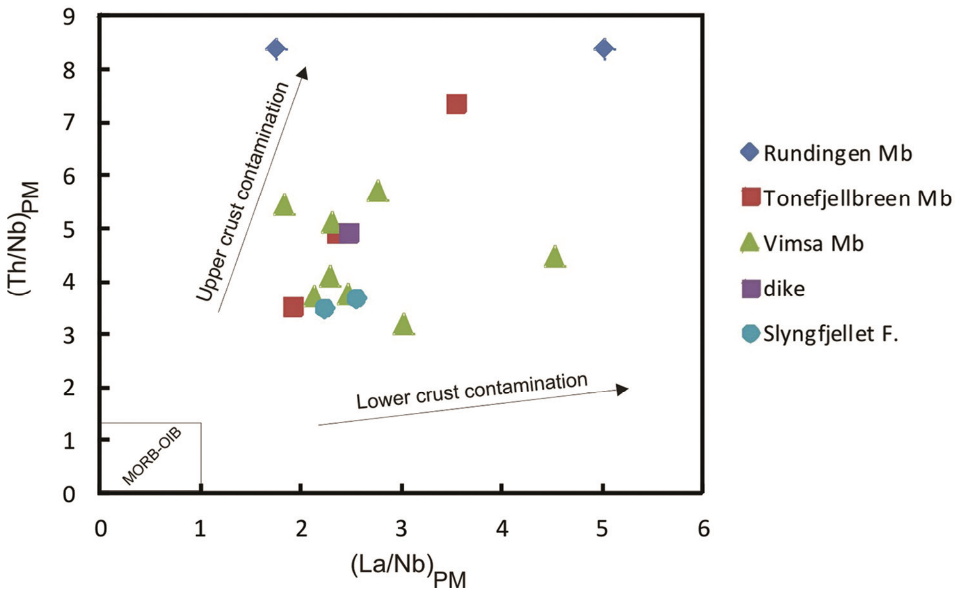

Fig. 10. Th/Nb vs La/Nb normalized to primitive mantle showing relative enrichment for Th and La for all samples from the Jens Erikfjellet Formation.

6. Conclusion

It is difficult to robustly assess whether the Sr isotope composition and wide range of LILE were caused exclusively by crustal contamination opposed to metamorphism. However, the good correlation between LILE, the elevated La and Th, Th/Yb vs Nb/Yb, the depletion in Nb, and the Sr-Nd isotope systematics suggest that a record of crustal contamination is preserved. Notwithstanding, the scatter in major elements, especially the depletion in Ca and enrichment in Na, indicate that the variability of these elements was influenced by metamorphism including mobilization by fluids during spilitization. It is possible that the strong correlation of LILE contents could have been caused by crustal contamination and later influenced by metamorphism. The high correlation of REE with HFSE and evident fractional crystallization trends, indicates that they have survived the metamorphic event undisturbed and provide a robust record of magmatic processes. All of the rock samples collected show evidence of crustal contamination, to different extents for all members. Those from the Vimsa Member are less contaminated and are spilitized, whereas those from the Rundingen Member and from the Slygnfjellet Group are the most contaminated.

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7. References

Anczkiewicz, R., Platt, J. P., Thirlwall, M. F., & Wakabayashi, J. (2004). Franciscan subduction off to a slow start: evidence from high precision Lu-Hf garnets ages on high grade-blocks. *Earth and Planetary Science Letters, 225*(1-2), 147–161. DOI: 10.1016/j.epsl.2004.06.003.

Anczkiewicz, R., & Thirlwal, M. F. (2003). Improving precision of Sm-Nd garnet dating by H_2SO_4 leaching: a simple solution to the phosphate inclusion problem. In D. Vance, W. Mueller & I. M. Villa (Eds.), *Geochronology: Linking the Isotopic Record with Petrology and Textures* (pp. 83–91). Special Publications, 220. London: Geological Society.

Arghe, F., Skelton, A., & Pitcairn, I. (2011). Spatial coupling between spilitization and carbonation of basaltic sills in SW Scottish Highlands: evidence of a mineralogical control of metamorphic fluid flow. *Geofluids*, *11*(3), 245–259. DOI: 10.1111/j.1468-8123.2011.00335.x.

Armstrong, H. A., Nakrem, H. A., & Otha, Y. (1986). Ordovician conodonts from the Bulltinden Formation, Motalafjella, central-western Spitsbergen. *Polar Research*, *4*(1), 17–23. DOI: 10.1111/j.1751-8369.1986.tb00514.x.

Balashov, Y. A., Peucat, J. J., Tebenkov, A. M., Ohta, Y., Larionov, A. N., Sirotkin, A. N., & Bjørnerud, M. (1996). Rb-Sr whole rock and U-Pb zircon datings of the granitic-gabroic rocks from Skålfjellet Subgroup, southwest Spitsbergen. *Polar Research*, *15*(2), 167–181. DOI: 10.1111/j.1751-8369.1996.tb00467.x.

Balashov, Y. A., Tebenkov, A. M., Ohta, Y., Larionov, A. N., Sirotkin, A. N., Gannibal, L. F., & Ruyngenen, G. I. (1995). Grenvillian U-Pb zircon ages of quartz porphyry and rhyolite clasts in a metaconglomerate at Vimsodden, southwestern Spitsbergen. *Polar Research*, *14*(3), 291–302. DOI: 10.1111/j.1751-8369.1995.tb00716.x.

Bernard-Griffiths, J., Peucat, J. J., & Otha, Y. (1993). Age and nature of protoliths in the Caledonian blueschist-eclogite complex of western Spitsbergen: a combined approach using U-Pb, Sm-Nd and REE whole-rocks system. *Lithos*, *30*(1), 81–90. DOI: 10.1016/0024-4937(93)90007-Y.

Birkenmajer, K. (1991). The Jarlsbergian unconformity (Proterozoic/Cambrian boundary) and the problem of Varangian tillites in South Spitsbergen. *Polish Polar Research*, *12*(3), 269–278.

Bjørnerud, M. (1990). An Upper Proterozoic unconformity in northern Wedel Jarlsberg Land, southwest Spitsbergen: Lithostratigraphy and tectonic implications. *Polar Research*, *8*(2), 127–139. DOI: 10.1111/j.1751-8369.1990.tb00381.x.

Czerny, J. (1999). *Petrogenesis of metavolcanites of the southern part of Wedel Jarlsberg Land (Spitsbergen)*. Prace Mineralogiczne, 86. Kraków: Wydawnictwo Oddziału PAN.

Czerny, J., Kieres, A., Manecki, M., Rajchel, J. (1993). *Geological map of the SW part of Wedel Jarlsberg Land, Spitsbergen, 1:25 000*. A. Manecki (Ed.), Kraków: Institute of Geology and Mineral Deposits AGH.

Czerny, J., Majka, J., Gee, D. G., Manecki, A., & Manecki, M. (2010). Torellian Orogeny: evidence of a Late Proterozoic tectonometamorphic event in southwestern Svalbard's Caledonian basement. 29th Nordic Geological Winter Meeting, 11-13 January 2010 (pp. 35-36). Oslo, Norway. NGF Abstract and Proceedings of the Geological Society of Norway.

Dallman, W. K., Hjelle, A., Otha, Y., Salvigsen, O., Maher, H. D., Bjørnerud, M., Hauser, E. C., & Craddock, C. (1990). *Geological map of Svalbard 1:100,000, B11G Van Keulenfjorden. With description*. Norsk Polarinstitutt Temakart, No. 15.

Dallmeyer, R. D., Peucat, J. J. , & Otha, Y. (1990). Tectonothermal evolution of contrasting methamorphic complexes in northwestern Spitsbergen (Biskayerhalvøya): Evidence from 40Ar/39Ar and Rb-Sr mineral ages. *Geological Society of America Bulletin*, *102*(5), 653–663. DOI: 10.1130/0016-7606(1990)102<0653:TEOCMC>2.3.CO;2.

Davis, J. C. (1986). *Statistics and Data Analysis in Geology* (2 ed.). New York: John Wiley & Sons.

Frey, F. A., Weis, D., Borisova, A. Y., & Xu, G. (2002). Involvement of continental crust in the Formation of the Cretaceous Kerguelen Plateau: New perspectives from ODP Leg 120 Sites. *Journal of Petrology, 43*(7), 1207–1239. DOI: 10.1093/petrology/43.7.1207.

Gee, D. G. (1986). Svalbard's Caledonian terranes reviewed. *Geologiska Föreningens Stockholm Förhandlingar*, *108,* 284–286.

Gee, D. G., & Page, L. M. (1994). Caledonian Terrane assembly on Svalbard: New evidence from Ar/Ar dating in Ny Friesland. *American Journal of Science*, *294*(9), 1166–1186. DOI: 10.2475/ajs.294.9.1166.

Gee, D. G., & Tebenkov, A. M. (2004). Svalbard: a fragment of the Laurentian margin. In D. G. Gee & V. Pease (Eds), The Neoproterozoic Timanide Orogen of Eastern Baltica. *Geological Society, London, Memoirs, 30*, 191–206. DOI: 10.1144/GSL.MEM.2004.030.01.16.

Harland, W. B., Hambry, M. J. & Waddams, P. (1993). The Vendian geology of Svalbard. *Norsk Polarinstitutt Skrifter*, *193*, 1-130. Oslo: Norwegian Polar Institute..

Higuchi, H., & Nagasawa, H. (1969). Partition of trace elements between rock-forming minerals and the host volcanic rocks. *Earth and Planetary Science Letters, 7*(3), 281-287. DOI: 10.1016/0012-821X(69)90066-1.

Jones, R. H., & Layne, G. D. (1997). Minor and trace element partitioning between pyroxene and melt in rapidly cooled chondrules. *American Mineralogist, 82*(5-6), 534-545.

Larionov, A. N., Tebenkov, A. M., Gee, D. G., Czerny, J., & Majka J. (2010). Recognition of Precambrian Tectonostratigraphy in Wedel-Jarlsberg Land, Sothwestern Spitsbergen. 29th Nordic Geological Winter Meeting, 11-13 January 2010 (pp. 106). Oslo, Norway. NGF Abstract and Proceedings of the Geological Society of Norway.

Leeman, W. P., & Scheidegger, K. F. (1977). Olivine/liquid distribution coefficients and a test for crystal-liquid equilibrium. *Earth and Planetary Science Letters 35*(2), 247-257. DOI: 10.1016/0012-821X(77)90128-5.

Majka J., Czerny J., Mazur S., Holm D.K., & Manecki M. (2010). Neoproterozoic metamorphic evolution of the Isbjørnhamna Group rocks, southwestern Svalbard. *Polar Research, 29*(3), 250-264. DOI: 10.1111/j.1751-8369.2010.00186.x.

Majka J., Larionov A.N., Gee D.G., Czerny J., Pršek J. (2012). Neoproterozoic pegmatite from Skoddefjelet, Wedel Jarlsberg Land, Spitsbergen: Additional evidence for c. 640 Ma tectonothermal event in the Caledonides of Svalbard. *Polish Polar Research 33*(1), 1-17. DOI: 10.2478/v10183-012-0003-6.

Majka J., Mazur S., Manecki M., Czerny J., & Holm D. K. (2008). Late Neoproterozoic amphibolite facies metamorphism of a pre-Caledonian basement block in southwest Wedel Jarlsberg Land, Spitsbergen: new evidence from U–Th–Pb dating of monazite. *Geological Magazine*, *145*(6), 822– 830. DOI: 10.1017/S001675680800530X.

Miller, R. L. & Kahn, J. S., (1962). *Statistical Analysis in the Geological Science*. New York: John Wiley and Sons.

Manecki, M., Holm, D. K., Czerny, J., & Lux, D. (1998). Thermochronological evidence for late Proterozoic (Vendian) cooling in southwest Wedel Jarlsberg Land, Spitsbergen. *Geological Magazine*, *135*(1), 63-69.

Mazur, S., Czerny, J., Majka, J., Manecki, M., Holm, D., Smyrak, A., & Wypych, A. (2009). A strike slip terrane boundary in Wedel Jarlsberg Land, Svalbard, and its bearing on correlations of SW Spitsbergen with the Pearya terrane and Timanide belt. *Journal of the Geological Society*, *166*(3), 529-544. DOI: 10.1144/0016-76492008-106.

Onuma, N., Higuchi, H., Wakita, H., & Nagasawa, H. (1968). Trace element partition between two pyroxenes and the host lava. *Earth and Planetary Science Letters, 5*(1), 47-51. DOI: 10.1016/S0012-821X(68)80010-X.

Otha, Y. 1979. Blue schists from Motalafjella, western Spitsbergen. *Norsk Polarinstitutt Skrifter*, *167*, 171–217. Oslo: Norwegian Polar Institute.

Pearce, J. A. (2008). Geochemical fingerprints of oceanic basalts with application to ophiolite classification and the search for Archean oceanic crust. *Lithos*, *100*(1-4), 14–48. DOI: 10.1016/j.lithos.2007.06.016.

Peryt, T. M., Hryniv, S. P., & Anczkiewicz R. (2010). Strontium isotope composition of Badenian (Middle Miocene) Ca-sulphate deposite in West Ukraine: a preliminary study. *Geological Quarterly 54*(4), 465–476.

Reimann, C., Filzmoser, P., & Garrett, R. G. (2002). Factor analysis applied to regional geochemical data: problems and possibilities. *Applied Geochemistry*, *17*(3), 185–206. DOI: 10.1016/S0883-2927(01)00066-X.

Rudnick, R. L., & Gao, S. (2003). The Composition of the Continental Crust. *Treatise on Geochemistry*, *3*(1), 1–64. DOI: 10.1016/B0-08-043751-6/03016-4.

Scrutton, C. T., Horseield, W. T., & Harland, W. B. (1976). Silurian fossils from western Spitsbergen. *Geological Magazine*, *113*(6), 519-523. DOI: 10.1017/S0016756800041261.

Skelton, A., Arghe, F., & Pitcairn, I. (2010). Regional mapping of pre-metamorphic spilitization and associated chemical mobility in greenschist-facies metabasalts of the SW Scottish Highlands. *Journal of the Geological Society*, *167*(5), 1049–1061. DOI: 10.1144/0016-76492009-130.