Geochemical changes accompanying mylonitisation of granite at the base of the Helgeland Nappe Complex, Nord-Trøndelag, central Norway

DAVID ROBERTS & AUGUST L. NISSEN

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A progressive conversion of megacrystic granite into mylonites at the base of the Helgeland Nappe Complex in the Caledonides of central Norway is reflected in microstructural, textural and modal changes. These mylonites record a considerable, regional, Scandian thrust deformation followed by a late-Scandian phase of major extension. The chemical changes that accompanied the structural and mineralogical conversion are also quite significant. Major oxides generally show wt.% losses (e.g., Al_2O_3 down >12% and CaO 50%) except for SiO_2 which gains 10%, partly reflecting a twofold increase in modal quartz. Of the trace elements, Sr and Ba fall markedly, up to 60%, a feature that reflects their affinity for the modally diminishing feldspars (65 vol.% in granite to <20 vol.% in mylonites). An application of normalised mylonite/protolith ratio plots for selected oxides indicates that this regionally important mylonitic shear zone is of the volume-gain/isovolume variety. Such volume-gain systems, commonly involving fluid-enhanced silicification, are more typical of extensional shear situations. These results conform well with the regional structural picture wherein the major, extensional, late-Scandian, Kollstraumen detachment zone occurs in the footwall to the mylonitic base of the Helgeland Nappe Complex; and extensional structures overprint the thrust fabric in the mylonitised granite.

David Roberts & August Nissen, Geological Survey of Norway, 7491 Trondheim, Norway.

Introduction

During the last decade, structural geological studies in the Caledonides of central Norway have focused largely on the extensional history that accompanied the waning stages of the Late Silurian-Mid Devonian Scandian orogeny and continued intermittently into the post-Caledonian era (Braathen et al. 2000, 2002, Nordgulen et al. 2002, Osmundsen et al. 2003, 2005, 2006, Kendrick et al. 2004). These studies have dealt with the kinematic aspects of the high-strain zones, their mylonitic and late brittle fabrics, and also involved dating the mineral phases associated with these separate movements. This work has followed on from, and partly overlapped with diverse investigations along and adjacent to the Møre-Trøndelag Fault Complex (Grønlie & Roberts 1989, Grønlie et al. 1991, Séranne 1992, Roberts 1998, Watts 2001, Redfield et al. 2004, 2005, Sherlock et al. 2004).

Earlier, a study of progressive mylonitisation along and above the basal thrust contact of the Helgeland Nappe Complex in the Kongsmoen area (Fig. 1) had concentrated on the microstructural and mineralogical changes that had accompanied the conversion of a porphyritic granite into mylonites and ultramylonites (Roberts et al. 1983). Subsequently, a geochemical study of this progressive mylonitisation was undertaken and briefly documented, in Norwegian, in a Geological Survey report (Roberts & Nissen 1996). This work was also touched upon in a paper dealing with different types of high-strain zone in central parts of the Norwegian Caledonides (Roberts 1998); and in the case of the Helgeland Nappe Complex noting that both contractional and extensional events had influenced the process of conversion of protolith granite to mylonite and ultramylonite.

In this contribution we present the geochemical data and interpretations, the main features of which are indicating that an overall, bulk, volume-gain system was operative during the mechanical and compositional conversion of the granite into fault rocks. Such volume-gain systems are generally accepted as being more characteristic of extensional shear rather than thrusting regimes. In the case considered here, however, we are dealing with a polyphasal mylonite zone involving both contractional and extensional deformation.

General geology and structure

In the Kongsmoen district, Palaeoproterozoic orthogneisses of the Central Norway Basement Window (Braathen et al. 2000) in the west are tectonically overlain to the east by diverse amphibolite-facies supracrustal rocks of the Skjøtingen (Seve) Nappe and by the extensive granitoid rocks of the Bindal Batholith, part of the Helgeland Nappe Complex (Nordgulen 1993, Nordgulen et al. 1993, Roberts 1997, Roberts et al. in press) (Fig. 1). A megacrystic granite to granodiorite, termed the Kongsmoen Massif (Nordgulen 1993), dominates this part of the Bindal Batholith. Although the Kongsmoen Massif is not dated, porphyritic granitoid plutons of comparable, mainly calc-alkaline composition within the Bindal Massif fall in the age range 448-430 Ma (Nordgulen et al. 1993, 2002, Bingen et al. 2002, Nissen et al. 2006).

As noted above, the Kongsmoen Massif is progressively mylonitised towards the base of the nappe, which is characterised by a zone of mylonites ranging from 200 to 600 metres in thickness. The mylonitic foliation dips at moderate angles to the east-southeast in this particular area. Farther north, the basal mylonites swing into a NW-SE strike trend and dips are northeasterly. Kollung (1967) was the first to describe the 'tectonisation' of the granite and its transformation into augen gneiss, blastomylonites and mylonites, but he believed that the granite, and the nappe, had been thrust from east to west. Later workers favoured the opposite thrust vergence, based on a combination of structural features, kinematic indicators and regional-geological considerations (Roberts et al. 1983, Nordgulen et al. 1993, 2002). It was also realised that the highly ductile mylonites, related to east-northeastward thrusting, had been overprinted by extensional shear bands and associated or younger cataclastic features indicative of east- to east-southeast-directed shear (Roberts & Nissen 1996, Roberts 1998). These include thin bands of foliation-parallel cataclasite or microbreccia and millimetre-thin veins of pseudotachylite.

Subsequent work (Braathen et al. 2000, 2002, Nordgulen et al. 2002) over a wider area along the base and particularly in the footwall of the Helgeland Nappe Complex has shown that the extensional shear component dominates the structural picture; and the term Kollstraumen detachment zone was introduced (Braathen et al. 2000) to signify the importance of this 1-2 km-wide zone of extensional shear deformation (Fig. 1). In a detailed study, Nordgulen et al. (2002) noted that it is difficult in many cases to separate the ductile, syn-thrusting structures from the near-colinear extensional structures. However, in one area located c. 25 km northwest of Kongsmoen, a strongly deformed pegmatite sheet U-Pb-dated to 401 ± 3 Ma (Schouenborg 1988) serves as a marker separating the thrusting and extensional events. The work of Nordgulen et al. (2002), over a distance of more than 80 km of strike along the Kollstraumen detachment, showed that plunges of both Scandian contractional and late-Scandian, Devonian, extensional stretching lineations vary and interchange between northeast and east-southeast (Fig, 1).

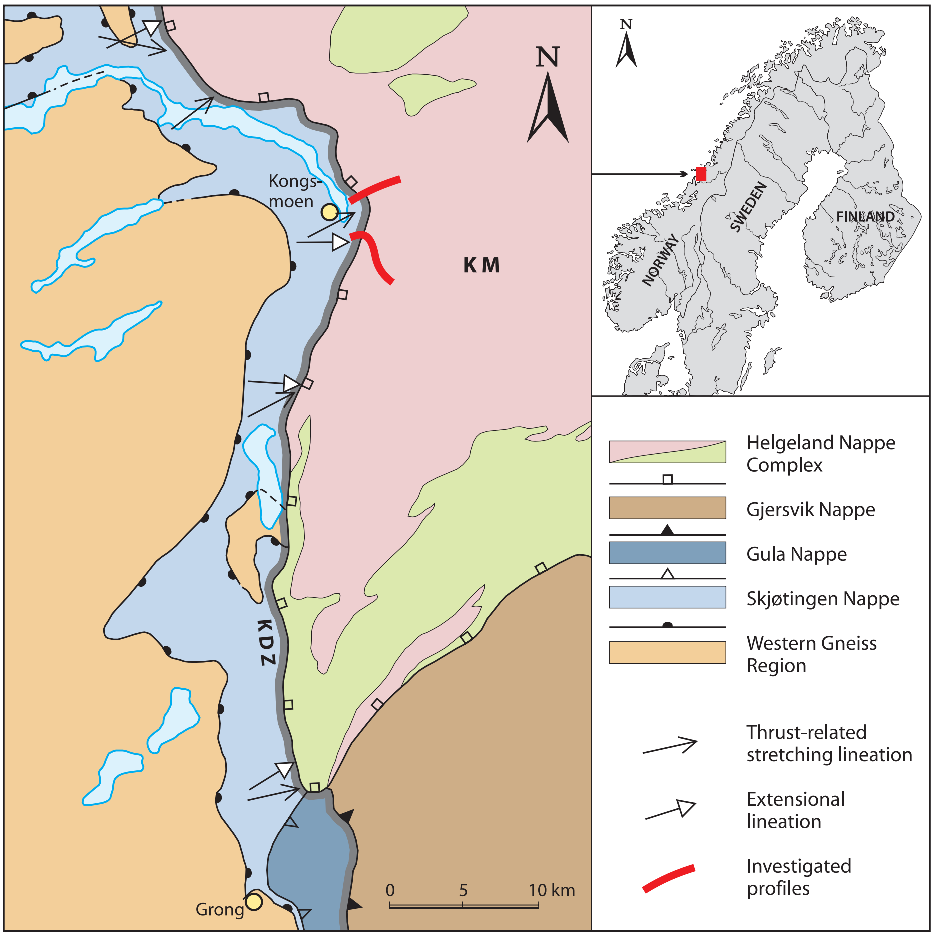

Fig.1. Simplified map of the tectonostratigraphy of the Kongsmoen-Grong region showing the locations of the investigated profiles. KM – Kongsmoen Massif. The lineation data are largely taken from stereoplots in Nordgulen et al. (2002), except for the data recorded close to Kongsmoen (own observations). KDZ – Kollstraumen detachment zone. The Helgeland Nappe Complex is here divided into granite/granodiorite (pink) and metasedimentary rocks (green).

Mylonitisation of the granite

The mesoscopic and microscopic structures, mineralogical and textural changes, and inferred dynamic processes involved in the progressive conversion of the Kongsmoen granite to foliated granite, augen granite and ultimately to diverse forms of mylonite have been described and illustrated in some detail earlier (Roberts et al. 1983). Only a summary of these features and changes will therefore be given here.

The principal changes observed are:- (1) The progressive development of a mylonitic foliation, from incipient millimetre-thin shear seams that pervade the granite and anastomose, coalesce and increase in density and thickness downwards, into augen granite, protomylonites, blastomylonites and, in places, ultramylonites. (2) A gradual grain-size reduction of all principal minerals, and the rock in general, notably with 3 cm-size megacrysts of microcline progressively reduced to relict clasts less than 1 mm in size. (3) Polygonisation of quartz, initially in microcrystalline lenticular grain aggregates, or polygonised granular mosaics, with at least two neocrystallisations, the later one associated with the formation of diffuse polygranular quartz veinlets. (4) An increasing presence of string- and flame-perthite. (5) Sericitisation of plagioclase and chloritisation of biotite, in places with new, tiny chlorite grains.

In addition, there are notable progressive changes in modal compositions, illustrated by a series of samples, along one profile, between the two end members – i.e., megacrystic granite and ultramylonitic layers in blastomylonite (Roberts et al. 1983, table 1). With increasing strain, the quartz content increases twofold from 20 vol.% in the granite to c. 40% in mylonitic rocks, whereas the feldspars gradually drop from 65% in the two-feldspar granite to 15-20 vol.% in the ultramylonites. Although other modal mineralogical changes are less dramatic, there are notable small increases in the contents of epidote, chlorite, sericite and fine-grained muscovite, more especially in the mylonites and ultramylonites that have been most affected by the late-stage, extensional shear.

Geochemistry

The relative significance of chemical and mechanical processes in the genesis of mylonites is a question that has provoked discussion and, in the former case, there is the added difficulty of knowing whether the deformation occurred as an open system reaction or was strictly isochemical. An important parameter in the classification of major shear zones relates to the observed or calculated changes in rock volume in terms of elemental gain or depletion (Gresens 1967, Bailey et al. 1994). Based on this criterion,

Table 1. Major element analyses of 19 metacrystic granites and 7 mylonites/ultramylonites from the western part of the Kongsmoen Massif. AVG – Median values. Contents in wt.%.

No	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CO_2	H_2O^+	H_2O^-
L983	65.39	15.89	0.42	0.85	1.71	0.05	1.26	2.98	4.00	4.40	0.19	0.21	0.39	0.06
L2184	66.69	16.19	0.50	0.86	1.65	0.03	0.87	2.41	4.20	4.11	0.15	0.03	0.54	0.04
L2284	67.87	15.86	0.44	0.76	1.44	0.03	0.80	2.28	4.30	3.85	0.15	0.03	0.50	0.08
6177	68.39	16.50	0.34	0.40	1.24	0.05	0.63	2.11	3.35	4.94	0.09	0.04	0.97	0.03
7077	65.78	16.06	0.55	0.73	1.86	0.04	1.00	2.45	3.70	4.25	0.19	0.15	0.44	0.04
2478	66.84	17.43	0.31	0.70	0.79	0.05	0.42	1.85	3.48	6.00	0.06	0.04	1.90	0.04
5381	65.03	15.99	0.44	1.41	1.17	0.04	1.31	2.87	5.50	4.26	0.19	0.11	0.80	0.00
6083	64.92	15.86	0.45	1.18	1.39	0.10	1.11	3.02	4.00	4.81	0.19	0.25	0.01	0.10
6283	64.49	15.28	0.45	1.13	1.37	0.05	1.09	2.96	4.60	3.86	0.18	0.67	0.26	0.11
6583	66.49	15.57	0.43	1.09	1.45	0.04	1.16	2.63	3.70	5.27	0.19	0.16	0.50	0.03
6683	66.55	16.55	0.39	0.98	1.44	0.04	1.21	2.86	4.30	4.84	0.18	0.11	0.27	0.23
7083	66.29	15.96	0.45	1.31	1.44	0.05	1.36	3.12	4.30	3.74	0.21	0.12	0.24	0.11
1082	67.40	15.16	0.39	1.52	0.87	0.04	1.13	2.25	4.20	3.83	0.17	0.11	1.10	0.15
1782	71.20	14.89	0.31	0.89	0.84	0.04	0.61	1.89	4.30	4.17	0.10	0.12	0.89	0.05
1882	70.37	15.07	0.30	0.69	0.86	0.02	0.45	1.51	4.10	4.80	0.09	0.16	0.62	0.10
4282	67.67	16.40	0.40	0.80	1.21	0.02	0.66	1.64	3.90	5.27	0.13	0.12	0.93	0.00
4382	69.85	15.38	0.36	0.82	1.15	0.03	0.77	1.70	3.70	4.95	0.12	0.11	0.29	0.57
6082	67.37	16.47	0.32	1.08	0.98	0.04	0.87	2.26	4.40	4.95	0.13	0.13	0.71	0.16
6482	64.34	16.85	0.49	1.72	1.21	0.05	1.48	2.82	4.80	3.96	0.22	0.15	1.18	0.16
AVG	67.00	15.97	0.41	0.99	1.27	0.04	0.96	2.40	4.14	4.54	0.15	0.15	0.66	0.11

No	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CO_2	H_2O^+	H_2O^-
3782	75.04	13.39	0.04	0.07	0.14	0.01	0.12	0.60	3.20	5.89	0.04	0.12	0.23	0.33
5281	74.06	14.48	0.09	0.73	0.35	0.02	0.12	1.50	3.70	4.23	0.02	0.09	0.66	0.00
6383	74.10	13.71	0.07	0.26	0.31	0.01	0.06	1.27	3.40	4.75	0.01	0.11	0.19	0.13
6883	74.69	13.90	0.06	0.38	0.42	0.03	0.08	1.35	3.60	4.46	0.01	0.14	0.15	0.03
6983	73.87	13.73	0.07	0.42	0.37	0.02	0.08	1.46	3.40	4.33	0.01	0.11	0.46	0.00
582	75.37	13.94	0.05	0.36	0.07	0.01	0.02	0.92	3.80	5.19	0.01	0.20	0.57	0.03
5283	71.88	14.64	0.16	0.33	0.95	0.02	0.24	1.27	4.00	4.23	0.09	0.13	0.21	0.04
AVG	74.14	13.97	0.08	0.36	0.37	0.02	0.10	1.20	3.60	4.73	0.03	0.13	0.35	0.08

high-strain zones have been classified as either volume-loss or volume-gain shear zones, with cases of isovolume chemical reactions generally being categorised together with the latter (Ramsay 1980, O'Hara 1988, Tobisch et al. 1991, Bailey et al. 1994).

In the case of the Kongsmoen Massif, the clear and progressive changes from megacrystic granite to augen granite and, further, into blastomylonite and mylonite offered an unusually good opportunity to try to detect possible chemical changes allied to the deformation. In this study we included nineteen analyses of the granite sampled at or close to the eastern ends of the profiles indicated in Fig. 1 or from nearby parts of the massif, and seven analyses of mylonite or ultramylonite from at or close to the western ends of the same profiles. The major and trace elements were measured on an automatic Philips 1450/20 XRF instrument at NGU, Trondheim, on fused glass beads and pressed powder pellets, respectively. Calibration curves were made with common international standards. The analyses are presented in Tables 1 and 2. For a rapid comparison of the two end members, median values are also given.

From an inspection of the major element average values, the most significant change from granite to mylonite is that of SiO_2, showing a marked wt.% increase of close to 10% from 67% to >74% (Table 1). The other major oxides all show losses, with the exception of K_2O (a small 4% gain). Oxides such as CaO and TiO_2 show losses of 50% and 80%, respectively, whereas the second major oxide in terms of volume, Al_2O_3, records a fairly significant loss of >12%. In general, these noteworthy changes in major oxide abundances are a reflection of the observed modal changes that are, in turn, a consequence of the textural changes attending the process of mylonitisation.

Of the more prominent trace elements, in terms of highest ppm content, Sr and Ba show losses of 66% and 49%, respectively (Table 2). Such marked losses are readily explained by the fact that these particular elements are largely bound in the lattices of the feldspars, which diminish from 65 vol.% in the granite to <20% in the mylonites. Negative changes can be seen in almost all other trace elements, e.g., Zr down 66%, Y by 55% and V dropping 74%, the only exception being that of the Rb content which shows a very small gain.

A curiosity with regard to trace element changes, and to strontium in particular, is that of Sr positive anomalies recorded in stream sediments in the tract from Grong to

Table 2. Trace element abundances (ppm) of the same 19 metacrystic granites and 7 mylonites as in Table 1.

No	Nb	Zr	Y	Sr	Rr	Zn	Cu	Ni	Cr	V	Ba	Sn	W
L983	13	186	17	1300	131	62	< 5	17	37	50	1100	< 10	< 10
L2184	12	248	13	973	131	71	< 5	6	9	38	977	< 10	< 10
L2284	13	254	15	921	130	60	< 5	7	8	33	888	< 10	< 10
6177	14	183	14	836	153	51	< 5	< 5	6	23	951	< 10	6
7077	16	254	17	968	139	70	< 5	10	12	38	1000	< 20	< 20
2478	10	157	13	912	163	39	< 5	6	6	21	1200	< 10	13
5381	13	240	18	1400	131	68	5	18	30	40	1000	< 10	< 10
6083	25	199	54	964	161	53	< 5	16	30	40	1100	< 10	< 10
6283	21	196	24	1200	124	56	< 5	16	30	47	1000	< 10	< 10
6583	16	190	17	1400	147	58	< 5	17	34	45	1400	< 10	< 10
6683	12	176	14	1400	142	56	< 5	16	28	40	1200	< 10	< 10
7083	14	202	19	1300	130	68	< 5	18	32	46	872	< 10	< 10
1082	13	197	18	882	111	64	< 5	14	27	32	887	< 10	10
1782	14	137	11	611	148	50	< 5	5	8	23	597	< 10	10
1882	9	157	< 5	603	141	45	< 5	< 5	< 5	19	754	< 10	10
4282	16	207	16	927	168	57	< 5	< 5	< 5	26	1200	< 10	< 10
4382	21	210	18	656	193	49	< 5	6	11	25	820	< 10	< 10
6082	14	185	18	1300	162	48	< 5	11	17	30	1200	< 10	13
6482	16	231	23	1200	107	68	< 5	19	36	47	1100	< 10	< 10
AVG	14	191	17	992	145	54	5	11	18	33	982	10	11

No	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Cr	V	Ba	Sn	W
3782	7	95	6	247	186	8	< 5	< 5	< 5	7	549	< 10	< 10
5281	9	80	8	556	124	19	< 5	< 5	< 5	8	886	< 10	< 10
6383	8	59	7	381	150	15	< 5	< 5	< 5	9	543	< 10	< 10
6883	5	52	< 5	294	139	19	< 5	< 5	< 5	10	347	< 10	< 10
6983	5	45	< 5	429	128	17	< 5	< 5	< 5	10	635	< 10	< 10
582	21	58	16	177	170	9	7	< 5	< 5	< 5	150	< 10	< 10
5283	10	90	12	393	144	34	< 5	< 5	< 5	17	466	< 10	< 10

Kongsmoen and beyond (Sæther et al. 2005). A certain structural control on these Sr concentrations relates to the fact that the anomalies are significantly prominent along the MTFC and the northern faulted margin of the Grong-Olden Culmination, as well as along the line of the Kollstraumen detachment zone.

Discussion

The chemical changes noted above are, for the most part, a reflection of the tangible modal and textural changes, although the question of the actual fate of all the disappearing elements remains open to debate. Some may reside in microscale intra-foliation or vein mineral segregations either within or marginal to the high-strain zone, rather than having been extracted and deposited outside the system. Low- to medium-grade shear zones, for example, are known to facilitate the channelling and connectivity of fluids (Watson & Brennan 1987), and fluid-enhanced element migration has almost certainly occurred (Tobisch et al. 1991). There is also the possibility that some of the losses may be partly apparent rather than real, reflecting the diluting effect of an appreciable input of silica to the system during the process of grain-size reduction and mylonitisation. This, in turn, acknowledges the importance of assessing volume changes (Gresens 1967) when investigating and comparing the end-member compositions in deformation processes of this type.

Calculating changes in rock volume in volume-gain or volume-loss situations (Ramsay 1980, O'Hara 1988, Bailey et al. 1994) was taken a step further in Condie & Sinha's (1996) study of many shear zones from around the world. These authors devised plots of normalised mylonite/protolith ratios for selected oxides, in particular SiO_2, Al_2O_3, Na_2O and TiO_2, that allowed discrimination between volume-loss and volume-gain shear deformation and mylonitisation processes. These discriminants have been applied in the case of the mylonites and ultramylonites derived from the Kongsmoen Massif and they show quite clearly that we are here dealing with the volume-gain/isovolume category of high-strain shear zone (Fig. 2) (Condie & Sinha 1996). Taking into account the 9% gain in SiO_2 and marked increase in modal quartz content, signifying that fluid-enhanced silicification is likely to have accompanied the mylonitisation, then it is most probable that the high-strain reworking of granite into mylonite and ultramylonite in the actual case considered here is one of an overall slight volume gain. Separating the contributions of the two deformation pulses – contractional and extensional – to this bulk volume-gain situation is fraught with difficulty. This complication is also evident on the scale of the outcrop (Nordgulen et al. 2002), and is no

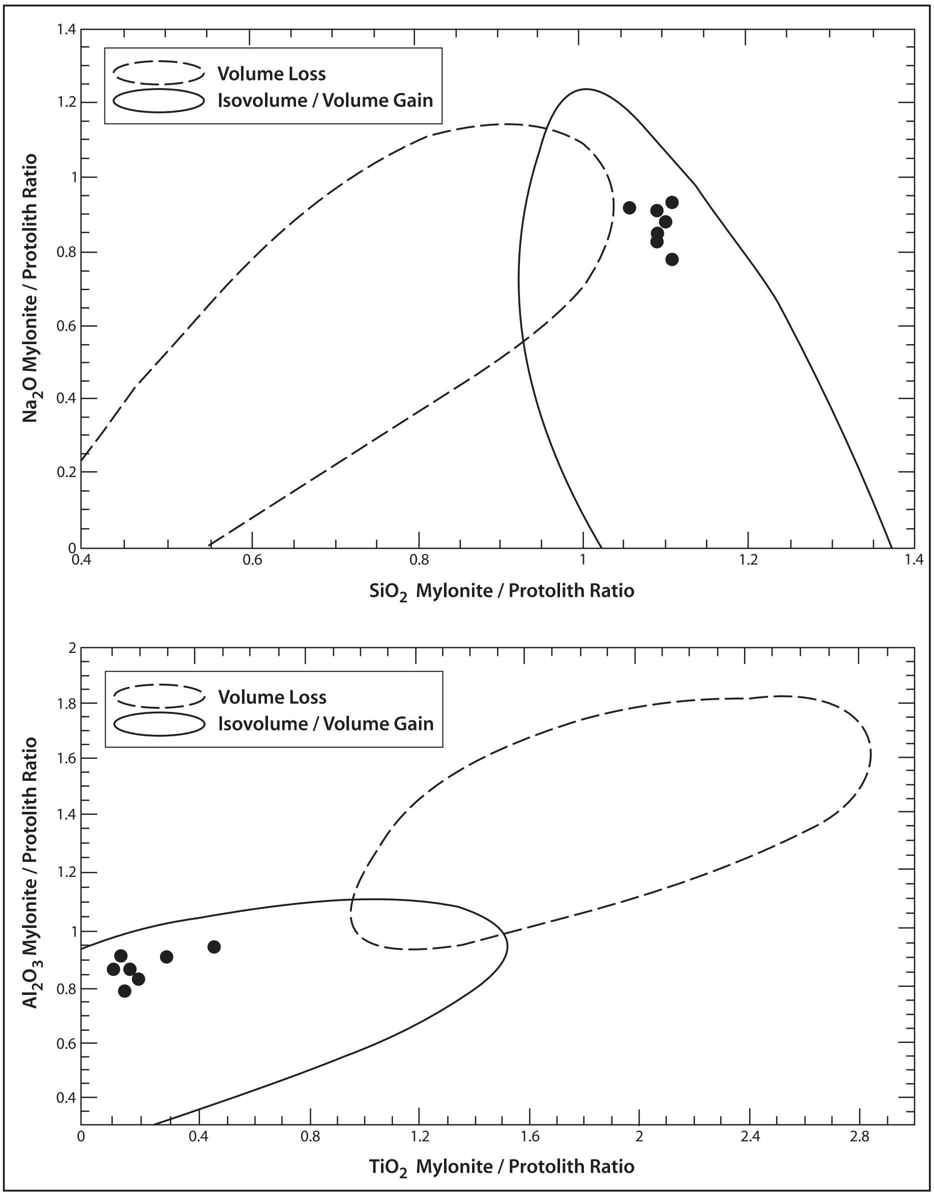

Fig. 2. Plot of concentration ratios mylonite/granite protolith (a) for Na_2O and SiO_2 and (b) Al_2O_3 and TiO_2 for the seven mylonites or composite mylonites/ultramylonites used in this investigation. The fields for volume-loss and isovolume/volume-gain mylonitic shear zones, determined from 'isocon analyses' calculated from published chemical analyses worldwide, are approximations from data given in Condie & Sinha (1996).

easier to resolve at the microscale considered here. However, the most silicified ultramylonites with clear indications of extensional shear bands occur at the very base of the nappe, corresponding to the top of the Kollstraumen detachment zone.

Comparisons with other mylonitic shear zones throughout the world in terms of geochemical and volume changes have been made by, e.g., Sinha et al. (1988), Tobisch et al. (1991) and Condie & Sinha (1996). A majority of cases of volume loss during mylonitisation relate to clear examples of thrusting in compressional tectonic regimes (Sinha et al. 1986, 1988, O'Hara 1988, 1990, O'Hara & Blackburn 1989, Tobisch et al. 1991). As pointed out by Hippertt (1998), this scenario is not unreasonable in that the requisite crustal shortening is readily achieved by volume loss. Losses of this kind are ascribed to diverse deformation mechanisms, notably dissolution and solution transfer, facilitated in part by syndeformational fluid flow. In the case of extensional shear zones, on the other hand, the increments of space that were created during progressive extension, in theory at least, would involve increased porosity and permeability, facilitating enhanced fluid flow in what should be a volume-gain or isovolume situation (Owen 1988, Tobisch et al. 1991, Condie & Sinha 1996). There are exceptions to this general rule, however (e.g., Glazner & Bartley 1991), but this may not be too unexpected considering that many mylonite zones in orogenic belts record histories of fault reactivation, commonly with extension succeeding thrusting. Thus, unless homogeneous and pervasive extensional overprinting has occurred, many such shear zones may be internally and laterally segmented, carrying volume-loss and volume-gain segments (Bailey et al. 1994).

As noted above, the mylonites described here are first and foremost associated with Scandian nappe emplacement, but also show abundant minor structures indicative of late-Scandian extensional reworking (Roberts & Nissen 1996, Braathen et al. 2000, Nordgulen et al. 2002). Moreover, the footwall to the mylonitic thrust zone is now dominated by the thick Kollstraumen detachment zone. Taken as a whole, therefore, the juxtaposed basal granitoid mylonites and subjacent Kollstraumen detachment zone carry a substantial extensional component, and such a zone with its many heterogeneities would have been a site of focused fluid flow and expected volume gain. In the case described here, we are reporting a small volume-gain situation for just the mylonites, yet this must be regarded as a finite or bulk overall gain. It is possible, indeed probable, that a measure of volume loss accompanied the contractional event and that this was subsequently counterbalanced by an equal or greater measure of volume gain during the regionally significant, late-Scandian extensional stage.

Conclusions

A megacrystic granite within the Bindal Batholith in the Helgeland Nappe Complex shows progressive downward changes into blastomylonite, mylonite and ultramylonite at the very base of the nappe. The microstructural, textural, mineralogical and modal changes coincident with this mylonitisation have been described earlier. In a nutshell, the mylonites provide a record of significant Scandian thrust deformation followed by a late-Scandian phase of extensional deformation.

In the present contribution we document the chemical changes that accompanied the conversion of granite into mylonite, based on end-member analyses. Of the major oxides, all except SiO_2 show wt.% losses, Al_2O_3 dropping >12% and CaO 50% from the protolith to the mylonites. SiO_2 shows a c. 10% increase, partly reflecting a twofold increase in the modal percentage of quartz. Among the trace elements, Sr and Ba diminish markedly (60% and 49%, respectively), a feature which goes hand in hand with disintegration and partial replacement of feldspars, from 65 vol.% in the granite to <20 vol.% in the mylonite.

Application of plots of normalised mylonite/protolith ratios for selected oxides (Condie & Sinha 1996) to help determine the bulk changes that may have taken place in terms of rock volume, show that our mylonitic shear zone belongs to the volume-gain/isovolume category. Such volume-gain systems are more typical of extensional situations, where fluid-enhanced silicification is not unusual. These results fit well with the local and regional structural-geological picture where the major late-Scandian, Kollstraumen detachment zone occurs in the immediate footwall to the mylonitic base of the Helgeland Nappe Complex, and extensional structures overprint the earlier thrust-related fabric.

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