

## Retrogressive metamorphic processes in shear zones with special reference to the Lewisian complex

A. BEACH

Department of Geology, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, U.K.

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**Abstract**—Metamorphic processes in shear zones are discussed primarily with reference to the major structures in the Lewisian complex of NW Scotland as typical and well known examples of shear zones cutting Archean high grade gneiss terrains. Metamorphic reaction was broadly coeval with strong deformation in the shear zones and resulted in the transformations  $\text{pyx} \rightarrow \text{hbl}$ ,  $\text{hbl} \rightarrow \text{biot}$ ,  $\text{hbl} \rightarrow \text{chl}$ , and  $\text{fsp} \rightarrow \text{musc}$ . All the reactions are hydration processes and the amount of water required to produce the scale of metamorphism is very large. The reactions are also hydrolysis reactions, consuming  $\text{H}^+$  and releasing base metal cations. This emphasises the hydrothermal nature of the metamorphism in the shear zones and the importance of fluid-rock interaction. Mineral stabilities under such conditions are not just dependent on the conventional variables  $P$ ,  $T$ ,  $P_{\text{H}_2\text{O}}$ , but are very susceptible to changes in the activities of ions, etc., in the fluid phase. As the reactions consume  $\text{H}^+$  ions, it is proposed that dissociation of aqueous silica provides a buffer for  $\text{H}^+$ , while  $P_{\text{O}_2}$  is buffered by the ferromagnesian minerals.

Large scale diffusion is required firstly to supply water, and secondly to supply  $\text{K}^+$  essential for biotite formation and remove  $\text{Ca}^{2+}$ , which is released during most reactions. Diffusion of this sort in an open system allows chemical irregularities to be smoothed out between different rock types as ions, etc. move from sufficient to deficient sites. Redistribution of Mg, Fe, Mn, Ti, Na, Al, Ca, etc. and loss of excess Fe, Ca allowed attainment of rather uniform hornblende and plagioclase compositions in the shear zone and produced a very high degree of correlation between major element pairs throughout the shear zone, e.g.  $\text{Fe}^{3+}/\text{Fe}^{2+}$ , Fe/Mg, etc. Metamorphism may be isochemical within the shear zone as a whole, merely involving large scale redistribution of elements.

Metamorphic processes occur by diffusion, solution, nucleation and growth, and closely resemble deformation processes. During metamorphic reaction, rocks in the shear zone will show a strongly enhanced ductility because the rate of strain by diffusion processes is high, grain size is very small as new minerals nucleate, grain boundaries are disorganised, and maybe cohesionless, allowing grain boundary flow. As the metamorphic reactions decline, grains start to grow, and the early stages of high deformation rate by diffusion processes become overprinted by a dislocation mechanism of deformation. The grain textures now observed in shear zone rocks are the typical product of dislocation processes and these often mask the early stages of deformation by diffusion processes. Metamorphic reactions may not be an essential part of shear zones, but are commonly seen to have occurred during deformation in such structures, and provide a mechanism for extensive strain softening in the early stages of formation of the zone as water is drawn into the zone and metamorphic reactions are initiated. The early strain softening of reactive rocks starts the long history of ductile strain now observed in many shear zones.

### INTRODUCTION

DEFORMATION in shear zones has been evaluated (Ramsay & Graham 1970) on the demonstration that the strong deformation within these zones is flanked by undeformed material outside the zone. This boundary condition applies also to metamorphism in shear zones — material in the zone shows a metamorphism not recorded by the undeformed rocks outside it. This simple relationship allows an appreciation of the relations between metamorphism and deformation, and also of the metamorphic process through a comparison of the assemblages in the shear zone with the pre-existing assemblages outside it. Teall (1885) was the first to recognise that distinctive metamorphic fabrics, textures and mineral assemblages developed within and were confined to shear zones, and this theme has recurred in more recent literature (for example Sutton & Watson 1959, 1962, Ramsay & Graham 1970, Beach 1976).

Metamorphism in shear zones is often retrogressive because the mineral assemblages produced are usually more hydrated etc. and formed at lower  $P$ ,  $T$  than the pre-existing rocks that the shear zones traverse. The more familiar retrogressive metamorphism produced during uplift of an orogenic zone, where rocks may

remain essentially undeformed by comparison with shear zones, results in patchy alteration and replacement of pre-existing minerals without extensive recrystallisation and formation of strong fabrics. That ductile deformation and metamorphism occurred simultaneously in shear zones separates these structures as a distinct class of metamorphic problem.

A simple observational account of the mineralogy of a shear zone is often sufficient to indicate that a fluid phase was involved in the metamorphism (for example, Teall 1885, Boyle 1961, Beach 1973, Heimlich 1974). The approach to metamorphism offered by the hydrothermal geologist (for example, Helgeson 1967, 1969, 1974) emphasises that a fluid phase existed during metamorphism, showing how mineral assemblages form as a result of fluid-rock interaction, and is clearly applicable to metamorphic processes in shear zones. The role of the fluid phase in shear zones is clear where these structures are mineralised, either with sulphides etc. or with quartz or carbonate vein systems (for example, Boyle 1961, Guha & Koo 1975, Kerrich *et al.* 1977). However, even if a shear zone lacks obvious mineralisation, the occurrence of retrograde metamorphism throughout the zone will often require a large quantity of fluid. For example, consider a shear zone 1 km wide in

which the rocks contain an average 10% hornblende by volume, formed from earlier pyroxene by an average 1% by weight hydration. A segment of shear zone 10 km long and deep (i.e. volume = 100 km<sup>3</sup>) will contain 10<sup>16</sup> cm<sup>3</sup> hornblende containing 3 × 10<sup>14</sup>g of newly added water. Many shear zones are wider than 1 km, and correspondingly longer, and contain higher proportions of minerals formed by greater than 1% by weight hydration. The scale of fluid ingress into such shear zones must at least equal the scale of dehydration, etc. proposed by Fyfe (1976) for progressive metamorphism. Fluid will be migrating through a unit volume at a particular point in a shear zone during deformation and metamorphism, and this metamorphism must be considered to have occurred in an open system. Even if equilibrium between fluid and rock is approached at one point as the fluid migrates into a different chemical and physical environment it will come into contact with rocks with which it is not in equilibrium and continued fluid-rock interaction is to be expected. Because small scale shear zones do not always show evidence of the hydrothermal processes commonly seen in large shear zones, and may have formed as more isolated or closed metamorphic systems, they do not necessarily form metamorphic analogues for the study of processes in large scale structures.

Many of the major shear zones discussed in the literature are of Precambrian age, cutting through Archean high grade gneiss terrains; they are often essentially steep transcurrent structures recording large lateral displacements, though shallow-dipping overthrust zones are also known (Andrews *et al.* 1973, Bridgwater *et al.* 1973a, b, Coward *et al.* 1973, 1976, Sheraton *et al.* 1973b, Tarney 1973, Watson 1975, Beach 1974a, Bak *et al.* 1975a, b, Escher *et al.* 1975, Davies & Windley 1976, Davies 1978, Watterson 1978). Many of the Archean gneisses were metamorphosed in the granulite or upper amphibolite facies, and within the shear zones cutting these gneisses, metamorphism ranging from upper amphibolite to lower greenschist facies is seen. The scheme of reactions is very simple in the ordinary acid to basic gneisses — pyroxene, hornblende, feldspar and quartz are the essential minerals in the Archean gneisses, whilst hornblende, actinolite, biotite, chlorite, white mica, feldspar and quartz are the essential minerals in the shear zone assemblages.

In the paragraphs that follow, the nature of the metamorphic reactions seen to have occurred during deformation and metamorphism in shear zones will be examined, the implications of fluid-rock interaction will be studied, and the effect that such interaction has on the fluid phase composition as well as on rock chemistry and mineralogy will be discussed.

## METAMORPHIC REACTIONS

The discussion here is based on the writer's direct experience of shear zones in the Lewisian complex (see Fig. 1 and Table 1 for their locations and mineral assemblages) but it is clearly applicable to metamorphism in shear zones elsewhere. It is emphasised that this account considers only the major metamorphic reactions in the most abundant rock type,

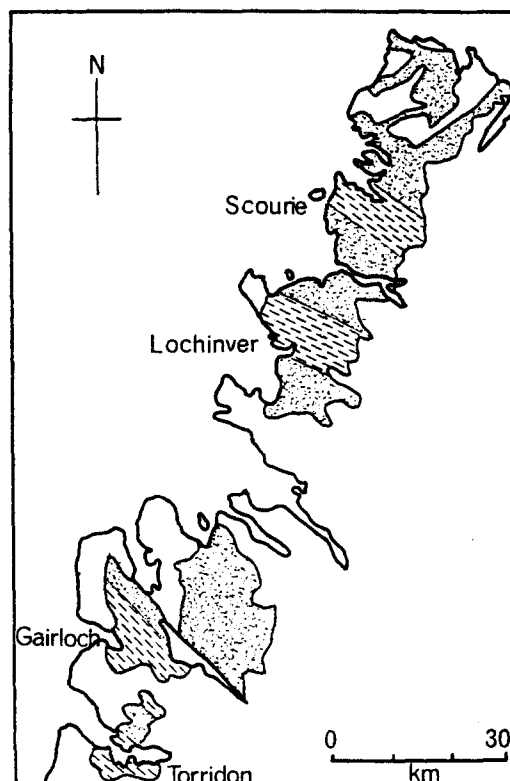


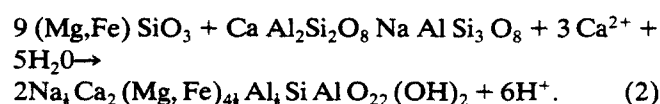
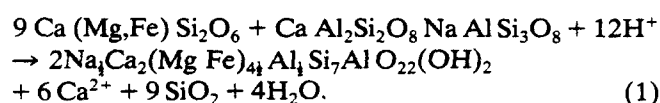
Fig. 1. Location of the major shear zones, referred to in the paper, cutting the Archean gneisses of the Lewisian complex of NW Scotland, U.K.

Table 1. Major shear zones in the Lewisian complex, their principal rock types and mineral assemblages

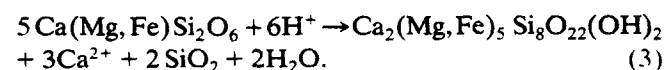
	Archean gneisses outside shear zone			Gneiss deformed + metamorphosed in shear zone	
	Rock type	Metamorphic facies	Mineral assemblage	Metamorphic facies	Mineral assemblage
Scourie	Acid to basic	Granulite	Cpx, opx, plag, qtz, garnet, parg.	U. amphibolite	Hbl, biotite, plag, qtz.
Lochinver	Acid to basic	Granulite	Cpx, opx, plag, qtz, garnet, parg.	M. amphibolite	Trem-hbl, hydrobiotite, plag., qtz.
Gairloch	Amphibolite	Amphibolite	Hbl, plag.	L. amphibolite - greenschist	Trem-hbl, chlorite, plag, qtz, calcite
	Acid - intermediate	Amphibolite	Plag, K fsp, qtz, hbl.	L. amphibolite - greenschist	Plag, K fsp, qtz, calcite musc, biot.
Torridon	Acid - intermediate	Amphibolite	Plag, K fsp, qtz, biot, musc, epid.	L. amphibolite	Plag, K fsp, qtz, biot. musc. epid.

the acid to basic gneiss series (Sheraton *et al.* 1973a) i.e. those that are quantitatively the most significant (cf. Beach 1973).

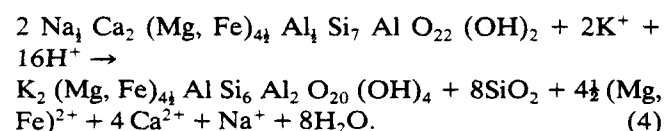
In the Scourie and Lochinver areas large shear zones cut through Archean granulite facies gneisses, transforming pyroxene into hornblende and biotite bearing rocks. The following reactions describe this process, taking clinopyroxene and orthopyroxene separately. These and the other reactions are balanced as ionic equilibria, a convention that emphasises the importance of fluid-rock interaction.



In the Scourie shear zone there is evidence that the modal percentage of quartz increases during the transition from pyroxene to hornblende assemblages (Beach 1976). Reaction (1) produces hornblende and quartz in the approximate volume ratio 3/1; it is not clear whether all the new silica released is precipitated as quartz or whether some remains in the fluid phase as the aqueous complex. It is clear however that no new calcium bearing phase is formed in the shear zones to accommodate the released calcium, and this is written as  $\text{Ca}^{2+}$  to indicate its presence in and removal by the fluid phase. Reaction (2) does consume  $\text{Ca}^{2+}$ , but in general clinopyroxene is much more abundant than orthopyroxene, so that reaction (1) is quantitatively more important than (2) and the combined breakdown of two pyroxenes still results in a net production of  $\text{Ca}^{2+}$ . The plagioclase involved in the reactions in reality becomes more albitic during amphibolisation (Tarney 1973, Beach 1974b, 1976), but this makes little difference to the overall nature of the reaction. Further south from Scourie, in the Lochinver shear zone, amphibolisation produces a more tremolitic hornblende, with a correspondingly lesser involvement of plagioclase, as shown by the following end member reaction:

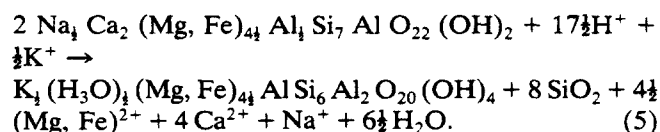


In the Scourie area, biotite is an important mineral in the shear zone assemblages alongside hornblende, and its formation from hornblende can be described by the following reaction:



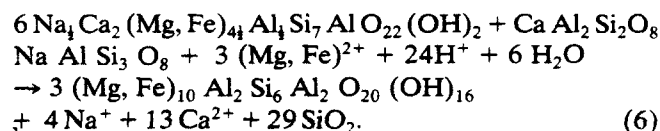
This reaction releases further  $\text{Ca}^{2+}$  along with  $(\text{Mg,Fe})^{2+}$  and  $\text{Na}^+$ . Whilst the latter is probably incorporated as a more albitic plagioclase, calcite does not usually form alongside biotite as a reaction product,

and iron may be lost from the system (Beach 1976). Again, silica may form quartz (the approximate volume ratio of biotite and quartz produced by reaction 4 is 3/2) or remain in part in solution. A major source of  $\text{K}^+$  is required for this reaction as up to 20% modal biotite is seen in the shear zone gneisses. Whilst the biotites in the Scourie area are true potash biotites, those in the Lochinver area are often potash-poor and may be hydrobiotites formed as follows:



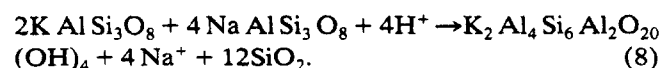
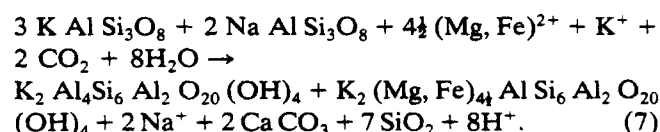
Reactions (1) and (2) combined and (3)–(5) are quantitatively the most important types of reaction in the Scourie and Lochinver shear zones, and all have one common feature — they consume  $\text{H}^+$  ions; this will be discussed later.

In the Gairloch shear zone, greenschist and lower amphibolite facies assemblages are seen, with chlorite commonly forming from hornblende in the abundant amphibolites:



The reaction of actinolitic hornblende to chlorite is very similar to (6), involving more plagioclase to supply Al. Reaction (6) produces chlorite and quartz in the approximate volume ratio of 2/1. Abundant syntectonic quartz-carbonate veins in the Gairloch shear zone indicate that the chemical conditions necessary for extensive precipitation of these minerals existed, whether the silica and calcium, etc. were derived from reactions such as (6) or from higher grade reactions such as (1–5) going on at deeper levels in the shear zone.

Apart from amphibolite, the other common rock type in the Gairloch shear zone is granite gneiss, and this shows the common development of muscovite-biotite-quartz-carbonate assemblages (cf. Drury 1974), which can be described by reactions such as the following, involving both plagioclase and potash feldspar:



## REACTION EQUILIBRIA

In this section the variables that might affect the equilibria of the reactions are examined. The new mine-

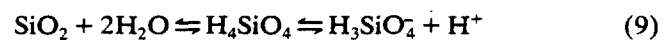
erals forming — hornblende, biotite, chlorite, muscovite — all have their own experimentally determined fields of stability in  $P, T$  space (Boyd 1954, 1959, Yoder & Tilley 1962, Ernst 1966, Binns 1969, Eugster & Wones 1962, Wones & Eugster 1965, Rutherford 1973, Turnock 1960, Fawcett & Yoder 1966, Bird & Fawcett 1973, Evans 1965, Althaus *et al.* 1970). The retrograde reactions are all hydration reactions and will only proceed on introduction of water into the rocks. There is no way of determining the magnitude of  $P_{\text{H}_2\text{O}}$  relative to  $P_{\text{TOTAL}}$  during metamorphism, or of knowing whether other vapour phases were present in the fluids that were not involved in the reactions, and thus nothing is known of the activity of  $\text{H}_2\text{O}$ . Possibly the rate of retrograde metamorphism was controlled by the diffusion of water to the reaction site (cf. Fyfe 1976, Fisher 1977, 1978) and at least initially the hydration reaction probably buffered  $P_{\text{H}_2\text{O}}$  locally as the reaction proceeded on the univariant curve in  $P, T$  space separating the hydrate and anhydrate stability fields. That the temperature at which hydration reactions occur is affected by varying  $P_{\text{H}_2\text{O}}$  is shown by the examples in Vernon (1976). Mineral pairs such as pyroxene–hornblende are not seen as recrystallised, equilibrium assemblages in the shear zones, indicating that sufficient water was available to promote these reactions to completion.

The water pervading the shear zone during metamorphism, even if its pressure is buffered locally during reaction, will have a characteristic  $P_0$ , dependent on the  $P, T$  conditions prevailing, and if excess water is present, the fluid phase may have the capacity to buffer the oxidation state of the minerals (such as hornblende and biotite) by fluid–rock interaction, producing uniform  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratios throughout the shear zone (Beach 1976, Beach & Tarney 1978). Oxidation also affects the  $P, T$  stability of silicates containing iron; for example, with hornblende, biotite and chlorite, the more iron rich the mineral, the lower will be its breakdown temperature relative to the magnesian end member for given oxidation conditions (Turnock 1960, Wones & Eugster 1965, Ernst 1966).

In addition to being hydration processes, all the reactions are also hydrolysis equilibria involving metasomatism — hydrogen ions are added to the rock, base metal cations are released and the pH of the fluid is changed. The large scale alteration observed in the shear zones can only occur via a pervasive fluid phase. Thus the activities of ions in solution appear as an additional set of variables just as important as  $P, T, P_{\text{H}_2\text{O}}, P_{\text{O}_2}$  in determining the stability of the new minerals formed in the shear zones. Though the mineral assemblages in the shear zones indicate that hydration reactions went to completion, indicating an excess of  $\text{H}_2\text{O}, \text{H}^+$ , the coexistence of, for example, the mineral pair hornblende–biotite in the Scourie shear zone indicates that  $\text{K}^+$  was not present in excess and that its activity was important in controlling this reaction equilibrium. A number of ionic activities may be important in any one reaction. While the thermal stability of the hydrate minerals mentioned here are quite well known, very

little is known of their ionic stability, with the exception of muscovite (Meyer & Hemley 1967). It is worthwhile comparing the phase diagrams of Althaus *et al.* (1970) and Meyer & Hemley (1967) and trying to visualise the existence of analogous diagrams for hornblende, biotite and chlorite.

Although the reactions are written as ionic equilibria, the buffering of the fluid may be partly ionic and partly molecular in its chemistry. As in all hydrothermal metamorphism, ‘hidden’ equilibria within the fluid phase alone, involving aqueous complexes etc. may have a profound effect on ionic activities and on mineral equilibria. In addition to supplying  $\text{H}^+$ , the fluid must have removed much of the  $\text{Ca}^{2+}$  and possibly  $\text{SiO}_2$  where these are not precipitated in minerals. The evidence for this is most unequivocal in high grade shear zones where  $\text{Ca}^{2+}$  is not precipitated in a new mineral; instead it appears abundantly in the lower amphibolite to greenschist facies shear zones. In addition the presence of abundant quartz veins in these zones, suggests that much of the silica released by high grade reactions was precipitated alongside silica released by lower grade reactions at the lower temperature, etc. of this regime. If  $\text{Ca}^{2+}$  and  $\text{SiO}_2$  are removed on a large scale in the fluid and precipitated in veins elsewhere, a buffer for their concentrations in the fluid phase at the site of their release may not have existed. For example, open-ended, one way schemes such as



must exist to provide a large solubility sink for released silica and calcium (Crerar & Anderson 1971, Helgeson 1974). Movement of  $\text{K}^+, \text{Na}^+, \text{Mg}^{2+}, \text{Fe}^{2+}$  is also required in some reactions and probably occurred to a greater extent than the simple reactions suggest (cf. Beach & Tarney 1978). Like  $\text{Ca}^{2+}$ , these ions probably exist as chloride complexes in the hydrothermal solution. At low  $P, T$  the chlorides are fully dissociated, but under conditions of metamorphism at temperatures above about  $400^\circ\text{C}$ , they are largely tied up in neutral molecular complexes. In general, for a dissociation equilibrium such as



The dissociation constant

$$K = \frac{(\text{Na}^+)(\text{Cl}^-)}{(\text{NaCl})}$$

is less than one above  $400^\circ\text{C}$ . Ion association increases with temperature and is only partly offset by increases in pressure, so that with pressures up to 5–6 kbar in the temperature range 4– $700^\circ\text{C}$ , chloride complexes can be considered to be largely undissociated (Helgeson 1969, 1974). These dissociation equilibria thus lend to maintain very low concentrations of the ions  $\text{Ca}^{2+}$ , etc. in the fluid. In a simple fluid,  $\text{H}^+$  ions are derived by dissociation of  $\text{H}_2\text{O}$ , but as  $\text{H}^+$  are consumed by the metamorphic reactions and pH rises, a more effective source of  $\text{H}^+$  is provided by the presence of the silica complex in

solution (reaction 9 above), a simple buffer of large capacity for the fluid pH. Extensive precipitation of quartz as seen in the Gairloch shear zone, will then be brought about by the appearance of an equilibrium that provides a large concentration of  $H^+$  ions. Both sulphide and carbonate equilibria may be related to this, since minerals of these are also common in the Gairloch shear zone.

One of the consequences of fluid-rock interaction in an open system is the scope that exists for changing rock chemistry and smoothing out chemical irregularities as some ions etc. are taken up from the fluid to form new minerals and other excess ions etc. are released into and removed by the fluid until they reach sites of reaction where they themselves become deficient ions. This idea has been discussed in some detail for the Lochinver shear zone (Beach & Tarney 1978). Within the shear zone a restricted mineralogy of hornblende, plagioclase, quartz developed and redistribution of elements led to a number of distinct geochemical features: (a) the composition of the hornblende has a restricted range, (b) an original wide spread of plagioclase compositions in the Archean gneisses is reduced to a much narrower, and generally more albitic, range in the shear zones (cf. Helgeson 1974), and (c) as a consequence of these, strong correlations were established between different pairs of major elements, for example, uniform Fe/Mg,  $Fe^{3+}/Fe^{2+}$ , Mg/Mn, Na/Al ratios, throughout the sheared gneisses (Beach & Tarney 1978). Other minerals in other shear zones may establish different geochemical trends during retrogressive metamorphism.

#### METAMORPHISM AND DEFORMATION IN SHEAR ZONES

The two principal mechanisms of deformation under crustal conditions are thought to involve diffusion along grain boundaries and movement of dislocations. Metamorphic processes also involve grain boundary diffusion, as well as solution, nucleation and growth. Shear zones provide the clearest examples of the similarity and close interrelationships between deformation and metamorphic processes (see discussion in Beach 1976). A mechanism of deformation in shear zones has been suggested from quartz grain studies (Watterson 1975, White 1976), based on the observation that the grain size in a shear zone is often less than that in the adjacent undeformed rocks, an observation interpreted as the deformation having produced grain size reduction. Briefly, the rate of deformation by dislocation processes is grain size independent, whereas that by diffusion processes is inversely proportional to the cube of the grain size. Initially, the deformation process is dominated by a dislocation mechanism, giving rise to smaller sub-grains; as the grain size is reduced, the amount of deformation brought about by a diffusion mechanism gradually increases. White (1976) describes mylonite shear zones cutting quartzites forming in this way.

Modal analyses of even the most acidic rocks observed in the Lewisian shear zones (Torridon area) rarely show more than 30% quartz, and in the gneisses in the Scourie shear zone, modal quartz ranges from 0 to 30% (Beach 1976). In most of the common acid to basic Lewisian rocks, feldspar is the most abundant mineral and usually ranges from 40 to 50 modal%. In the high grade shear zones, feldspar enters into the metamorphic reactions as a source for Al during the formation of hornblende. In low grade shear zones in the greenschist facies and right down to the environment in which the quartz mylonites studied by White (1976) were formed (cf. Mitra 1978), feldspar undergoes extensive and sometimes complete reaction to white mica (muscovite, phengite or illite, according to metamorphic grade). Normally such rocks show a grain size smaller than that of the original undeformed rock, but this is not an expression of grain size reduction, but of arrested grain growth of new minerals.

Any new minerals formed by metamorphic reactions from old grains must start as submicroscopic nuclei and grow to their present observed size. Very small grains will exist all the time that the metamorphic reaction is proceeding and the rate of deformation by diffusion mechanisms will be high. When the reaction has gone to completion or ceased, grain growth will lead to a decline in deformation by diffusion processes and an increase in deformation by dislocation processes. Thus the final observed textures of these minerals may often suggest deformation by dislocation processes, masking the early stages of deformation by diffusion mechanisms (cf. White & Knipe 1978). The same effects will occur during the reactions of pyroxene  $\rightarrow$  hornblende  $\rightarrow$  biotite  $\rightarrow$  chlorite seen throughout the Lewisian shear zones, and will also apply to quartz to the extent that some quartz in a rock may be a reaction product. An example of a partial record of grain growth is shown by some shear zones at Scourie where the grain size of hornblende formed from pyroxene is seen to increase from 0.003 mm in the undeformed marginal areas of the shear zones, to 0.5 mm in the more metamorphosed and deformed centres of these zones (Beach 1974b).

There is little known about the size of the grain boundary diffusion path in rocks undergoing a metamorphic reaction, but even so, the existence of many small new grains and the enhanced diffusion along cohesionless and disorganised grain boundaries with their increased numbers of vacancies, and the additional possibility of grain boundary flow under these conditions, will lead to potentially fast strain rates in shear zones during the reaction stage (cf. White & Knipe 1978). Since most of the rocks deformed in the shear zones are banded gneisses, the more mafic layers will be zones of greatly enhanced ductility during metamorphic reactions, and will become zones of high strain, though this may be masked by subsequent deformation by dislocation mechanisms during grain growth. It would seem reasonable that the deformation mechanism maps of White (1976) and Rutter (1976) would have little application to such reaction enhanced strain rate — they are probably orders of magnitude out.

Thus, while metamorphic reactions may not always be an essential part of shear zone formation and while deformation in some cases may proceed without any dramatic metamorphic change, the common occurrence of reactions during deformation in shear zones provides a mechanism for considerable strain softening and early development of high strains in those lithological layers in which the reactions occur.

A final comment on the timing of metamorphic reactions during the evolution of a shear zone is pertinent to this discussion. The source of the large amounts of fluid phase involved in the metamorphic process in the shear zones is still in doubt (cf. Tarney 1973, Drury 1974, Beach 1976, Beach & Tarney 1978). Sibson *et al.* (1975) formulated the concept of seismic pumping to explain the observed large increases in fluid discharge from faults following fault movement. Fluid is drawn into a dilatant zone around the fault from a very large surrounding volume of rock during the build up of stress. Fault movement and stress relief lead to rapid collapse of this dilatancy and hence to rapid discharge of fluid along the fault zone, frequently causing extensive mineralisation. Watterson (unpublished work) has suggested that the site of a large shear zone is initially determined by an elastic stress distribution in the same manner as for faults. In this early elastic stage of development of a shear zone, the same process of the drawing in of fluid into a dilatant zone may occur. Metamorphic reactions will begin in the zone of fluid build-up and the consequent strain softening may play an important role in initiating the ductile strain history of what becomes a shear zone. As deformation proceeds, the effect of the metamorphic reactions declines whilst the deformation of other unreacted minerals increases as dislocation mechanisms gradually reduce their grain size. In this general model, metamorphic reactions are seen to occur during the earliest stages of formation of a shear zone, and this is confirmed by the observation (Sheraton *et al.* 1973b, Tarney 1973, Evans & Lambert 1974, Beach & Tarney 1978), that in areas such as the Lochinver and Scourie shear zones, the hydration of pyroxene to hornblende and the major geochemical changes in the gneisses occurred at an early stage and over a much larger area than the particular zones that evolved into ductile shear zones. However, it is important to remember that whilst certain hydration/hydrolysis reactions may be initiated very early in the history of a shear zone, others, such as the cation exchange alteration of calcic to sodic plagioclase, are often dependent on strain induced recrystallisation.

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