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The Interrelations of Fluid Transport, Deformation, Geochemistry and Heat Flow in Early Proterozoic Shear Zones in the Lewisian Complex

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The interrelations of fluid transport, deformation, geochemistry and heat flow in early Proterozoic shear zones in the Lewisian complex

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The Lewisian complex of northwest Scotland shows a pattern of evolution typical of a number of early Proterozoic provinces. During the period 2500–1600 Ma, deformation occurred along steeply dipping shear zones, resulting in both vertical and lateral movements. The largest of these shear zones, forming the northern boundary to the Scourian granulites (Archaean), must have penetrated to considerable depth, possibly to the mantle.

Modal and chemical analysis of rocks from shear zones are presented and discussed in relation to rocks sampled outside shear zones. The mineralogy and composition of all rocks deformed in the shear zones have been considerably altered by synkinematic metasomatism. In the early stages, immediately prior to and during the intrusion of the regional doleritic dyke swarm, this metasomatic activity involved addition of H_2O and Na to the rocks. Subsequently, more significant changes in rock chemistry occurred (addition of H_2O, K, Na, loss of Fe, Ca, Mg). These changes resulted from the interaction between large volumes of water and the rocks in the shear zones along which the fluid travelled. A combination of modal and chemical data allow general chemical reactions to be written which describe the evolution of the gneisses during reworking and retrogression from pyroxene bearing granulite facies rocks to hornblende and biotite bearing amphibolite facies rocks in shear zones. The reactions are written as ionic equilibria and suggest that the fluid phase in the shear zones had a low pH.

Adiabatic transport of water upwards through the crust will result in moderate warming of the fluid, and can cause large temperature increases above the pre-existing geothermal gradient in rocks through which the fluid travels. It is suggested that both deformation and metamorphism in these shear zones are related to transport of fluid by hydraulic fracturing. Grain size reduction by hydraulic fracturing increases the strain rate in the shear zones. Deformation may cease in a shear zone when the fluid pressure drops and hydraulic fracturing no longer occurs. Thus fluid transport, mineral reactions, chemical changes, grain size reduction and convective heat flow will cease. A close relation should exist between the intensity of deformation, the extent of metasomatism and the thermal history in these important shear belts.

1. Introduction

In the last decade, numerous attempts have been made to determine the composition of both small and large areas of Archaean and early Proterozoic metamorphic complexes with a view to deducing the geochemical evolution of the Earth's crust over this period of time. It is unfortunate that many of the thousands of chemical analyses obtained from such rocks have been treated as groups and presented as averages. For example, Fahrig & Eade (1968) collected and averaged 14000 specimens from the whole of the Canadian shield. Eventually, two analyses were presented, an average of the Proterozoic and an average of the Archean. While the two differ in certain respects, there is no indication of the possible numerical significance of the differences. Similarly, no clear recognition is made of metamorphosed Proterozoic sediments, Proterozoic igneous intrusions or reworked Archaean rocks.

Some writers have recognized for many years (see, for example, Watson 1973) that large tracts of Archaean gneiss were reworked during the early Proterozoic in many parts of the world (Bridgwater, Watson & Windley 1973*b*; Sutton & Watson 1969). In many cases reworking occurred along essentially linear zones in the Earth's crust, found to be made up in detail of many shear zones, often recording large amounts of overthrust or transcurrent displacement (see, for example, Bridgwater, Escher & Watterson 1973*a*).

The Lewisian complex of northwest Scotland is perhaps the most studied segment of the Precambrian and it too has suffered from averaged chemical analyses.

Much more useful information is obtained when sampling procedures recognize the record of deformation in the rocks. For example, Burwash & Krupicka (1969, 1970) were able to show that parts of the western Canadian shield underwent reworking during the early Proterozoic and that their samples showed changes in chemistry approximately in proportion to the intensity of deformation seen in hand specimen and thin section. For example, the deformed (i.e. reworked) gneisses contain substantially less Fe, Mg and Ca, and more K than the undeformed Archaean gneisses. However, averages of analyses give no indication of any systematic relations between elements that might be established during reworking.

Nash (unpublished data) has analysed selected samples of leucocratic gneiss from both a large early Proterozoic shear zone and the adjacent Archaean rocks in west Greenland. There is no statistically significant difference between the average gneiss from outside the shear zone and that from within the shear zones. This procedure led Sheraton, Skinner & Tarney (1973*a*) to conclude that reworking of the Assynt granulite facies gneisses in shear zones produced no significant geochemical changes.

However, calculation of correlation matrices for these groups of analyses shows that significant differences do exist between reworked and undeformed gneisses. Correlation matrices are presented in table 1 for both the Assynt and the west Greenland gneisses (printed in italic type). correlation coefficient A in the amphibolite facies half of the matrix indicates a significant (i.e. > 0.30) increase in correlation between these two variables compared with the granulite facies gneisses. A correlation coefficient (in bold type) indicates a significant decrease in correlation.

Inspection of table 1 shows that there is a significantly higher degree of correlation between some oxide pairs in the reworked shear zone samples than in the undeformed granulite facies gneisses. It is the main purpose of this paper to examine such chemical changes in detail and in relation to the deformation and the mineralogical changes in the shear zones.

The areas studied form parts of the northwest trending zones of early Proterozoic reworking in the Lewisian complex (figure 1). Two areas of Archaean rocks are present on the mainland of Scotland – the first lying to the north and south of the Assynt district and consisting of granulite facies gneisses, the second lying to the north of Loch Torridon and consisting of granites and granitic gneisses metamorphosed in the amphibolite facies (see figure 1). Both of these areas suffered reworking in linear zones during the early Proterozoic.

Characteristically, reworking in the Lewisian involved deformation and metamorphism in shear zones formed on all scales from a few centimetres to several kilometres wide. Figure 2 is a map of the Assynt–Laxford area, showing the principal shear zones. Two belts of extensive reworking are present, between Lochinver and Drumbeg, and between Scourie and Laxford. One of the critical sections discussed in this paper is that between Scourie and Tarbet, across the margin of one of the major belts of reworking. A map of this area is shown in figure 3.

Table 1. Correlation matrices for analyses from the granulite facies complexes and amphibolite facies shear zones from northwest Scotland and west Greenland

(*a*) Greenland (Nash)

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
SiO_2		−0.75	−0.73	−0.62	−0.35	−0.48	−0.77	−0.51	−0.07	−0.22	−0.59
Al_2O_3	−0.53		0.20	0.18	−0.02	−0.05	0.32	0.30	0.49	0.29	0.34
TiO_2	−0.45	−0.31		0.79	0.57	0.68	0.89	0.33	−0.38	0.09	0.69
Fe_2O_3	−0.44	−0.25	0.83		0.25	0.75	0.83	0.55	−0.21	−0.21	0.63
FeO	−0.56	−0.20	*0.97*	*0.77*		0.42	0.54	0.13	−0.60	0.28	0.20
MnO	−0.58	−0.08	0.76	0.70	*0.79*		0.77	0.65	−0.41	−0.24	0.39
MgO	−0.62	−0.13	0.89	0.85	*0.91*	0.76		0.50	−0.27	0.06	0.64
CaO	−0.77	0.56	0.25	0.39	0.29	0.46	0.46		−0.03	−0.47	0.25
Na_2O	*0.57*	**−0.10**	*−0.79*	*−0.69*	−0.79	*−0.70*	*−0.76*	*−0.56*		−0.02	0.25
K_2O	0.08	−0.05	0.20	−0.01	0.23	0.08	0.02	−0.53	−0.17		0.20
P_2O_5	−0.28	−0.06	0.73	0.65	*0.63*	0.61	0.61	0.22	*−0.64*	0.24	

Granulite facies gneisses (22 samples)

Amphibolite facies gneisses from shear zones (16 samples).

(*b*) Northwest Scotland (Sheraton)

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O
SiO_2		0.31	−0.30	−0.50	−0.78	−0.78	−0.71	−0.73	0.83	0.35	0.47	−0.42
Al_2O_3	0.11		−0.01	−0.37	−0.34	−0.31	−0.73	0.05	0.44	0.30	−0.18	−0.52
TiO_2	*−0.81*	−0.26		0.37	0.54	0.47	−0.16	0.31	−0.07	−0.18	0.16	−0.26
Fe_2O_3	*−0.90*	−0.39	*0.90*		0.28	0.37	0.36	0.23	−0.34	−0.16	−0.17	0.37
FeO	−0.88	−0.51	*0.85*	*0.95*		0.96	0.38	0.63	−0.68	−0.40	−0.37	−0.02
MnO	−0.83	−0.49	*0.79*	*0.91*	0.93		0.43	0.69	−0.68	−0.38	−0.41	0.0
MgO	−0.89	−0.48	*0.78*	*0.92*	*0.94*	*0.88*		0.23	−0.75	−0.30	−0.43	0.75
CaO	−0.91	−0.32	*0.78*	*0.88*	0.91	0.85	*0.89*		−0.61	−0.41	−0.50	−0.13
Na_2O	**0.41**	0.73	*−0.58*	−0.63	−0.70	−0.62	−0.66	−0.59		0.30	0.55	−0.43
K_2O	0.40	−0.12	−0.34	−0.34	−0.28	−0.33	−0.29	−0.50	−0.03		0.33	0.0
O_2O_5	−0.12	*0.53*	0.02	−0.09	−0.21	−0.19	**−0.09**	**0.0**	0.41	−0.22		−0.23
H_2O	−0.44	−0.31	0.52	0.55	*0.54*	*0.52*	0.61	0.31	−0.49	0.18	−0.07	

Granulite facies gneisses (64 samples)

Amphibolite facies gneisses from shear zones (51 samples)

2. The anatomy of the reworked zones

(a) *Structures in the Lewisian*

The Scourie–Laxford area has long been recognized as one in which granulite facies rocks (*ca.* 2900 Ma) are sharply juxtaposed against a series of amphibolite facies granitic gneisses and are extensively reworked in a zone about 5 km wide south of this junction.

Deformation within this belt occurred over a protracted period (probably from 2500 to 1600 Ma (see Sheraton, Tarney, Wheatley & Wright 1973*b*)), its most essential feature being

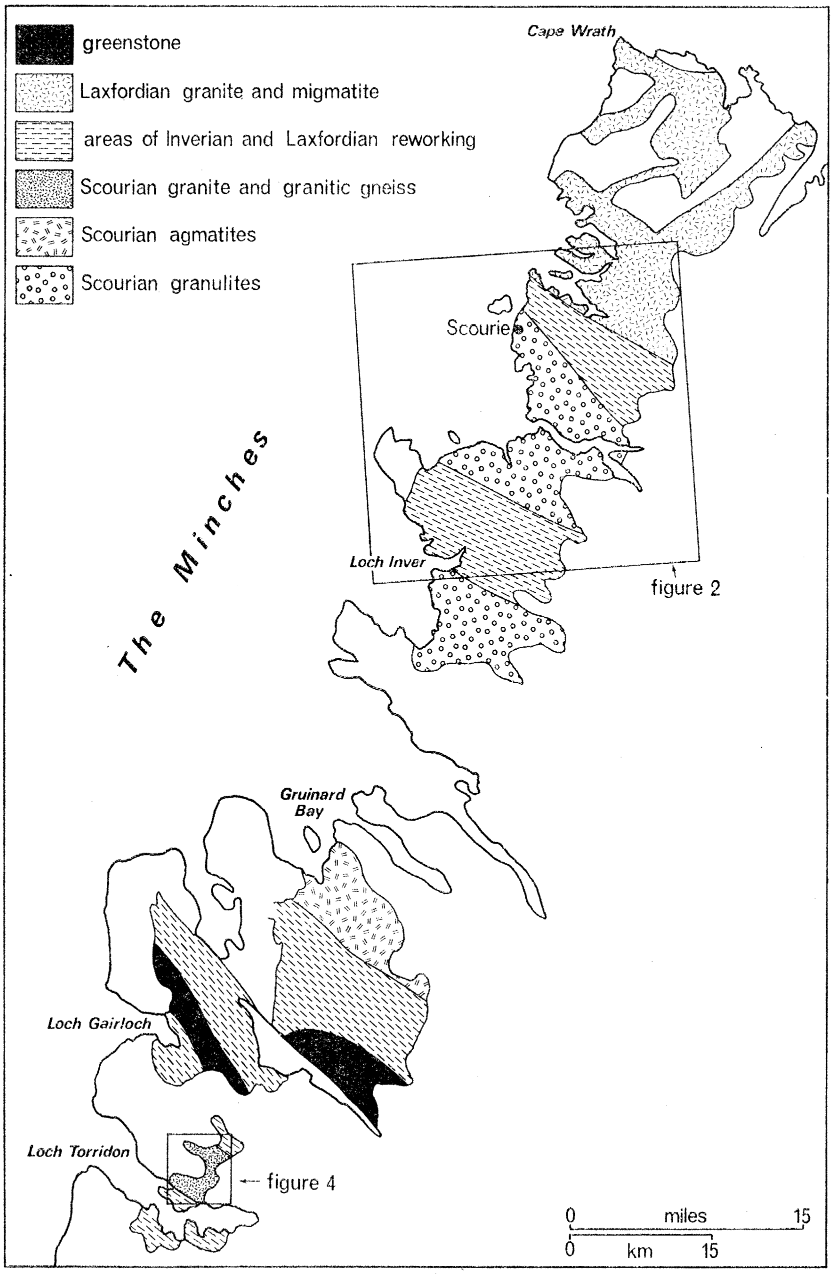

FIGURE 1. The Lewisian complex of the mainland of northwest Scotland, showing the areas in which extensive reworking of Archaean gneisses occurred during the early Proterozoic (Inverian and Laxfordian).

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a large component of simple shear. Where the shear zones cut and displace marker horizons, it is usually possible to estimate the displacement across the zones. Thus, by using members of the regional doleritic dyke swarm, estimates have been made of displacements on shear zones which manifestly post-date and deform the dykes (Beach 1974*a*). These data provide an order of magnitude estimate of the Laxfordian displacement, and indicate that this movement had significant vertical and horizontal components.

Study of the detailed structure within the belt shows that deformation and displacement occurred heterogeneously. Narrow discrete zones record high values of shear strain, while the areas in between record very low strains (Beach 1974*a*).

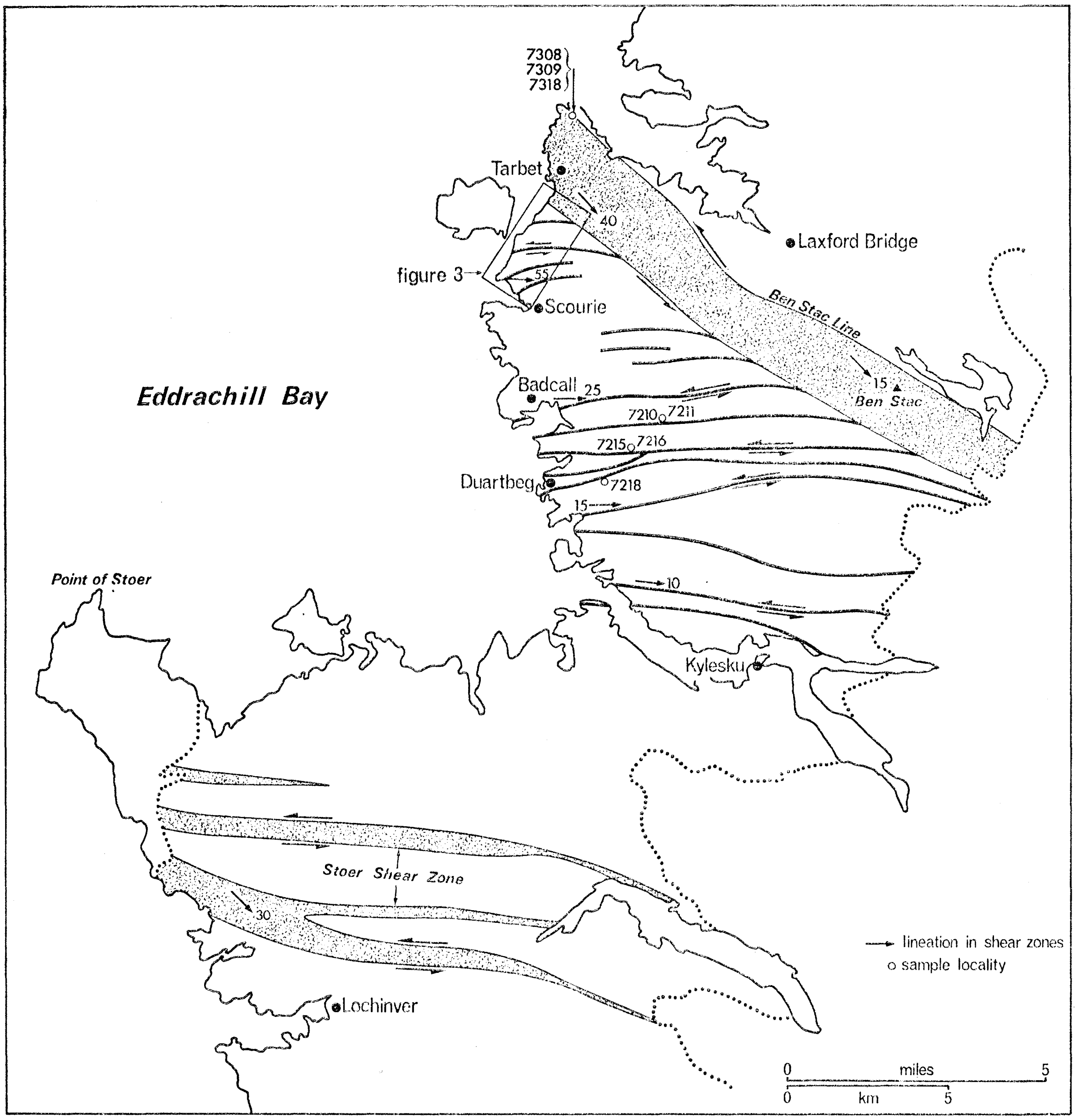

FIGURE 2. The principal shear zones of the Assynt–Laxford area. Arrows show the sense of horizontal movement on these zones. Localities of samples referred to are indicated.

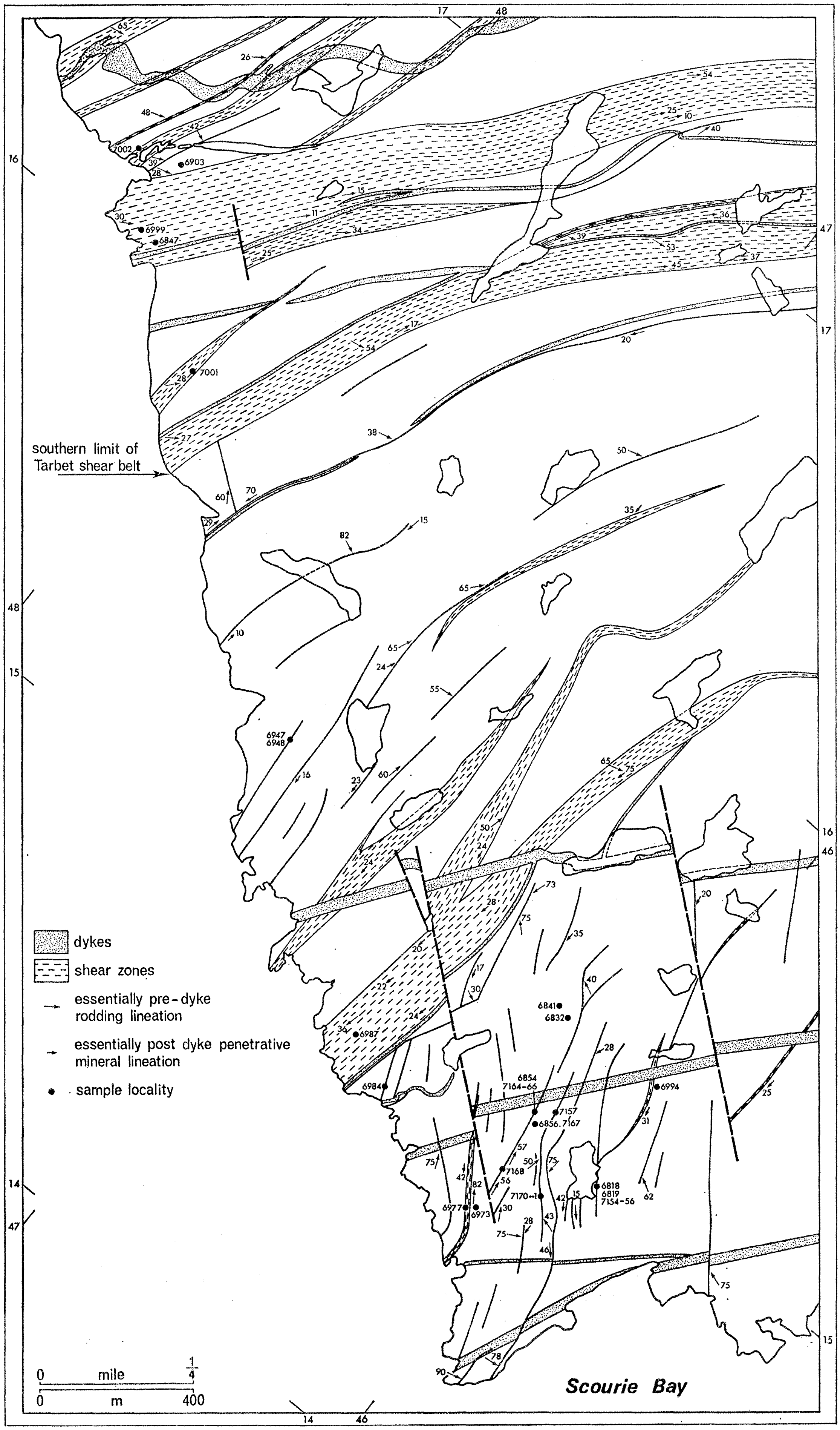

FIGURE 3. Shear zones in the area between Scourie and Tarbet (see figure 2 for location of area). Large shear zones are in dashed ornament, narrow zones are drawn as solid lines. Localities of samples referred to are indicated.

Table 2. Details of early Proterozoic shear zones referred to in this paper

area	Laxford-Tarbet	S. Tarbet-Scourie	Badcall-Kylesku	Stoer-Lochinver	Torridon
pre-dyke deformation	E–W trending folds	narrow shear zones	narrow shear zones	E–W trending folds	variable
post-dyke deformation	shear zones	shear zones	shear zones	shear zones	shear zones
strike of shear zones	ESE–SE	NE–ENE	E–ENE	E–ESE	SE–SSE
dip of shear zones	60° to SW	vertical–steep to SE	vertical	60° to SW	70° to NE
estimated Laxfordian shear strain, γ	10	1	1	no estimate, but probably less than Tarbet	no estimate
plunge of Laxfordian mineral lineation in shear zones	20–40° to SE	ESE at 40°–NE at 60°	E at 0°–20°	SE at 30°	SE–NE at 40°–60°
sense of movement	sinistral oblique-normal NE side upwards	sinistral oblique-normal and normal N side upwards	sinistral transcurrent —	sinistral oblique-normal NE side upwards	sinistral oblique-reversed NE side upwards
see figure, this paper	2, 3	3	2	2	4
references to quoted data	Beach *et al.* (1974) Beach (1974*a*)	Beach (1974*b*) Beach (1973)	Beach (1974*a*)	Sheraton *et al.* (1973*b*)	Cresswell (1972) Sutton & Watson (1969)

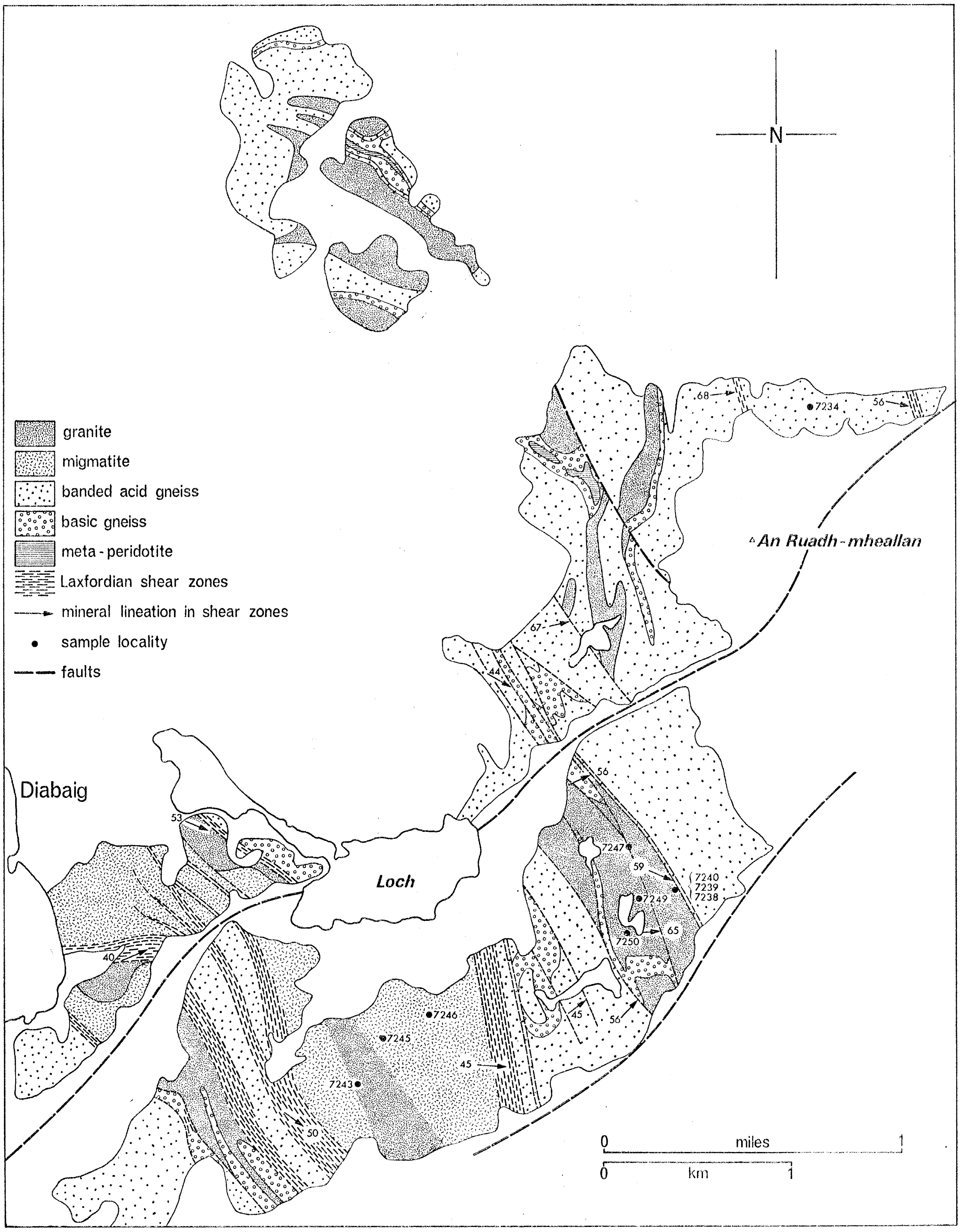

FIGURE 4. Lithologic map of the Archaean gneisses north of Loch Torridon. Proterozoic shear zones are shown, but members of the dyke swarm have been omitted (see figure 1 for location of area). Localities of samples referred to are indicated.

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Data on the variation in deformation, orientation of shear zones, etc., for the areas under discussion are presented in table 2. Some of the data are taken from the literature, and references are given in the table.

Rocks of Archaean age occupy a relatively small area north of Loch Torridon (figure 1) and are surrounded on three sides by Torridonian sediments. The Archaean rocks are dominantly banded gneisses of granitic composition intruded by irregular domes of granite (figure 4).

The banded gneisses have been reworked along a relatively narrow zone into migmatites which contain irregular patches of granite. The whole complex was subsequently cut by a number of shear zones formed contemporaneously with the intrusion of the regional doleritic dyke swarms (S. Jack, private communication). Details of the structures are presented in table 2.

(*b*) *Discussion*

Following the chemical and mineralogical studies of gneisses reworked during the early Proterozoic by Burwash & Krupicka (1969, 1970), Burwash, Krupicka & Culbert (1973) present deep crustal seismic profiles in part of the Churchill province of west Canada. The crust in this region is characterized by discontinuities in thickness, which the authors interpret as faults and shear zones extending to the mantle. These authors suggest also that these shear zones channelled mantle derived fluids upwards through the crust during Proterozoic reworking.

There are no similar seismic profiles for northwest Scotland. However, the major shear zone in the Scourie–Laxford region, with its significant vertical and horizontal movement, almost certainly penetrated to the mantle.

Small scale shear zones show decreases in displacement along their length of the order of 1 cm in 10 cm. Arguing the same order of magnitude for large shear belts, a displacement of 20 km would die out in a distance of 200 km in the direction of displacement. However, large shear zones cannot penetrate such distances vertically downwards because of the changes in composition encountered in the upper mantle. It is possible that a zone of decoupling exists at the base of the lithosphere.

3. Mineralogical changes during reworking

An important conclusion first recorded by Teall (1885) and re-emphasized in recent years is that most gneisses that have been reworked in both small and large shear zones have a mineralogy very different from that of the original gneiss. It appears that the extent to which mineralogical changes occur is often in proportion to the intensity of deformation. These changes also imply distinct chemical differences between the parent gneiss and the sheared rock. A study of Laxfordian shear zones around Scourie clearly illustrates these points (Beach 1973).

In this section, samples from a slightly larger area, effectively from the Scourie–Tarbet section, are discussed. Representative modal analyses of samples from early shear zones (pre-dyke) and later shear zones (post-dyke) illustrate changes in mineralogy through time. In addition, samples from larger shear zones at Tarbet are discussed. Details of the samples studied are given in table 3, while the modes are presented in table 4.

Three rock groups are represented by these samples – acid to intermediate gneisses, granite sheets and basic to ultrabasic gneiss. Acid and intermediate gneisses form about 90% of the Scourian complex in this region, and the mineralogical changes that occurred during

TABLE 3. DETAILS OF SAMPLES DISCUSSED IN THIS PAPER

area	location	rock types	sample numbers	modal-chemical analysis given in this paper		structure from which sample was collected or or reference to data source
Laxford granite zone	see ref.	deformed dolerite dykes		—	—	Burns (1958)
Ben Stac Line	figure 2	metagabbro	7308		yes	Relict Scourian mass of low Laxfordian deformation
		sheared metagabbro	7309, 7310		yes	Laxfordian shear zone
Tarbet	figure 3	basic pod	7002	yes		Laxfordian shear zone
		Scourian granite sheet	6847	yes		Laxfordian shear zone
		gneiss	6903	yes		Strong Inverian deformation, low Laxfordian deformation
		gneiss	7001	yes		small Laxfordian shear zone
		gneiss	6999	yes		large Laxfordian shear zone
area NW of Scourie	figure 3	basic pod	6987	yes		Scourian granulite facies
		basic pod	6977	yes		Inverian shear zone
		basic pod	6984	yes		Laxfordian shear zone
		Scourian granite sheet	6818	yes		undeformed
		Scourian granite sheet	7156		yes	undeformed
		Scourian granite sheet	6819	yes		Laxfordian shear zone
		Scourian granite sheet	7155, 7154		yes	Laxfordian shear zone
		gneiss	6832	yes		partly amphibolitized, flat lying Scourian granulite facies
		gneiss	6841, 6948	yes		small Inverian shear zone
		gneiss	6947	yes		large Inverian shear zone
		gneiss	7168, 7170, 7171		yes	small Laxfordian shear zones
		garnet hypersthene granulite	6973, 6994, 7159, 6856		yes	undeformed Scourian granulite
		g-h granulite in shear zones	6854		yes	low deformation in Laxfordian shear zone
			7165, 7164, 7166		yes	moderate deformation in Laxfordian shear zone
			7157, 7158		yes	high deformation in Laxfordian shear zone
Duartbeg	figure 2	gneiss	7210, 7211		yes	Geisgil shear zone (Laxfordian)
		gneiss	7215, 7216		yes	Ruadh Gisgil shear zone (Laxfordian)
			7218		yes	Auskaird shear zone (Laxfordian)
Scourie–Kylesku	see ref.	granulite facies gneiss		—	—	Muecke (1969)
Assynt	see ref.	granulite facies gneiss		—	—	Sheraton *et al.* (1973*a*)
		shear zones		—	—	Sheraton *et al.* (1973*a*)
Torridon	figure 4	banded gneiss	7234		yes	Scourian gneiss
		banded gneiss	7246	yes	yes	Scourian gneiss
		migmatitic granite	7245, 7243	yes	yes	Inverian reworking of banded gneiss
		granite	7249, 7250	yes	yes	Scourian
		granite	7238, 7239, 7240, 7247	yes	yes	deformed in Laxfordian shear zones

deformation in shear zones are clearly shown by these gneisses. Each of the three groups in table 4 is arranged in order of increasing intensity of deformation, with the exception of 6903, which is representative of the areas of low Laxfordian deformation between shear zones in the Tarbet belt.

In general, these modal analyses show that during reworking of the Scourian gneisses, pyroxene is first replaced by hornblende, and then the hornblende is replaced by biotite. Accompanying the growth of biotite is a large increase in the modal percentage of quartz.

Table 4. Modal analyses from the Scourie area

	basic pods				granite sheets			acid to intermediate gneisses							
	6987	6977	7002	6984	6818	6819	6847	6832	6841	6948	6947	7001	6999	6903
plag.	17.1	—	9.7	8.0	55.0	52.8	42.3	52.0	50.3	45.2	55.5	54.0	48.6	47.0
qtz.	—	11.0	—	9.3	32.0	28.6	34.5	0.3	7.0	14.5	17.0	19.4	27.6	13.3
kfsp.	—	—	—	—	6.9	4.0	7.0	—	—	—	—	—	—	—
cpx.	28.1	—	—	—	—	—	—	21.4	6.8	—	—	—	—	—
opx.	12.0	—	—	—	—	—	—	—	—	—	—	—	—	—
parg.	36.1	—	—	—	—	—	—	—	—	—	—	—	—	—
hbl.	6.7	82.5	48.7	29.6	—	—	—	13.8	34.3	36.4	18.7	15.7	—	26.5
biot.	—	—	31.9	34.7	6.0	8.4	4.4	—	1.3	1.3	5.9	8.0	18.2	—
musc.	—	—	—	—	—	6.1	11.7	—	—	—	—	—	—	—
chl.	—	—	—	—	—	—	—	—	—	—	—	—	—	2.9
epid.	—	—	2.4	3.8	—	—	—	—	—	—	—	0.5	4.7	4.4
op.	—	1.8	0.6	tr	0.1	0.1	0.3	2.2	0.2	2.2	2.6	2.1	0.9	0.6
rut.	—	2.6	—	—	—	—	tr	—	1.2	—	—	—	—	—
ap.	—	2.1	0.2	1.8	tr	tr	0.3	0.3	0.5	0.4	0.3	0.3	tr	0.4
cal.	—	—	4.3	12.8	—	tr	—	—	—	—	—	—	—	2.2
sph.	—	—	2.2	—	—	—	—	—	—	—	—	—	—	1.7
count	3200	2100	7800	3600	2500	2600	4900	4900	10100	3500	3700	2500	5300	4700
plag.-an. (%)	46	—	30	30	n.d.	12	4	37	37	34	31	25	24	32

Scourian granite sheets occur sporadically throughout the granulite facies complex and the most significant feature of these rocks is the occurrence of muscovite in the shear zones. Much larger masses of Scourian granite occur north of Tarbet, in the Claisfearn and Foindle zones of Sutton & Watson (1962). These granites record strong Laxfordian shearing and contain abundant muscovite.

In marked contrast to the rocks of the Scourie area, the Torridon complex consists dominantly of amphibolite facies rocks of granitic composition. Two types of reworking have been studied in this area. The later of the two occurs in shear zones of variable width which traverse the complex (see figure 4). However, prior to the intrusion of the dykes, banded gneisses were reworked into migmatites with irregular patches of granite. There now exists a complete transition from banded gneiss containing biotite but little or no potash felspar, to migmatitic granite containing less biotite and significant quantities of muscovite and potash felspar (tables 3 and 5).

Reworking in shear zones is best studied in those zones that cut one of the homogeneous granites in the area. No clear differences exist between the mineralogy of the shear zones and the original granite. However, there is a significant variation in the amounts of muscovite and potash felspar in the shear zone samples (table 5).

Burwash & Krupicka (1969, 1970) interpreted extensive mineralogical changes in a series of acid gneisses in west Canada as the result of reworking of these rocks in shear zones during

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the early Proterozoic. These authors recorded a decrease in modal plagioclase, biotite and hornblende and an increase in modal microcline, epidote, chlorite and muscovite. Thus again reworking of Archaean rocks involved not only deformation and metamorphism, but changes in bulk composition of the deformed rocks.

TABLE 5. MODAL ANALYSES FROM THE TORRIDON AREA

	banded gneiss		migmatitic granite		granite		shear zones			
	7234	7246	7245	7243	7249	7250	7247	7238	7240	7239
plag.	50.0	48.5	48.9	30.5	45.0	42.5	41.9	46.6	43.0	49.8
qtz.	22.2	28.0	29.0	26.2	26.6	26.8	23.9	32.6	28.4	28.4
kfsp.	0.1	1.0	12.4	11.3	12.5	11.6	16.1	11.7	10.0	2.5
hbl.	0.5	—	—	—	—	—	—	—	—	—
biot.	20.1	16.4	5.1	3.3	6.9	5.9	9.6	6.2	9.9	9.5
musc.	—	0.5	3.2	17.5	4.7	7.7	4.5	1.3	3.1	7.1
epid.	5.1	3.4	1.1	11.2	2.9	5.0	3.5	1.5	4.6	2.2
op.	0.1	0.1	tr	tr	0.5	0.2	0.1	tr	tr	0.2
rut.	0.5	0.5	—	—	0.5	—	—	—	—	—
ap.	0.9	1.1	0.3	tr	0.1	tr	0.3	0.1	0.7	0.3
cal.	tr	0.1	—	—	—	—	—	—	—	—
zir.	0.5	0.4	tr	—	0.1	0.3	0.1	—	0.3	—
count	2100	2100	1400	1600	1700	1600	1500	1500	1600	1600

The next section discusses a series of rock analyses that highlight the chemical changes that occurred in shear zones from the Scourie, Lochinver and Torridon areas. The subsequent discussion will then aim at defining the metasomatic processes operative during reworking.

4. GEOCHEMICAL CHANGES IN SHEAR ZONES

In recent years, a number of independent geochemical studies of the Lewisian have been made. Some of these have presented averages of large numbers of analyses, aimed at showing the bulk geochemical differences between the various segments of the Lewisian (Drury 1974; Holland & Lambert 1973; Sheraton 1970; Sheraton *et al.* 1973*a*; Tarney, Skinner & Sheraton 1972).

The exceptionally heterogeneous variation in mineralogy and intensity of deformation, recorded in the previous sections, would suggest that sampling programmes must be related to both the petrology of the rock and to the structural position of the sample in the field. To some extent the analyses of Sheraton (1970) can be used in the present study because they are divided into petrological groups, with samples from shear zones being treated separately. However, the analyses in this and subsequent papers are presented and discussed as group averages, and as will be seen below this procedure precluded these authors making certain important observations on the chemistry of these rocks.

In addition to these existing analyses, some carefully selected rocks from shear zones around Scourie and from Torridon have been analysed to illustrate the geochemical differences that exist between undeformed and sheared rocks. Sample localities have been shown on figures 2, 3 and 4, and details are given in table 3.

It is evident that mineralogical changes as extensive as those found in the shear zones reflect fundamental changes in rock chemistry. Chemical analyses merely substantiate and quantify such changes. The elements showing the greatest changes in concentration in the shear zones are K, Na, Ca, Fe and Mg.

That these changes in the Scourie area are primarily related to pyroxene ⟶ hornblende ⟶ biotite transformations, and only partly to changes in felspar composition, is shown by the relatively small compositional differences between deformed and undeformed gneisses which contain only a small percentage of mafic mineral. In contrast, felspar-muscovite are important during reworking of the gneisses at Torridon. These reactions are discussed in more detail in the next section.

The chief problem that hinders interpretation of the geochemistry of shear zone samples is the extreme variation in the chemistry of the undeformed parent granulite facies gneisses. Only where a distinct and homogeneous rock type can be traced into a shear zone can direct comparisons of chemistry be made. In the present study, this has been done with a few rock types at Scourie and with the granite at Torridon.

However, this problem can be partly surmounted. There are sufficient analyses of the Scourian pyroxene granulites (unretrogressed samples) available (Muecke 1969; Sheraton 1970) to enable any chemical variation or trend in these rocks to be defined. Analyses from shear zones can then be compared with these trends.

The correlation matrix for the Scourian granulite facies gneisses and the Assynt shear zones (table 1) shows clearly some significant correlations between element pairs in the shear zones that do not exist in the pyroxene granulites. Such features can only be the result of metamorphism in an open system. In particular, this correlation matrix shows that TiO_2, Fe_2O_3, FeO, MnO, MgO, CaO and Na_2O underwent substantial readjustment and increased correlation in the shear zones.

The discussion of the geochemical changes that occurred during reworking is divided into three sections – variation in (*a*) potassium and sodium, (*b*) iron and (*c*) calcium and magnesium.

(*a*) *Potassium and sodium*

Figure 5*a* shows a plot of Na_2O against K_2O for the Scourian pyroxene granulites and Assynt shear zones. The granulite facies gneisses show a range in Na_2O, but restricted variation in K_2O. The Assynt shear zones show considerable overlap with this field, and generally contain similar amounts of K_2O, but larger amounts of Na_2O.

Figure 5*b* plots the same variables for shear zones around Scourie (analyses table 6). Strongly deformed samples from major shear zones at Duartbeg (figure 2) plot in a similar position to the Assynt shear zones. Three samples of deformed gneiss from Scourie show slightly higher K_2O contents, while a Scourian granite sheet deformed into a shear zone at Scourie shows a decrease in Na_2O and an increase in K_2O. The latter rock type appears to have been initially chemically and texturally homogeneous. There is considerable enrichment in K_2O in shear zones cutting a garnet-hypersthene granulite (an unusual rock type in this area, discussed in detail by Beach 1973). Close to the northern limit of the Scourian block at the Ben Stac line (figure 2), a series of sheared basic metagabbros outcrop. These shear zones show the largest K_2O enrichment recorded, this being accompanied by a decrease in Na_2O.

It is an unfortunate fact that the dolerites making up the Scourie dyke swarm, initially reasonably homogeneous in composition, underwent little chemical change during Laxfordian shearing (cf. Burns 1966). Reworked dykes seldom contain more than a small percentage of biotite, and it is frequently possible to trace a Laxfordian shear zone from gneisses, where it contains abundant biotite, to a dyke, where it is biotite free, and back to gneisses where it is again rich in biotite. In contrast, where principal shear zones cross the basic metagabbros, they often contain biotite. Extreme potash enrichment is illustrated by the analyses of sheared metagabbro from the Ben Stac line. However, in many cases, Laxfordian shearing is concentrated around the margins of these metagabbros, the internal deformation recorded being low (see Sutton & Watson 1962).

In general, it appears that there is a regional pattern in the enrichment–depletion of soda and potash within shear zones. In the southern part of the exposed area of granulite facies gneisses, reworking in shear zones has resulted in little change in the potash content and in an

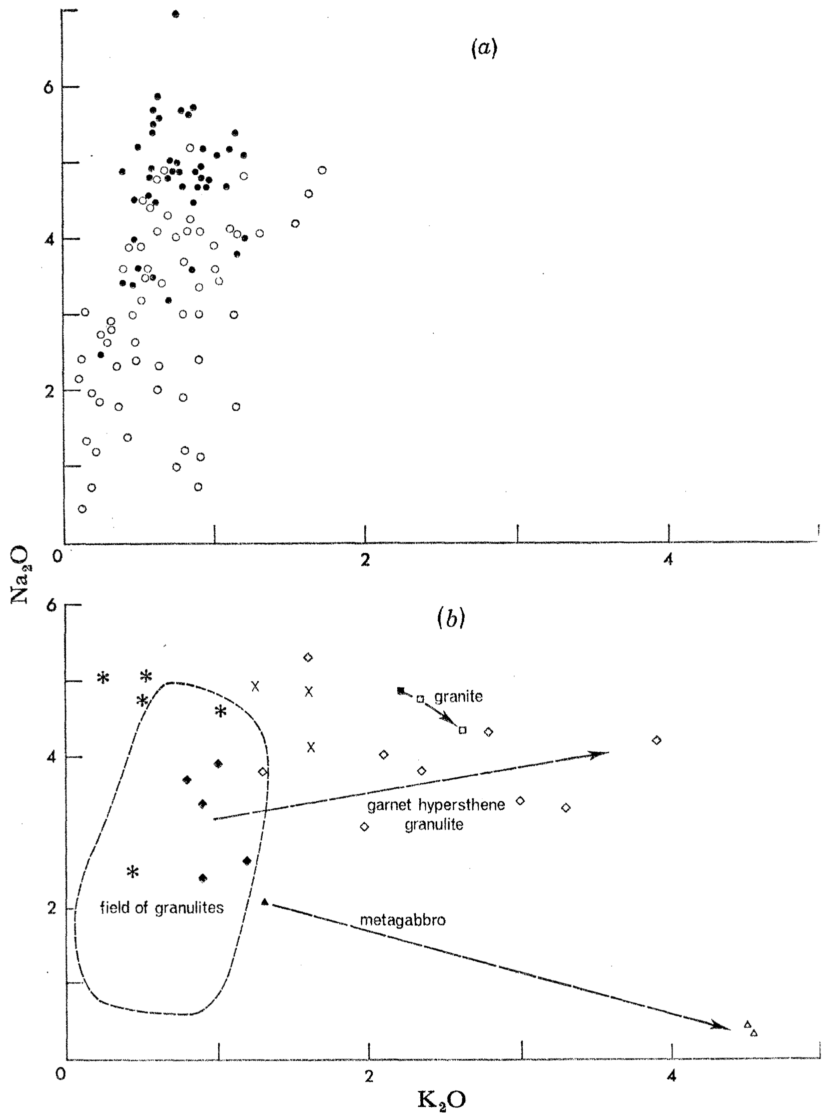

FIGURE 5. Graph of K_2O against Na_2O for (*a*) the Scourian granulite facies gneisses and Assynt shear zones, and (*b*) shear zones in the Scourie area. The following symbols have been used in figures 5*a*, *b*, 6*a*, *b*, 7*a*, *b*, 9*a*, *b*: ○, Scourian granulite facies gneiss; ●, gneisses from the Assynt shear zones; ⁎, gneisses from the Duartbeg shear zones; ×, gneisses from the Scourie shear zones; ■, Scourian granite sheet, undeformed, and □, in shear zone at Scourie; ◆ garnet hypersthene granulite, undeformed, and ◇, in shear zones at Scourie; ▲, metagabbro, undeformed, and △, in shear zone close to Ben Stac line.

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TABLE 6. CHEMICAL ANALYSES OF SAMPLES FROM THE SCOURIE AREA

	6973*	6994*	7159	6856*	6854	7165	7164	7166	7157	7158	7156	7155	7154	7308	7309	7310	7210	7211	7215	7216	7218	7168	7170	7171
	U†	U	U	U	S	SS	SS	SS	SSS	SSS	U	SS	SSS	U	SS	SSS	SSS	SSS	SSS	SSS	SSS	SS	SSS	SSS
SiO_2	54.3	57.2	55.9	56.2	52.9	62.8	61.2	58.8	69.4	55.6	71.2	69.9	71.6	50.0	48.6	49.8	55.7	59.8	51.6	65.6	64.9	64.2	60.0	57.7
TiO_2	1.2	1.0	1.0	1.0	1.2	0.8	0.9	0.9	0.5	1.1	0.1	0.3	0.4	0.7	0.3	0.4	1.2	0.7	0.9	0.5	0.5	1.4	0.7	0.8
Al_2O_3	16.3	16.0	17.3	17.0	20.5	16.8	17.8	19.3	15.5	19.2	16.6	16.2	14.8	11.1	8.4	8.7	16.5	16.4	16.4	15.8	16.4	16.9	16.7	17.6
Fe_2O_3	3.1	2.7	1.3	1.9	1.5	1.0	1.0	0.8	0.9	3.0	0.7	0.5	0.6	3.4	2.4	2.1	3.4	2.0	4.3	1.2	1.5	2.3	1.9	2.2
FeO	10.8	8.4	8.9	8.1	8.5	6.8	5.9	5.7	3.3	6.8	0.9	1.4	1.9	7.1	6.2	6.0	5.2	4.3	6.4	2.6	2.5	2.5	4.6	5.2
MnO	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2
MgO	4.6	4.3	3.9	4.3	3.1	2.0	2.4	2.3	1.4	2.6	0.5	0.7	0.9	12.8	18.5	18.3	3.9	3.6	6.0	1.8	2.2	1.4	3.2	3.0
CaO	4.1	3.1	3.5	4.5	2.0	1.6	1.4	2.5	2.0	2.9	2.8	2.3	1.6	8.5	6.4	5.7	6.7	5.7	9.4	4.6	5.1	4.1	3.9	3.5
Na_2O	2.4	3.9	2.8	3.7	4.2	3.4	4.3	5.3	3.0	3.8	4.8	4.8	4.3	2.1	0.4	0.3	5.0	5.0	2.5	4.6	4.7	4.9	4.1	4.7
K_2O	0.9	1.0	2.6	0.8	3.9	3.0	2.8	1.6	2.0	2.4	2.2	2.4	2.6	1.3	4.5	4.5	0.2	0.5	0.4	1.0	0.5	1.3	1.6	1.5
H_2O^+	1.1	1.1	1.4	1.1	1.1	1.1	0.9	1.5	1.1	1.4	0.5	0.8	1.3	1.8	1.8	1.6	0.9	1.0	1.1	0.8	1.0	0.7	2.0	2.0
P_2O_5	0.1	0.1	0.2	0.1	0.1	0.0	0.1	0.2	0.3	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.4	0.2	0.1	0.2	0.1	0.3	0.3	0.2
CO_2	—	—	0.2	—	—	—	—	—	—	—	—	—	—	—	0.4	0.4	—	—	—	0.7	—	—	—	—
Cr_2O_3	—	—	—	—	—	—	—	—	—	—	—	—	—	0.2	0.4	0.4	—	—	—	—	—	—	—	—
S	0.3	0.2	1.0	0.4	0.9	1.1	0.6	0.3	0.0	0.2	—	—	—	—	—	—	0.1	—	—	—	—	—	—	0.7
total	99.2	99.1	99.7	99.6	99.7	100.0	99.1	99.2	99.6	99.2	100.3	99.3	100.0	99.1	98.5	98.4	99.3	99.3	99.5	99.4	99.6	99.9	99.0	99.0

* Analyses by wet methods, except those marked (= XRF): analyst, M. S. Brotherton.

† U, undeformed sample adjacent to shear zone. S, SS, SSS, weakly deformed, moderately deformed, strongly deformed, respectively, samples from shear zones.

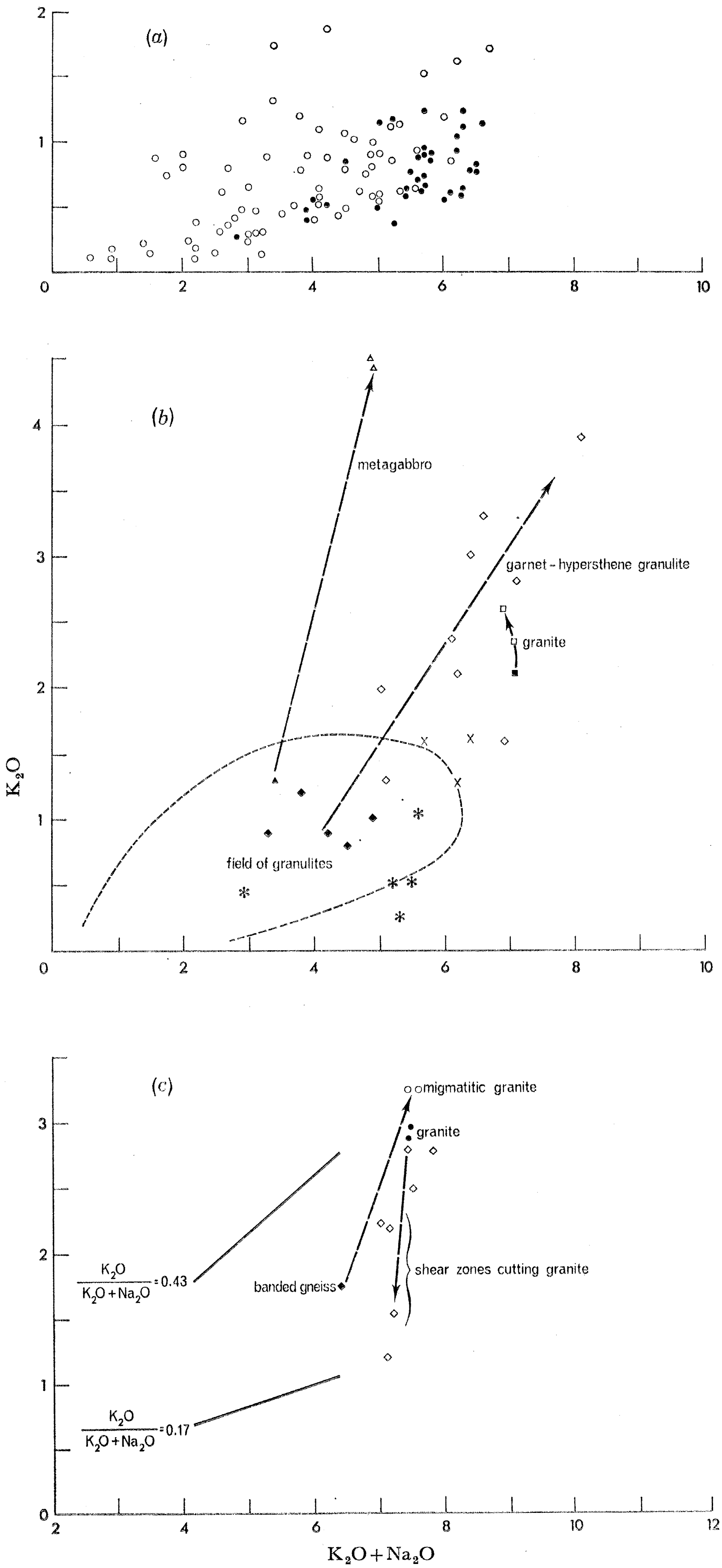

FIGURE 6. Graph of K_2O against (K_2O+Na_2O) for (*a*) the Scourian granulite facies gneisses and Assynt shear zones, (*b*) shear zones in the Scourie area and (*c*) the granitic rocks from north of Loch Torridon. Symbols used in (*a*) and (*b*) are as for figure 5.

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increase in the soda content. Northwards to Scourie and Laxford, increases in potash become increasingly significant and are accompanied by depletion of soda. This pattern could reflect a variation in the chemistry of the source area from which the alkalis were derived. This will be discussed later.

Variations in alkali contents are interpreted as the result of metasomatic activity focused along shear zones, enrichment of alkalis occurring during fluid transport along these zones. Analyses such as those from the garnet-hypersthene granulite show that the enrichment of potash is proportional to the intensity of deformation in a cross-section of a shear zone. The arrows on figure 5*b* show the general chemical trend with increasing deformation of the Scourian granite sheet, garnet-hypersthene gneiss and metagabbro.

TABLE 7. CHEMICAL ANALYSES OF SAMPLES FROM THE TORRIDON AREA

	7246	7245	7243	7249	7250	7247	7240	7238	7239
SiO_2	67.1	71.5	71.0	71.0	70.3	72.2	70.8	72.5	72.0
TiO_2	0.5	0.2	0.2	0.3	0.3	0.2	0.3	0.2	0.3
Al_2O_3	15.5	15.4	15.1	51.3	15.5	15.5	15.7	15.1	15.5
Fe_2O_3	0.9	0.4	0.4	0.8	0.8	0.4	0.4	0.4	0.5
FeO	2.8	1.0	0.9	1.1	1.3	1.4	1.5	0.9	1.2
MnO	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MgO	1.4	0.6	0.7	0.8	0.8	0.7	0.8	0.5	0.8
CaO	3.3	2.1	2.3	2.3	2.2	2.1	2.2	2.0	1.9
Na_2O	4.7	4.4	4.2	4.4	4.7	4.5	4.7	5.6	5.9
K_2O	1.8	3.3	3.3	3.0	2.8	2.8	2.2	1.5	1.2
H_2O^+	1.0	0.3	1.1	1.2	0.6	0.5	0.6	0.5	0.8
P_2O_5	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CO_2	0.2	tr	0.3	—	—	—	—	—	—
total	99.2	99.3	99.5	100.4	99.3	100.5	99.6	99.3	100.2

Analyses by wet methods: analyst, M. S. Brotherton.

Further relations between potash and soda are illustrated on figure 6 (K_2O against (K_2O+Na_2O)). Again, the Assynt shear zones plot in an overlapping, but different field compared with the granulite facies gneisses. In general, the Assynt shear zones show less scatter and have lower $K_2O/(K_2O+Na_2O)$ ratios than the pyroxene granulites (figure 6*a*). This is true also of the Duartbeg shear zones, while at Scourie, shear zones show an increase in the $K_2O/(K_2O+Na_2O)$ ratio, this trend culminating in the enormous increase in this ratio in the deformed basic rock from close to the Ben Stac line (figure 6*b*).

Figure 6*c* shows a similar plot for the Torridon analyses (table 7). During reworking of the banded gneiss (7246) to form migmatitic-granite (7245, 7243) there is a large increase in the $K_2O/(K_2O+Na_2O)$ ratio, mainly due to increase in potash. During subsequent shearing, this ratio shows a marked decrease in the shear zones compared with the granite (7249, 7250) they deform. The analyses indicate that this decrease was accomplished by loss of potash and gain of soda.

(*b*) *Iron*

In a preliminary investigation (Beach & Fyfe 1972), some importance was attached to variations in the oxidation state of shear zone samples. These variations were interpreted as the result of flow of large volumes of water along the shear zones. More detailed studies of the $Fe^{3+}-Fe^{2+}$ relations within shear zones shows that the interpretations presented in that paper were incorrect. In particular, many shear zone samples show changes in the total iron content relative to undeformed samples, in addition to variations in oxidation state.

Figure 7*a* shows a plot of Fe_2O_3 against FeO for the pyroxene granulites and the Assynt shear zones. The former show a great scatter on this graph, a feature indicative that each sample reached equilibrium in response to local oxidation conditions (presumably during granulite facies metamorphism) and that these conditions varied considerably throughout the

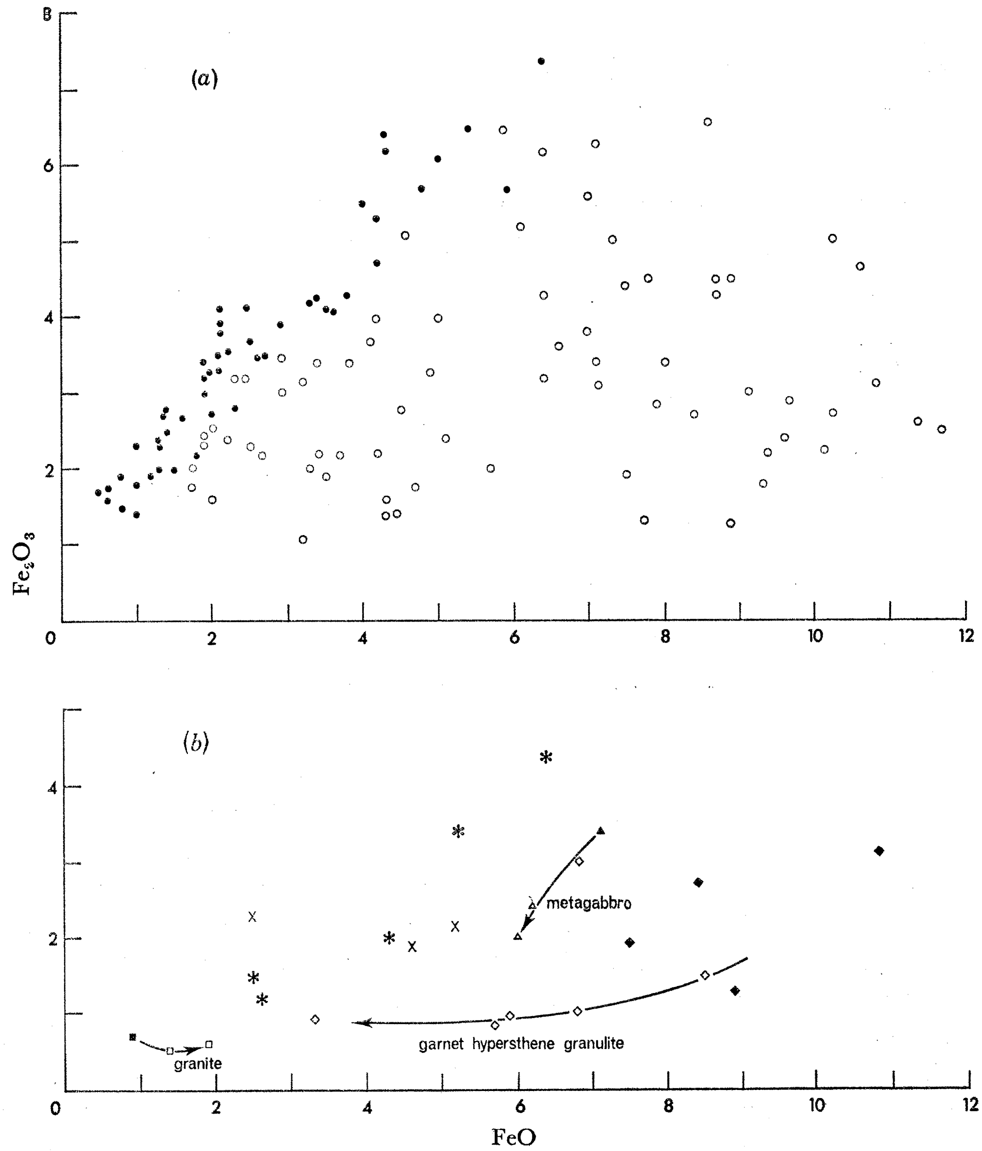

FIGURE 7. Graph of Fe_2O_3 against FeO for (*a*) the Scourian granulite facies gneisses and Assynt shear zones, and (*b*) shear zones in the Scourie area. Symbols used are as in figure 5.

granulite facies complex. It is possible that P_{H_2O} was very low during this metamorphism, and almost certain that water was virtually immobile on a regional scale when the observed oxidation of the rocks was attained.

In contrast, the Assynt shear zones plot in a narrow band with a fairly constant Fe_2O_3/FeO ratio that is higher than any of the granulites (cf. the correlation matrix, table 1).

The marked difference between the granulite facies gneisses and the shear zones suggests that the Fe_2O_3/FeO ratio in all the shear zones reflects an equilibrium between a fluid common to all shear zones and the solid phases in the rock. The properties of this fluid (temperature, pressure, composition) determined the Fe_2O_3/FeO ratio attained in the rock when at equilibrium with the fluid by two means: oxidation equilibria and depletion or enrichment in the shear zones of either Fe^{3+} or Fe^{2+}.

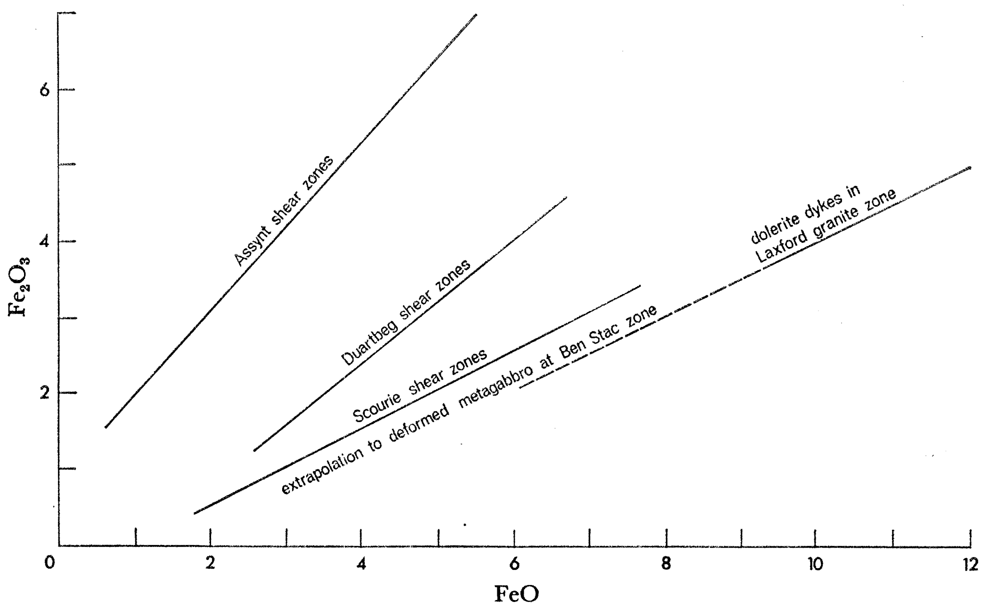

FIGURE 8. An intepretation of figure 7 showing the linear relation established between Fe_2O_3 and FeO in shear zones in different areas.

The second point is well illustrated by the analyses of the granite, metagabbro and garnet-hypersthene granulite from Scourie (table 6). The analyses are plotted on figure 7*b*. For example, shear zones cutting the garnet-hypersthene gneiss have been depleted in Fe^{2+} relative to the undeformed samples, while the sheared granite has been enriched in Fe^{2+}. Although the iron content of the granite at Torridon is low, the analyses suggest (table 7) depletion in Fe^{3+} in the shear zones cutting the granite. The metagabbro shows a loss of both Fe^{2+} and Fe^{3+} during shearing. All these observations indicate that iron was mobile in solution within the shear zones during deformation and metasomatism.

An interpretation of figure 7 is presented in figure 8. Since the Assynt shear zones plot along a straight line, with a strong correlation between Fe_2O_3 and FeO (cf. table 1), it is suggested that this may also be true of shear zones in other areas. Because of the observed proportionality between intensity of deformation and the extent of chemical and mineralogical change in shear zones, analyses of strongly deformed samples should define such a relationship if it exists.

Figure 8 shows the straight line for the Assynt shear zones, and similar relations for (1) five strongly deformed gneiss samples from the Duartbeg shear zones, (2) Scourie shear zones, with two strongly deformed gneiss samples, one strongly deformed granite and two strongly deformed garnet-hypersthene granulites of different composition, and (3) five samples from three metamorphosed dolerite dykes from the Laxford granite zone at Laxford Bridge (analyses from Burns 1958), with the deformed metagabbro, sampled very close to this zone (figure 2), plotting on the same line. Northwards from Assynt to Laxford the implied equilibrium Fe_2O_3/FeO ratio attained during reworking decreases in value.

(c) *Calcium and magnesium*

Modal analyses (table 4) suggest that in the Scourie shear zones biotite formed at the expense of hornblende. It has been inferred (cf. Beach 1973) that since no new calcium bearing phase is present in the shear zones, this element was lost from the shear zones.

A plot of Niggli values Ca against Alk (figure 9*a*) shows a partial separation of the fields

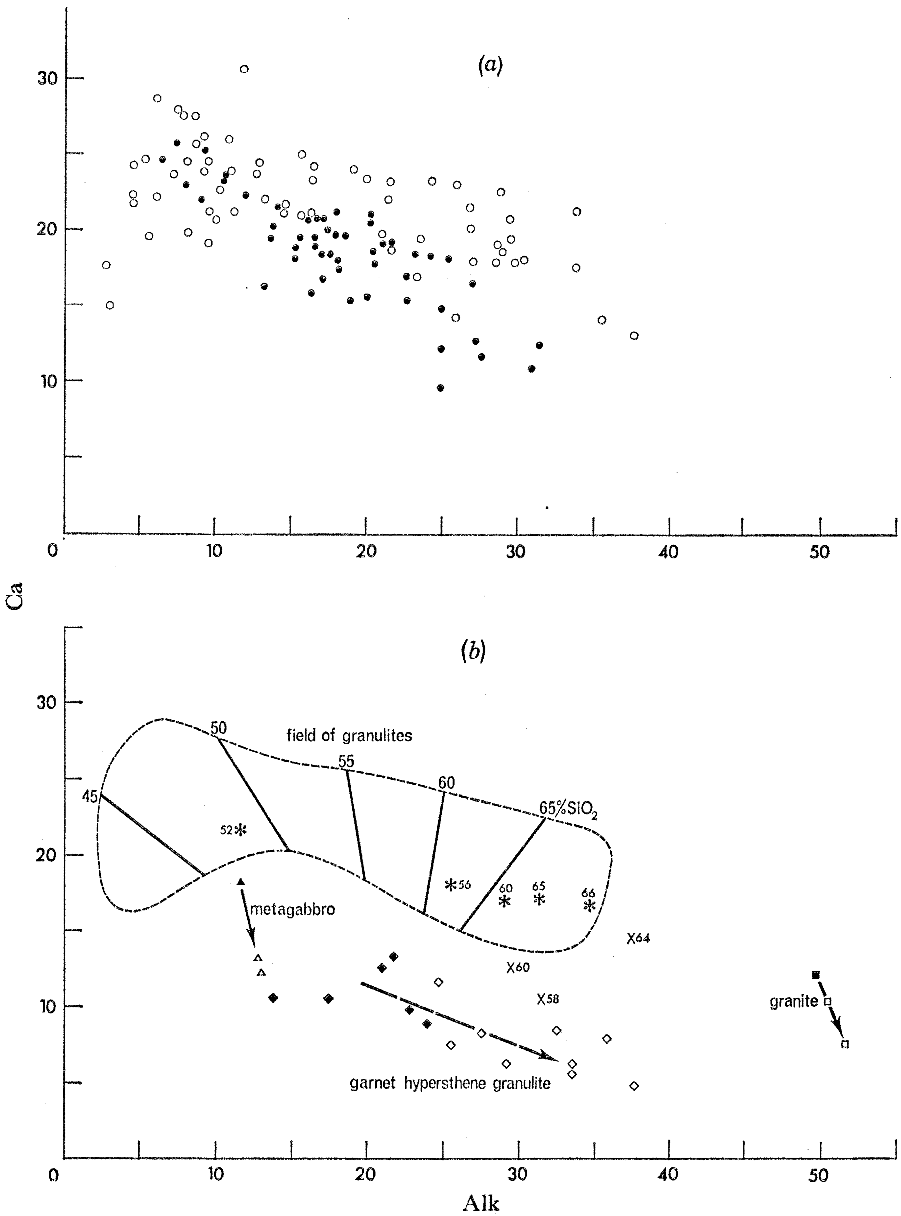

FIGURE 9. Graph of Niggli values Ca against Alk for (*a*) the Scourian granulite facies gneisses and Assynt shear zones and (*b*) shear zones in the Scourie area. The granulite facies field has been calibrated in terms of mass % SiO_2 of these gneisses and is shown in (*b*). Numbers against samples of gneiss from shear zones are the mass % SiO_2 of these rocks. Symbols used are as in figure 5.

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occupied by the pyroxene granulites and the Assynt shear zones. However, changes in calcium content of sheared gneisses are difficult to portray because such changes commonly move the point at which the sample plots along the compositional trend inherent in the pyroxene granulites (as shown for example in figure 9*a*). The Niggli plot illustrated has been used because it is possible to calibrate the field of granulite facies gneisses in terms of the mass percentage of silica of each sample. This is shown in figure 9*b*. When samples of gneiss from Scourie shear zones are plotted on this graph, they may plot in or close to the granulite facies field, but have been shifted in terms of their silica content with respect to the granulite facies rocks. Since there is no obvious evidence for massive silica depletion or enrichment in the shear zones, it is concluded that enrichment of alkalis was accompanied by loss of calcium. This process is clearly brought out by the relation between deformed and undeformed metagabbro, garnet-hypersthene gneiss and granite (figure 9*b*).

In general, magnesium shows a pattern of behaviour very similar to calcium, having suffered depletion from shear zones. The significant increases in correlation of MgO with other oxides in the shear zone samples (table 1) indicates that magnesium was mobile during metamorphism in these zones.

However, the deformed metagabbro from the Ben Stac line shows a large increase in magnesium relative to the undeformed rock (table 6). While many basic and ultrabasic pods, both small and large, in the Scourie area developed mineralogical zoning, analogous to reaction rims, during retrogression, it is true that extreme biotite enrichment is concentrated in zones of strong deformation along the Ben Stac line. It is suggested that the most extensive metasomatic activity seen in the area occurred along this line.

Variations in calcium, and particularly magnesium, contents of the Torridon rocks is slight because of the generally low concentration of these elements in granitic rocks. It is possible that slight calcium loss occurred during reworking of the banded gneiss to migmatitic granite.

5. Mineral reactions in shear zones

The chemical differences between shear zones and adjacent undeformed rocks are considered to have resulted from the interaction of a metasomatic fluid with the mineral phases in the rock. These differences arise partly by exchange reactions between the fluid and the existing phases, and partly by reactions which involve breakdown of existing phases and growth of new phases. A combination of the modal and chemical data allows some generalizations to be made about these mineral reactions. Specific examples have been discussed previously (Beach 1973).

The first stages of metasomatism resulted in the breakdown of pyroxenes in the granulite facies gneisses to hornblende. Detailed mineralogical studies (Beach 1974*b*) indicated that both plagioclase and pyroxene were involved in the reaction and that H^+, Na^+ and Ca^{2+} were mobile during the course of the reaction. This transformation can best be summarized as follows, a reaction that is consistent with the modal analyses presented. The reaction is broken down into two parts for simplicity. Determinations of plagioclase compositions are given in table 4. Mineral formulae are based on actual analyses of hornblende (and biotite) in these gneisses (cf. Beach 1973, 1974*b*).

$$3CaAl_2Si_2O_8 + 3Na^+ + 3Si^{4+} \longrightarrow 3NaAlSi_3O_8 + 3Ca^{2+} + 3Al^{3+}, \qquad (I)$$

$$10Ca(MgFe)Si_2O_6 + Na^+ + 3Al^{3+} + 4H^+ \longrightarrow 2Na_{0.5}Ca_{2.0}(MgFe)_{4.5}Al_{0.5}Si_7AlO_{22}(OH)_2 + 6SiO_2 + 6Ca^{2+} + (MgFe)^{2+}. \qquad (II)$$

Thus the complete reaction may be summarized as

$$3 \text{ anorthite} + 10 \text{ clinopyroxene} + 4Na^{+} + 10H^{+} \longrightarrow 3 \text{ albite} + 2 \text{ hornblende} + 3 \text{ quartz} + 9Ca^{2+} + (MgFe)^{2+} + 6(OH)^{-}.$$

This reaction involves a reduction in the volume of the solid phases of 4 %. Water is involved in the reaction in the form of dissociated ions. This reaction is quantitatively very significant since large areas of Scourian granulite facies gneiss have been amphibolitized and contain 10–30 % hornblende. Amphibolitization appears to have been important in shear zones that developed prior to (and perhaps during) the intrusion of the regional doleritic dyke swarm throughout the whole of the Scourie–Assynt area. During the subsequent Laxfordian reworking, amphibolitization almost certainly continued in the area, while in the Scourie–Laxford area alone, formation of biotite in shear zones also occurred.

Modal analyses indicate that biotite formed at the expense of hornblende, the reaction also producing quartz. At the same time, plagioclase tended to become more sodic (see table 4). Thus the reaction forming biotite may be written as a plagioclase equilibria (as above) and the following breakdown of hornblende:

$$2Na_{0.5}Ca_{2.0}(MgFe)_{4.5}Al_{0.5}Si_7AlO_{22}(OH)_2 + 2K^{+} + 8H^{+} \longrightarrow K_2(MgFe)_{4.5}AlSi_6Al_2O_{20}(OH)_4 + 8SiO_2 + 4.5(MgFe)^{2+} + 4Ca^{2+} + Na^{+} + 8(OH)^{-}.$$

This reaction involves a reduction in the volume of the solid phases of 7.5 % and portrays all the losses and gains of ions that are suggested by the rock analyses discussed in the previous section. Again, this reaction is quantitatively very significant in the evolution of this early Proterozoic belt in that large volumes of rock have been extensively biotized.

The above reactions have been written as ionic equilibria to emphasize the metasomatic nature of the system, i.e. the interaction of relatively large volumes of fluid with the rock in the shear zones. This procedure has been encouraged by Gresens (1974).

Volumetrically insignificant, but mineralogically interesting, reactions occur in shear zones that deform the garnet-hypersthene granulite and have been discussed previously (Beach 1973). From the mineral assemblages in these shear zones it was suggested that metamorphism occurred at about 600 °C and 600 MPa. The most significant feature of these reactions is that they produce kyanite and sillimanite.

Rocks of granitic composition occur only in small amounts in the Scourie area, and the following reactions have been deduced to have occurred during shearing of these rocks

$$3KAlSi_3O_8 + 2H^{+} \longrightarrow KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + SK^{+}, \qquad \text{(I)}$$

$$NaAlSi_3O_8 + CaAl_2Si_2O_8 + SiO_2 + 4.5(FeMg)^{2+} + 2K^{+} + 6(OH)^{-} \longrightarrow K_2(FeMg)_{4.5}AlSi_6Al_2O_{20}(OH)_4 + Na^{+} + Ca^{2+} + 2H^{-}. \qquad \text{(II)}$$

Thus the total reaction is

$$3 \text{ microcline} + \text{albite} + \text{anorthite} + 4.5(FeMg)^{2+} + 6(OH)^{-} \longrightarrow \text{biotite} + \tfrac{1}{2} \text{ muscovite} + 5 \text{ quartz} + Na^{+} + Ca^{2+}.$$

A similar reaction may be important during the reworking of the banded gneiss at Torridon, though it is difficult to formulate a reaction that accurately describes the mineral transformations in these rocks. Certainly, significant variations in microcline and muscovite content are found in the sheared granites. Epidote is also an important phase in some of these rocks.

6. The nature of the metasomatic fluid

In the reactions discussed above, three very important variables governing equilibria are the activities of Na^+, K^+, and H^+ in the metasomatic fluid. As suggested, reactions may be classified as (*a*) those involving hydrogen metasomatism, in which H^+ or OH^- are added to the rock and cations are released into the fluid, and (*b*) those involving cation exchange.

The geochemical data indicate that the type of metasomatic system active in the shear zones is that familiar to hydrothermal geologists and termed infiltration metasomatism by Korzhinskii (1970), i.e. a system with a significantly high water/rock ratio. In general, the rock will change its composition during metasomatism as it tends towards equilibrium with the fluid, such a process being accomplished by hydrogen metasomatism and cation exchange. The nature of the fluid phase is determined by the rocks in the source region where it originated and was presumably in equilibrium with these rocks. The fluid phase, once it has separated from its source and is travelling along shear zones through different rocks, will undergo a gradual change in nature as it interacts with these rocks.

Curiously, there is generally no evidence for massive depletion or enrichment of silica in shear zones. Water derived from a severely undersaturated source would undoubtedly give rise to desilication (as for example occurs during fenitization; Currie & Ferguson 1971; Curie 1971). Only in the Duartbeg shear zones south of Scourie do considerable syntectonic segregations of quartz occur. These do not appear to have been derived locally from surrounding rock and may indicate that silica was precipitated from supersaturated, cooling solutions. However, the question remains as to why there is generally no loss or gain of silica from shear zones in the Scourie–Laxford area.

Alkalis formed an important constituent of the metasomatic fluid, and the hydrothermal studies of equilibria between an aqueous phase and granite (Burnham 1967) may help one to understand the behaviour of alkalis in the shear zones. These studies showed that the $K/(K+Na)$ ratio in the aqueous phase was lower than in the coexisting granite solid. However, this ratio is virtually independent of temperature because the ratio in the solid remains constant. Different rock types will impart different $K/(K+Na)$ ratios to fluids in equilibrium with them. If such a fluid moves out of its source region, it will carry with it a $K/(K+Na)$ ratio characteristic of this region, and as the fluid travels along shear zones, the ratio in the shear zone rocks will be altered.

A fluid derived from a basaltic source region would be expected to have a very low $K/(K+Na)$ ratio, and could leach potash from a granite. A fluid derived from a granitic source would have a very much higher $K/(K+Na)$ ratio and would enrich intermediate composition gneisses in potash if brought into contact with them.

The supposition that chemical change might occur when fluid and rock interact in a shear zone depends on one very important factor – the nature of the reactions involved. If the reactions are of the cation exchange type, then adjustment of the alkali ratios may be attained fairly easily. This kind of process probably occurs in granitic rocks where metasomatic reactions may be dominated by cation exchange in felspars.

If the reactions involve growth of a new phase, e.g. biotite, then potash enrichment can only occur if biotite is stable with respect to hornblende. In the parts of the shear zones at Scourie that traverse doleritic dykes, there is no potash enrichment because hornblende remained stable with respect to biotite in these rocks.

It is therefore not justified to conclude at this stage that the fluid affecting the Assynt shear zones was derived necessarily from a potash poor region. The fluid affecting the Scourie shear zones was manifestly rich in potash. Not only was potash metasomatism restricted mainly to the Scourie–Laxford area, but it was also essentially Laxfordian in age. The earlier (Inverian) metasomatism resulted in extensive amphibolitization (Beach 1974*b*, cf. Elliott 1973; Field & Elliott 1974). Further, Sheraton *et al.* (1973*a*) state that metasomatic retrogression of the Assynt rocks was almost completely accomplished prior to the intrusion of the dyke swarm. In the Laxfordian shear zones in this region there was no further significant change in mineralogy, merely strong recrystallization of existing phases.

If the reactions (see previous section) for the formation of hornblende and biotite are reasonable descriptions of the real system, there are two significant points concerning these reactions

(*a*) the formation of hornblende involves addition of Na^+, the formation of biotite the addition of K^+;

(*b*) both reactions would only occur if the fluid involved had a low pH (reactions consume H^+, produce OH^-).

There are thus three possible reasons for the absence of extensive biotite formation in shear zones south of Scourie

(i) potash was absent from the metasomatic fluid;

(ii) the fluid had a high pH (low concentration of H^+);

(iii) the rocks were at a higher ambient temperature than those further north, making hornblende stable with respect to biotite, other factors being the same.

Returning briefly to the hydrothermal experiments referred to, Burnham (1967) also showed that the presence of dissociated chlorides in the fluid phase have two very important effects

(i) chloride solutions contain much greater proportions of K and Na;

(ii) the elements Ca, Fe, Mg, Mn, Ba, and Sr, practically immobile when in contact with pure water, occur in significant concentrations in chloride solutions.

The mobility of Ca, Fe and Mg in the shear zones is considered to indicate that the metasomatic fluid was a chloride solution. The presence of significant amounts of Ba in the biotite in some shear zones at Scourie has also been recorded (Beach 1973). Since large quantities of Ca^{2+} were released during retrogressive reactions (see preceding section), the absence of the phases calcite and anhydrite is indicative of low activity of CO_3^{2-} and SO_4^{2-} in the fluid.

Of particular interest is the variation in Fe_2O_3 and FeO within the shear zones, and the interpretation that can be made of these variations. Loss of iron from shear zones is just one of the effects of the chloride bearing fluid. Attainment of a constant Fe_2O_3/FeO ratio in a group of shear zones (see figure 8) suggests that equilibrium between the rock in the shear zones and a fluid phase with a uniform (buffered) Fe^{3+}/Fe^{2+} ratio, which was common to the shear zones, was reached.

In all the shear zones studied in the Scourie area (with the exception of the deformed granite), the rocks in the shear zone have higher oxidation ratios and lower FeO contents than their undeformed equivalents. Two very simple ways of considering Fe^{3+}/Fe^{2+} equilibria in solution are presented below, one for a chloride free aqueous phase, the other for an aqueous chloride solution.

In a chloride free aqueous phase, the Fe^{3+}/Fe^{2+} ratio may be considered to be buffered by the following hydrolysis equilibria

$$\begin{array}{ccc} Fe^{2+} & & Fe^{3+} \\ + & & + \\ 2(OH)^- & & 3(OH)^- \\ \updownarrow & & \updownarrow \\ Fe(OH)_2 + (OH)^- & \leftrightarrows & Fe(OH)_3 + e \end{array}$$

Although each species will be present in very small concentrations, the presence of a large volume of water will buffer the Fe^{3+}/Fe^{2+} ratio in solution. Also, a more accurate representation of the equilibria would involve the iron hydroxide ions $FeOH^+$ and $Fe(OH)_2^+$. However, thermodynamic data are not available for these species. By using tabulated free energy and entropy data (Robie & Waldbaum 1968; Krauskopf 1967), equilibrium constants for the three reactions at temperatures around 600 °C may be calculated. For a given $(OH)^-$ concentration and temperature, combination of the three equilibrium constants allows an estimate of the Fe^{3+}/Fe^{2+} ratio at equilibrium to be made. The ratio is found to be independent of $(OH)^-$ concentration, and varies with temperature as shown on figure 10.

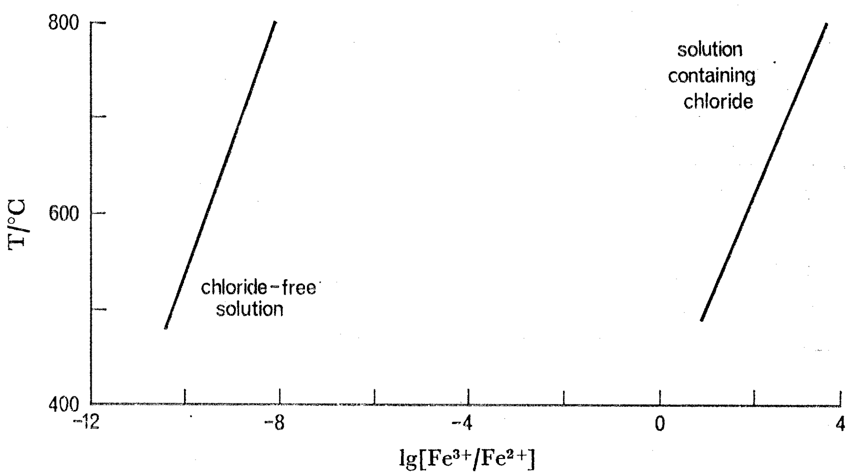

FIGURE 10. Temperature against lg (Fe^{3+}/Fe^{2+}) for the two equilibria discussed in the text.

In the presence of chloride, the equilibria buffering the Fe^{3+}/Fe^{2+} ratio in solution will be different, and may be considered as

$$\begin{array}{ccc} Fe^{2+} & & Fe^{3+} \\ + & & + \\ 2Cl^- & & 3Cl^- \\ \updownarrow & & \updownarrow \\ FeCl_2 + Cl^- & \leftrightarrows & FeCl_3 + e. \end{array}$$

Again, a more accurate representation of the equilibria would involve the complex iron chloride ions. The results of calculations similar to those carried out for chloride free solutions are also shown on figure 10. The equilibrium Fe^{3+}/Fe^{2+} ratio is independent of Cl^- concentration when Cl^- is available and present in excess in solution.

It is apparent that the presence of chloride ions in solution results in substantially higher

Fe^{3+}/Fe^{2+} ratios than in chloride free solutions. Rocks in shear zones undergoing metasomatism by chloride solutions might therefore be expected to adopt relatively high Fe^{3+}/Fe^{2+} ratios as new minerals (e.g. hornblende, biotite) grow. The ability of the new phase to accept Fe^{3+} ions forms an obvious limit to the Fe^{3+}/Fe^{2+} ratio that could be attained by the rock. In addition, haematite has been recorded as a new phase in a number of shear zones, whilst epidote, which is common in the Tarbet shear zones and persistently present in Laxfordian shear zones further south, will also be stabilized by the presence of Fe^{3+}.

In addition to the relations discussed in the Lewisian shear zones, the data of Nash (table 1) from west Greenland shows that a strong correlation between Fe_2O_3 and FeO was established in the shear zones. Currie & Ferguson (1971) have shown that chloride solutions at *ca.* 600 °C were important during fenitization, and their analyses of fenites show very high Fe^{3+}/Fe^{2+} ratios relative to unfenitized country rocks. Finally, Heimlich (1974) records variations in Fe contents in shear zones cutting amphibolites, and Elliott (1973) and Field & Elliott (1974) record adjustment of Fe^{3+}/Fe^{2+} and enrichment of Cl in amphibolites.

It is suggested that the presence of strongly ionized chlorides in solution has a very significant effect both on the mobility of iron and on iron redox equilibria.

In the area under discussion, metasomatic activity occurred over two distinct periods of time. The first event occurred over the time interval from about 2500–2400 Ma up to the intrusion of the dykes (see arguments of Sheraton *et al.* 1973*b*). It was a regional metasomatic event, causing extensive retrogression of the pyroxene granulites throughout the whole area between Lochinver and Laxford. It has been suggested that the metasomatic fluid was characteristically soda rich. The second event seems to be inevitably connected with the formation of the Laxford granites at about 2000–1800 Ma (Lambert & Holland 1972). Metasomatism was limited to a zone extending a few kilometres south of the granite zone, the metasomatic fluid being characteristically potash rich with a very low pH.

Amphibolitization of pyroxene granulites characteristically began before intrusion of the dolerite dyke swarm not only in Scotland but also in west Greenland (Bridgwater *et al.* 1973*a*; J. Watterson, private communication) and would appear to have world wide significance (cf. Escher, Jack & Watterson, this volume). The fluid causing amphibolitization was presumably derived from the mantle and was possibly connected in some way with the generation of basalt magma. It is interesting to note also that many of the doleritic dykes crystallized hydrous mineral assemblages (hornblende).

In conclusion, it is suggested that primary, mantle derived fluids caused extensive retrogression in the early Proterozoic. In contrast, more restricted metasomatism was caused by fluids derived from granite-migmatite in the lower crust. The latter is thought to be related to melting of granite after overthrusting of granite gneiss by the Scourian granulite facies complex (Beach 1974*a*).

7. Thermal effects in shear zones

The importance of three thermal effects in metasomatic shear zones must be considered. These are

(i) exothermic mineral reactions;
(ii) enrichment of radioactive elements;
(iii) convective transport of water.

(a) *Exothermic reactions*

In general a mineral reaction will be exothermic if it occurs at any pressure and temperature below equilibrium, where there is a net release of free energy. The energy released is proportional to the difference between the temperature of reaction and the temperature of equilibrium, multiplied by the entropy change of the reaction. Thus the effective heat produced will be related to

(1) the volumetric significance of the reaction in the rock;
(2) the magnitude of the entropy change for the reaction;
(3) the extent to which the reaction occurs below equilibrium.

Normally, these principles will only be applicable to retrograde mineral transformations.

Few thermodynamic data are available for complex ionic reactions such as those considered to have occurred within the shear zones; mineral stabilities are determined by the activities of a number of ions in addition to pressure and temperature. Thus no quantitative statement about the possible heating effects of exothermic reactions in shear zones can be made.

(b) *Enrichment of radioactive elements in reworked zones*

The geochemical work discussed earlier showed that extensive enrichment of potassium occurred in Laxfordian shear zones. Potassium enrichment is undoubtedly important during Proterozoic reworking of many Archean terrains (cf. Burwash & Krupicka 1969, 1970).

A small part of the potassium will be the radioactive isotope, and the question arises as to whether sufficient potassium is fractionated into shear zones for a short term thermal effect to become apparent. Undoubtedly, such fractionation rapidly concentrates heat sources in higher crustal levels and could be partly responsible for the long term effect of low heat flow over such areas at the present time.

Using the estimated abundance of ^{40}K at 2000 Ma (Bott 1971), the rate of heat production of potassium was 31.1×10^{-5} J g^{-1} a^{-1}. For an enrichment of 2.5 g K/100 per g rock the increase in heat production would be 9.4×10^{-13} cm^{-3} s^{-1}.

Clark (1969) presents a non steady state heat conduction solution applicable to problems where an additional heat source is introduced at a certain depth in the Earth's crust. His equations enable the temperature rise at any depth, resulting from the additional heat source operating over a specified period of time, to be calculated. Solutions have been obtained by using the estimated rate of heat production (given above) from potassium introduced into segments of the Earth's crust between 10 and 15 km, and between 15 and 20 km. After 10 and 100 Ma following introduction of the heat source, the rise in temperature of the rocks is of the order of 20 and 35 °C respectively. This assumes that the potassium is evenly distributed through the rock. More significant heating effects may occur where potassium is locally concentrated in shear zones. However, this process is unlikely to give rise to short term heating effects.

(c) *Convective transport of water*

By far the most important thermal consequence of metasomatism along shear zones is the relatively rapid convective transfer of heat that results from movement of large quantities of water. If a volume of water is separated from a source region somewhere in the lower crust or upper mantle and is transferred upwards, what will be its thermal evolution? Bailey (1970) refers briefly to this problem, pointing out that after upward transfer, water could be at a

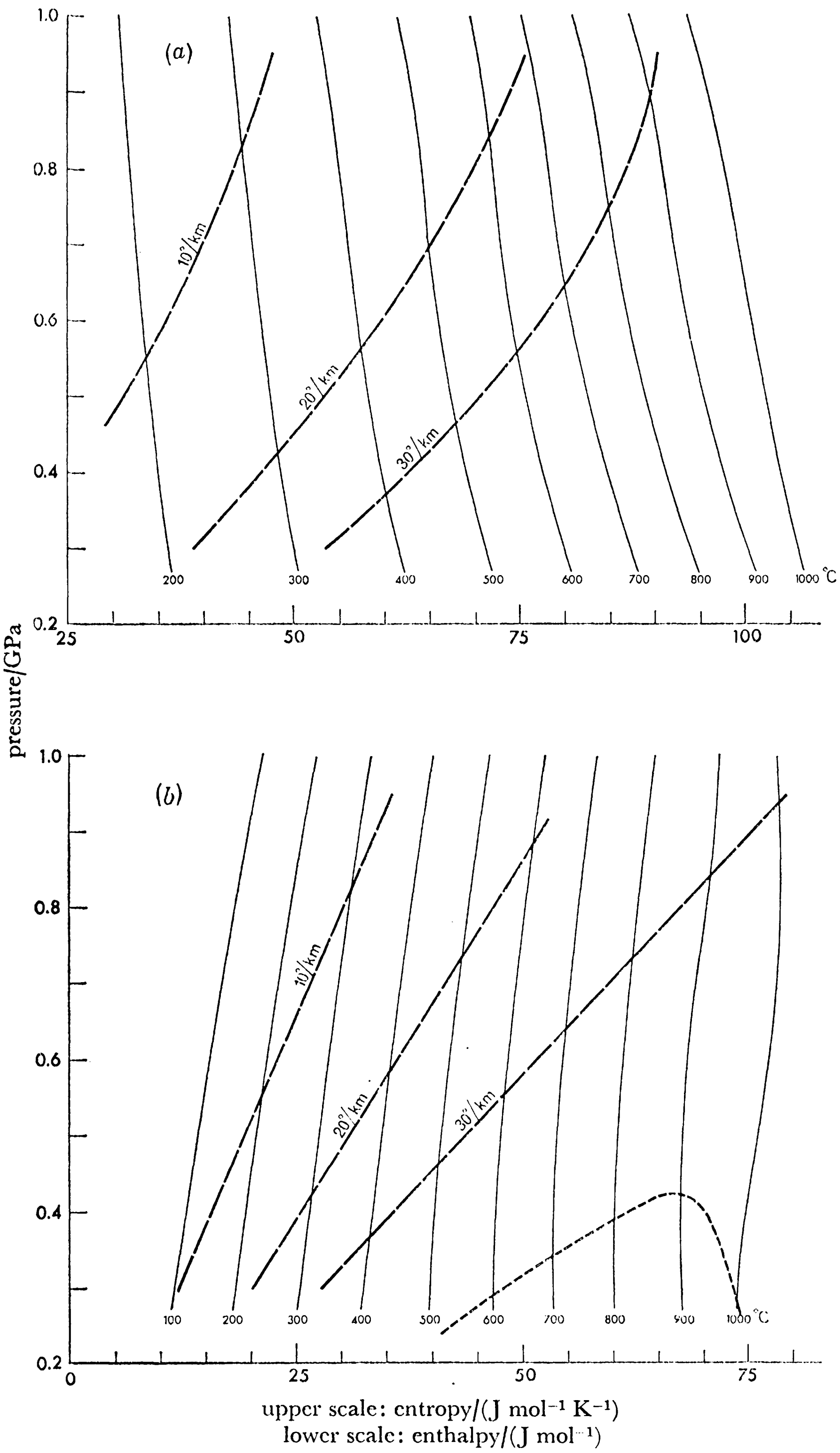

FIGURE 11. Isotherms on (*a*) pressure against entropy graph and (*b*) pressure against enthalpy graph for water. Three geothermal gradients are shown on each and on (*b*) the position of the Joule–Thompson inversion curve for water is indicated.

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temperature above that of its surroundings. In the upper parts of the crust the problem has received attention from the hydrothermal geologist. Their main concern is with processes that lead to cooling of a fluid and hence possible precipitation of dissolved minerals (cf. Toulmin & Clark 1967).

Geologists have considered the ideal cases of isentropic and isenthalpic expansion of water during upward transport through the crust. The former corresponds to slow reversible expansion, the latter to rapid irreversible expansion. This type of treatment ignores all the complexities of how the water passes through and interacts with the rock.

Bailey (1970) used the experiments of Rice & Walsh (1957) to work out temperature changes of water during expansion. The equation of state of Rice & Walsh was derived from shock wave experiments which simulated very high, rapidly varying and transient pressures. The results are not directly applicable to conditions in the lower crust. In contrast, Toulmin & Clark's (1967) concern was the cooling of water during expansion and their conclusions are only valid at very low pressures.

Figure 11 shows isotherms on pressure-entropy and pressure-enthalpy graphs for water; the data is taken from the most recent compilation of the thermodynamic properties of water (Burnham, Holloway & Davis 1969). Shown also are three different geothermal gradients. Both isentropic and isenthalpic transfer of water upwards through the crust result in the water attaining a higher temperature than the existing geothermal gradient. In the case of isenthalpic expansion, the temperature of the water itself actually rises. This is a property common to all imperfect gases at pressures above the Joule–Thompson inversion (cf. Denbigh 1968, p. 120). The maximum pressure on the Joule–Thompson inversion curve for water is about 0.42 GPa at about 900 °C (figure 11*b*).

Whichever type of expansion occurs geologically, it is inevitable that large volumes of water flowing along shear zones will attain significantly higher temperatures than surrounding rocks only a few kilometres above the fluid source region. Thus it is to be expected that the temperature of the shear zones and surrounding rocks will gradually rise during metasomatism and reworking.

It is possible that evidence for rising temperature during metamorphism in shear zones is seen at Scourie, where kyanite producing reactions were superseded by sillimanite producing reactions during the breakdown of garnet (Beach 1973). The high temperature reached during the formation of sillimanite bearing mylonite zones cutting high level granites in Peru (Pitcher, private communication) was probably the result of a similar upward transfer of water.

A more rigorous treatment of the problem would involve calculation of the non steady state heat loss from given quantities of water diffusing at different rates.

8. Deformation and related processes in shear zones

It has been established (Ramsay & Graham 1970) that the deformation state in shear zones can be interpreted as the result of progressive simple shear. Ramsay & Graham studied small shear zones, of the order of a few centimetres in width, but their results are immediately applicable to similar zones up to a few metres in width. It appears that deformation in shear zones several hundred metres in width also occurred by simple shear since these zones show the fabric and symmetry elements of their smaller analogues. For example, LS fabrics are present in larger belts, both foliation and lineation having a constant orientation for large distances, and the deformation appears to be plane. In addition, Escher & Watterson (1974) have presented arguments suggesting that deformation in large and small linear belts in the Earth's crust must be dominated by simple shear. These authors consider that the observed continuity of lithologic horizons across linear belts and the compatibility of the deformed belt with the adjacent undeformed rock indicate that simple shear was the principal deformation pattern.

One of the characteristic features of shear zones formed under metamorphic conditions is that profiles of shear strain against distance across the zone show very steep strain gradients at the edges and high, but fairly constant shear strain across the central portion. This is illustrated schematically in figure 12*a* (see also Ramsay & Graham 1970).

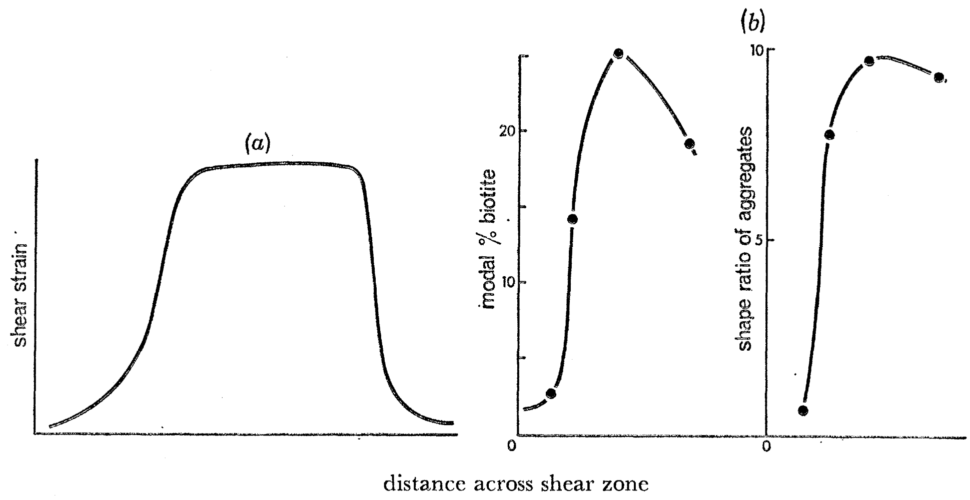

FIGURE 12. (*a*) Generalized profile of shear strain across a shear zone. (*b*) Percentage biotite and intensity of deformation across one half of a shear zone from Scourie.

The most important feature of a shear zone is that the rock outside the zone remained altered while deformation proceeded in the zone. This was the critical boundary condition used by Ramsay & Graham (1970) in their deformation studies, and it is an equally important boundary condition to metamorphic and geochemical studies.

Ideally, original metamorphic and igneous textures are preserved outside shear zones. This has been convincingly demonstrated where shear zones cut granulite facies gneisses, dolerites, granites, etc. (cf. Teall 1885; Ramsay & Graham 1970). Growth of new minerals, recrystallization of existing phases and formation of LS fabrics are entirely confined to the shear zone. Accounts of shear zones repeatedly recognize these features (see, for example, Teall 1885; Sutton & Watson 1959; Boyle 1961; Beach 1973; Sheraton *et al.* 1973*b*; Heimlich 1974; McCallum 1974).

In practice, some retrogression is often seen outside a shear zone, though the hornblende and biotite are always very ragged, poorly crystallized and show no preferred orientation. No recrystallization of existing phases has been found outside shear zones.

In those shear zones discussed in this paper, where new minerals formed, the profile of the percentage of these minerals matches very closely the profile of the intensity of deformation across the zone. This is illustrated in figure 12*b*, where the percentage biotite across a shear zone at Scourie is shown. The deformation in this zone has been judged from the elliptical shape of mineral aggregates.

In the author's experience, the mineral assemblages formed in shear zones are invariably more hydrated (or carbonated, etc.) than the undeformed rock outside the zone. Thus profiles of the percentage of volatiles in the shear zone (see, for example, Boyle 1961) again resemble those of intensity of deformation.

During the evolution of a shear zone, a number of processes occur which are confined to the shear zone. It is convenient at this point to summarize these processes and then to explore the relations that may exist between them.

(i) Deformation, dominated by simple shear type strains, giving rise to

(ii) formation of LS mineral fabrics in the shear zone.

(iii) Growth of new phases and recrystallization of existing phases, resulting in

(iv) overall reduction in grain size.

(v) Transport of large volumes of volatiles, leading to

(vi) mineral reactions and chemical changes, and in general, enrichment of these volatiles in the shear zone.

There is usually no evidence that any of the above processes occurred in the rocks outside the shear zones.

Many of the above processes lead to what can be adequately described as strain softening, that is, to an increase in ductility, or increased strain rate under constant loading conditions. The effect of grain size reduction on increasing ductility is marked and has been discussed by Watterson (1975) and Watterson & White (1975).

Grain size reduction is accomplished by cataclastic deformation and Watterson & White (1975) have suggested that the mechanism of deformation in shear zones was initially a dislocation mechanism. This accomplished grain size reduction leading to strain softening, the mechanism of deformation then being dominated by diffusion processes. The rate of strain by a diffusion mechanism is inversely proportional to the square or cube of the grain size, while that due to a dislocation mechanism is independent of grain size (Elliott 1973). The change in deformation mechanism during the evolution of a shear zone proposed by Watterson & White (1975) is due to the dominance of dislocation processes at large grain size and the increasing importance of diffusion processes as the grain size is reduced. The change is independent of temperature (cf. Elliott 1973). As Green (1970) has pointed out, if diffusion processes alone are the mechanism of deformation in polycrystalline aggregates, then there will be a steady decrease in strain rate as the grains become elongate. Thus steady state deformation can only be maintained if the grain shape remains unchanged, that is, if cataclastic processes continue to operate. Thus cessation of the processes leading to grain size reduction will lead to a decline in strain rate in the shear zone.

The mechanical evolution of deep seated shear zones must be very similar to that established for fault zones and shear zones in upper crustal rocks. The latter process involves the development of an increasing number of microfractures which gradually coalesce. Eventually, a through going shear zone forms. This process, which is entirely cataclastic, has been discussed by Lajtai (1971). The conventionally determined coefficient of sliding friction of a rock at failure is considered by Lajtai to be immaterial in determining the orientation of the shear zone with respect to the principal stresses since the shear zone developed at a very late stage and only after a prolonged history of microfracturing.

Rock deformation experiments have established that the formation of microfractures tends to be suppressed with increasing confining pressure. The almost universal record of cataclastic deformation in deep seated shear zones is at first sight contrary to this notion.

The continuity of deformation across deep seated shear zones (Ramsay & Graham 1970) indicates that fracturing occurs on a microscopic scale (fracture size the same or less than the grain size) during their formation. Macroscopic discontinuities generally do not develop during deformation in shear zones (with the important exception of fractures formed by the intrusion of dykes – see Escher, Jack & Watterson, this volume).

In contrast, macroscopic discontinuities are important in shear zones at higher crustal levels, these giving way to ordinary faults in the uppermost levels of the crust.

Experimental studies of the propagation of fractures (Bieniawski 1967) differentiate between stable and unstable fracture growth. The latter process gives rise to macroscopic fracture planes and loss of strength, the former to microscopic, distributed fractures without loss of strength. The transition from stable to unstable growth of fractures is effected by increasing the principal stress difference, increasing the principal stress ratio, or decreasing the mean stress (Bieniawski 1967; Price 1975).

Thus at deep levels in the Earth's crust, stable fracture propagation will dominate, since stress differences will be lower and mean stress greater than at higher levels (Price 1971, 1975).

The importance of large amounts of fluid in the evolution of shear zones has been demonstrated. Similarly, Phillips (1972) has shown that flow of fluid may be important in the formation or reactivation of macroscopic faults.

Fluids in rocks may move by either grain boundary diffusion or by hydraulic fracturing. It is perhaps inevitable that large volumes of fluid are transported by hydraulic fracturing. Certainly, the rate of flow of fluid during hydraulic fracturing will be much greater than by passive diffusion since in the former process the fluid creates its own permeability.

For hydraulic fracturing to occur, it is sufficient that the fluid pressure reduces the normal stresses acting on the system (principle of effective stress) until either tensile or shear fracturing occurs (cf. Phillips 1972). Rocks can undergo brittle fracturing by this mechanism at any depth in the Earth's crust.

It is suggested that fluid transport along shear zones was accomplished by the mechanism of hydraulic fracturing, this process causing much of the cataclastic deformation in the zones. This implies that the fluid pressure in the shear zones was approximately equal to the confining pressure. The chemical and mineralogical evidence presented indicates that these fluids did not diffuse laterally out from the shear zones and fluid pressures were probably very much lower in these rocks. Thus effective stresses were lower in magnitude in the shear zones than in adjacent rocks.

In addition to grain size reduction by cataclasis, metamorphic reactions, promoted by the presence of the metasomatic fluid, will have resulted in nucleation of small grains. These reactions must also be considered as a strain softening mechanism. Shear zone fabrics indicate that growth of new phases occurred only during deformation in the shear zones. Since the presence of the metasomatic fluid was essential to the continuance of these reactions, it becomes apparent that metasomatism did not continue after deformation had ceased. It is suggested that the converse of this may also be important in the formation of shear zones, that is, that deformation in the shear zones ceased when metasomatism (and therefore metamorphism) ceased.

Two further processes contribute to strain softening in shear zones. First, it has already been inferred that adiabatic expansion of water could result in considerable rise in temperature of shear zones as the water travels upwards. This would lead inevitably to an increase in ductility. Secondly, as hornblende and biotite producing reactions proceed there is a large increase in the modal percent of quartz in the shear zones (table 4). The more felsic rocks will be the more ductile.

In view of all the possible strain softening effects in shear zones, the question arises as to why deformation ceases at all. The conventional answer would perhaps be that the stress difference gradually diminished in value, though this in itself would not curtail hydraulic fracturing.

It is suggested that a more important factor may be the fluid pressure. A drop in the fluid pressure would result in an increase in the magnitude of the effective stresses, and hydraulic fracturing would cease. Transport of fluid along the shear zones by this mechanism would no longer occur, and both cataclastic deformation and mineral reactions would be arrested. The two most important strain softening mechanisms would no longer operate and thus the strain rate in the shear zone would gradually decrease. However, Watterson (1975) has pointed out that small grain size in shear belts is a semi-permanent feature and has invoked this as the reason for recurrent tectonic activity along some major lineaments.

9. Concluding remarks: some comments on the physical relations between processes in shear zones

The rather remarkable relation that exists between the intensity of deformation, the amount of metasomatic chemical change and the extent to which new phases formed in shear zones has been described. It has been suggested that the processes leading to this result were related to the flow of fluid along shear zones. Certainly the convective transport of heat along shear zones is directly related to fluid flow. Changes in chemistry of the rocks in the shear zones would not have occurred in the absence of fluid flow. The chemical changes were brought about by interaction between the metasomatic fluid and existing phases, producing growth of new phases. Thus metamorphism in the shear zones is also directly related to fluid flow along these zones.

A basis for the discussion of the relations between such processes is provided by the thermodynamics of irreversible processes. The essential concepts follow from the second law – that for a spontaneous, irreversible change there is an increase in entropy of a system. The rate of entropy production is proportional to the product of the rate at which the process proceeds and the generalized force causing the process.

In a system in which two or more processes occur simultaneously, the total rate of entropy production must be positive for the system to evolve spontaneously, even though the rate of entropy production for one of the processes may be negative. This provides one mechanism for coupling of processes in a system (cf. Prigogine 1967). In other words, a process which alone would not occur spontaneously may proceed in the presence of other processes which are spontaneous if the total rate of entropy production is positive.

The development of a shear zone represents an instability just as the development of folds in a layered medium is an instability. As discussed by Glansdorff & Prigogine (1971), instabilities develop thermodynamically in far from equilibrium situations as the result of competition between stabilizing dissipative effects and destabilizing convective effects. In the system under discussion, the point of instability (initiation of a shear zone) is reached at the minimum stress difference at which balance can be steadily maintained between the entropy generated through dissipative, homogeneous diffusion processes (generated by variations in mean stress) and the corresponding entropy flow carried away by displacement fluctuations (generated by variations in shear stress). If this entropy flow overcomes the entropy generated through dissipative processes, the fluctuation will grow and penetrate through the system. The effect of hydraulic fracturing in a rock is to lower the threshold at which instability develops, i.e. a shear zone would not grow in areas where hydraulic fracturing did not occur. This relation exists because the process of inter- and cross-granular hydraulic fracturing results in repeated loss of cohesion and friction between grains where the fracture grows. For this reason, displacement fluctuations will be much larger than in a fluid free rock under the same conditions.

The shear zones discussed in this paper, and those developed in many deep seated basements during the early Proterozoic, are considered to be initiated in and generated from the source area of the metasomatic fluid that was so important in their evolution. In many cases the fluid undoubtedly originated in the upper mantle, for example, the fluids causing the Inverian retrogression of the Scourian granulite facies gneisses, the retrogression of the granulites in west Greenland and gneisses in west Canada, etc. Less commonly, it is possible that granulite facies gneisses formed in the lower crust were tectonically emplaced over wet rocks.

A fluid source area, whether localized in regions of overthrusting or laterally more extensive through the upper mantle, will be an area of intense hydraulic fracturing as fluids are released. The processes generating the fluids in the upper mantle are not clear, but could be related to the widespread generation of basaltic magma, partly recorded in the early Proterozoic dyke swarms. It is suggested that the shear zones propagated upwards from the fluid source area as instabilities produced by intense hydraulic fracturing. Thus the shear zones developed essentially as channels for the upward flow of fluid. It is concluded that deformation in the shear zones studied occurred only as a process coupled to fluid flow and chemical reactions related to this flow.

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