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The role of shear belts in the structural evolution of the South Harris igneous complex

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Abstract—Metamorphosed igneous masses in the Lewisian of South Harris are tectonic pods, less deformed than the metasediments associated with them and bounded by shear zones which locally coincide with belts of metasediment. Shear zones have been important in the structural evolution of the region though the deformation in these zones is probably more complex than simple shear alone. Restoration of the igneous rocks to their pre-shear configuration suggests that the pods were derived from a very large layered body analogous with layered bodies in other Archaean high grade terrains. Most of the important deformation is Archaean, modified somewhat during Proterozoic regeneration.

INTRODUCTION

The rocks of the Outer Hebrides are quartzo-feldspathic banded gneisses with subordinate metamorphosed igneous rocks and metasediments. In most places the important structures and the (amphibolite facies) mineral assemblages are Proterozoic (Laxfordian), but locally, particularly in the basic rocks, Archaean (Scourian) structures are preserved, and the rocks are in granulite facies.

The most important igneous rocks and sediments in the Hebrides are in South Harris, in a NW–SE trending belt sandwiched between two major antiformal areas of regenerated banded gneiss, the Harris granite–migmatite complex and the North Uist Antiformal zone (on which structures in the Sound of Harris are parasitic) (Figs. 1 and 2).

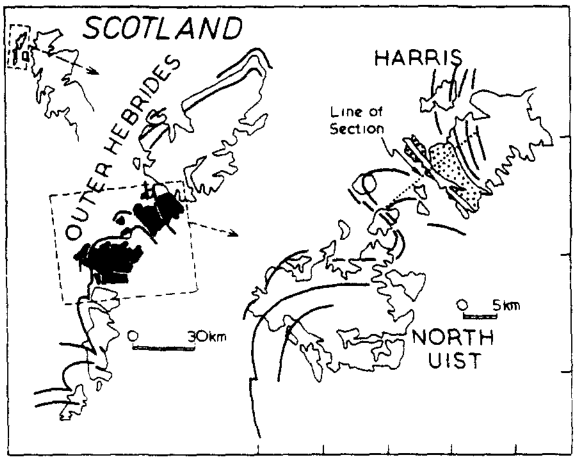

Fig. 1. Location map. South Harris Igneous Complex is shown stippled. The general trend of gneissic banding is shown.

The geology of South Harris has been the subject of much work and little agreement (Davidson 1944, Dearnley 1963, Myers 1971, Graham 1969, Palmer 1970, Dickinson 1974, Dickinson & Watson 1976). The aim of this particular paper is to demonstrate that shear zones are responsible for the shapes and distribution of the igneous bodies, and therefore have been of fundamental importance in the structural evolution of the region. By necessity, other aspects of the geology are overgeneralized.

ROCK TYPES

The metamorphosed igneous rocks of South Harris range from intermediate to ultrabasic in composition. Detailed petrological descriptions can be found in Davidson (1943) and Dearnley (1963).

There are four large masses and very many smaller sheets and pods of igneous rock. The main masses are anorthosite, metagabbro, norite, (termed 'Pyroxene granulite' by Dearnley 1963), and a composite intrusion of tonalite and diorite conveniently referred to as 'the Tonalite'. Metagabbro sheets mantle the anorthosite and tonalite, and metagabbro also exists in bands and pods within the NW–SE striking belt of supracrustal gneisses (the Leverburgh belt) which lies between the main igneous masses. Some of the pods of metagabbro within the Tonalite can be interpreted as xenoliths and serve to demonstrate a time relationship in the original intrusion. A belt of distinctive flaggy gneisses, containing abundant sedimentary relics, outcrops on islands in the Sound of Harris and another (the Langavat belt) flanks the igneous rocks on the northeast side. The

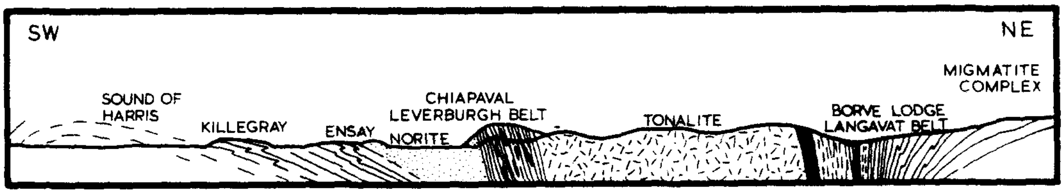

Fig. 2. Section from the South of Harris to the migmatite complex.

dominant rock types in these two belts are highly deformed, planar flaggy gneisses in amphibolite facies and containing metasediment which were termed 'metasediments sensu lato' by Coward *et al.* (1969). They may well be sediment derived, but one cannot prove it. In many places they could equally well have been derived from homogeneous granite by deformation.

Coarse-grained, coarsely banded quartzo-feldspathic gneisses containing a high proportion of sheets and more irregular patches of homogeneous granite and pegmatite form the 'migmatite complex' of northern South Harris and North Harris. These rocks give way southwards via a kilometre wide zone entirely made up of sheets of homogeneous granite, to the gneisses of the Langavat belt. The change from migmatite to sediment is comparable with that across the Laxford Front in mainland Scotland (Davidson 1951, Sutton & Watson 1951, Beach *et al.* 1973).

The igneous rocks and the Leverburgh paragneisses are in granulite facies, retrogressed to various degrees. As elsewhere in the Hebrides, granulite facies mineralogy tends to be preserved in the central parts of the igneous masses while retrogression to amphibolite facies has occurred in marginal parts and in shear belts.

The Scourian (Archaean) age of the rocks and their granulite facies metamorphism cannot be proven in Harris because there are no unambiguous Scourie dykes in either the igneous rocks or the Leverburgh paragneisses, and Lewisian chronology depends on these dykes. However, the metagabbros of Harris are identical with metagabbros on the Scottish mainland whose granulite facies assemblage unquestionably pre-dates the Scourie dykes (Peach *et al.* 1907, Sutton & Watson 1951). It is assumed here that the granulite facies metamorphism, and much of the important structure is Scourian.

STRUCTURE

It is possible to recognise several independent structural elements in the South Harris igneous rocks. Locally igneous layering and banding are visible, deformed by, and commonly parallel to an early penetrative planar or L–S fabric. Net veining, appinitic type brecciation, and locally a late phase of magma injection post-date this fabric but pre-date the granulite facies metamorphism. Ductile shear zones deform the earlier structures and the margins of the igneous bodies are almost all shear zones, i.e. the bodies are tectonic pips, not original plutons. Most of the shear zones are subvertical and trend NW–SE.

The early fabric is sub-vertical almost everywhere in South Harris. It curves in and out of the shear zones, but where least affected by the later deformation trends somewhere between NNE–SSW and E–W, i.e. it lies at a high angle to the shear zones and to the original trend of the igneous bodies (Figs. 3 and 4). It can either be an alignment of minerals of the granulite facies or it can be defined by individual mineral grains or aggregates in amphibolite facies (in the more marginal parts of the masses). It is conceivable that this reflects water availability at the time of deformation, but it is much more likely that the amphibolitization represents retrogression.

Rocks in the shear zones range from near mylonites to coarse grained amphibolites. The metamorphic state of the material outside a shear zone shows a rough correlation with the type of tectonite inside. If the parent is not amphibolized the shear zone rock is more mylonitic.

The fact that brecciation and net-veining post-date the penetrative fabric but are deformed by the shear zones confirms that this structure is older than the shear zones and not genetically linked with them.

The paragneisses of the Leverburgh belt show NW–SE trending banding and foliation, tight early folds, later open structures and NW–SE trending shear zones where some retrogression to amphibolite facies has occurred.

THE STRUCTURE OF THE METAGABBROS

Metagabbro sheets and pods exist throughout the Leverburgh belt and mantle the larger igneous masses. The largest body, marginal to the tonalite NE of Leverburgh is 500 m wide. All the sheets and pods are vertical or sub-vertical and most of the contacts are shear-zones. Pods can often be linked in trains and are clearly parts of once continuous sheets disrupted by boudinage or shear or both (Figs. 3 and 4).

The metagabbros usually do not show good tectonite fabrics, but almost all of them are banded. The banding can be up to several centimetres in thickness and is almost certainly an original igneous feature modified by strain. It is sub-vertical and very commonly trends E–W or ENE, WSW, at a high angle to the length of a sheet or pod. The direction is more or less the same even in widely separated pods (Figs. 3, 4 and 5).

One cannot seriously suppose that before deformation igneous banding ran across the trend of the sheets. The only reasonable assumption is to follow an original idea of Palmer (1970) and assume that the layering was parallel or sub-parallel to the margins of the original intrusion (or intrusions), and that the sheets we see today are tectonic slices–slabs cut from the original gabbro body (or bodies) by shear zones and translated along those shear zones (Fig. 5). The pods themselves have frequently suffered ductile shape change by simple shear (locally modified by flattening)—the largest of them, the mass of metagabbro on the southwest side of the tonalite east of Leverburgh (Fig. 3) exemplifies the shape of many smaller pods. The original orientation of the banding cannot be ascertained accurately, but the shape of the pods suggests that it cannot have been far from NE–SW over most of South Harris.

Important implications of a shearing mechanism for the formation of the metagabbro sheets are that: (1) the

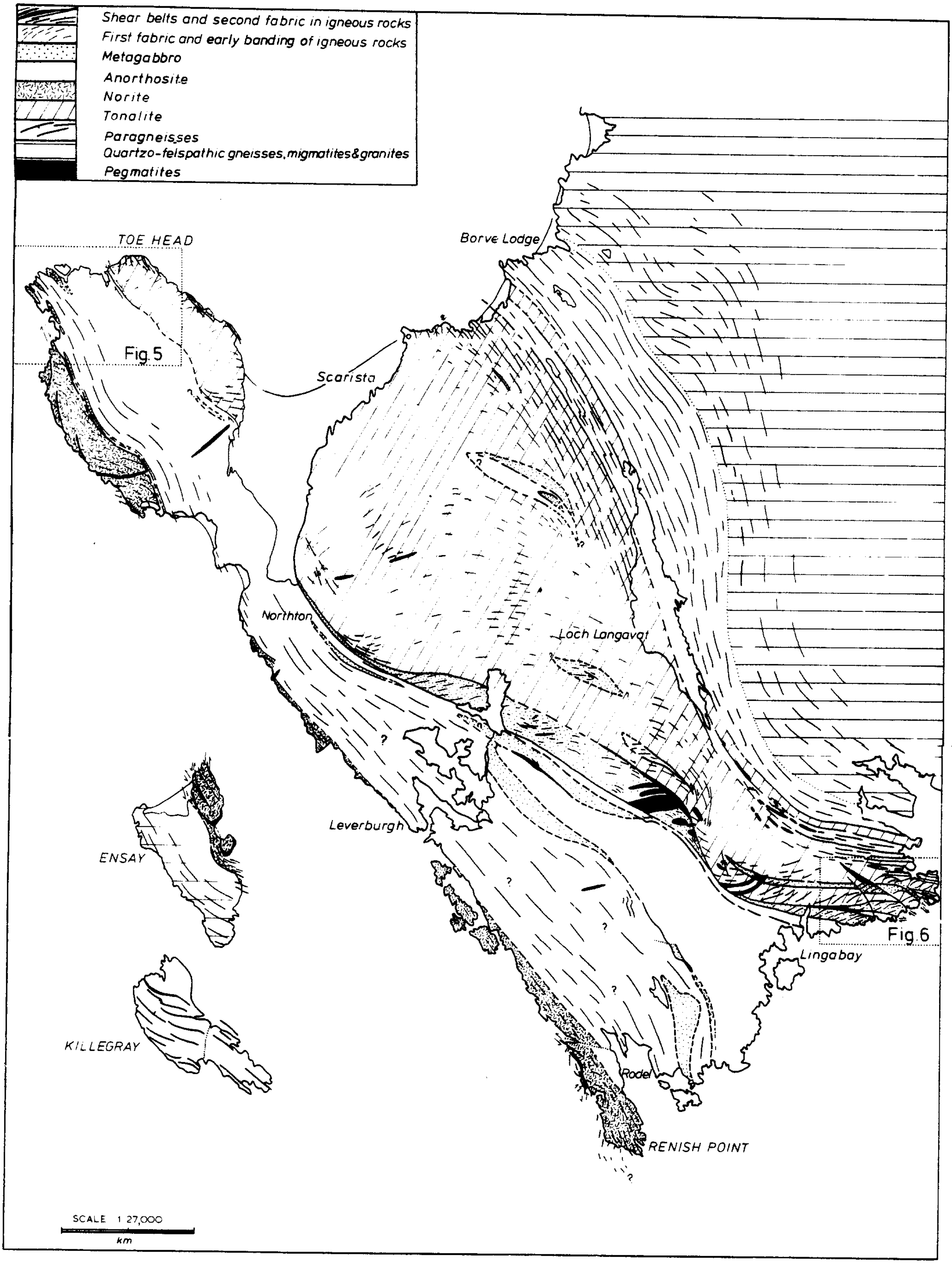

Fig. 3. Map of South Harris.

original igneous mass from which the biggest metagabbro sheet was derived must have been at least 3 km thick (the distance normal to the banding of the sheet) (Fig. 6); and (2) there must have been more than one mass, since metagabbro slices are separated by metasediments and tonalite (Figs. 3, 4 and 7).

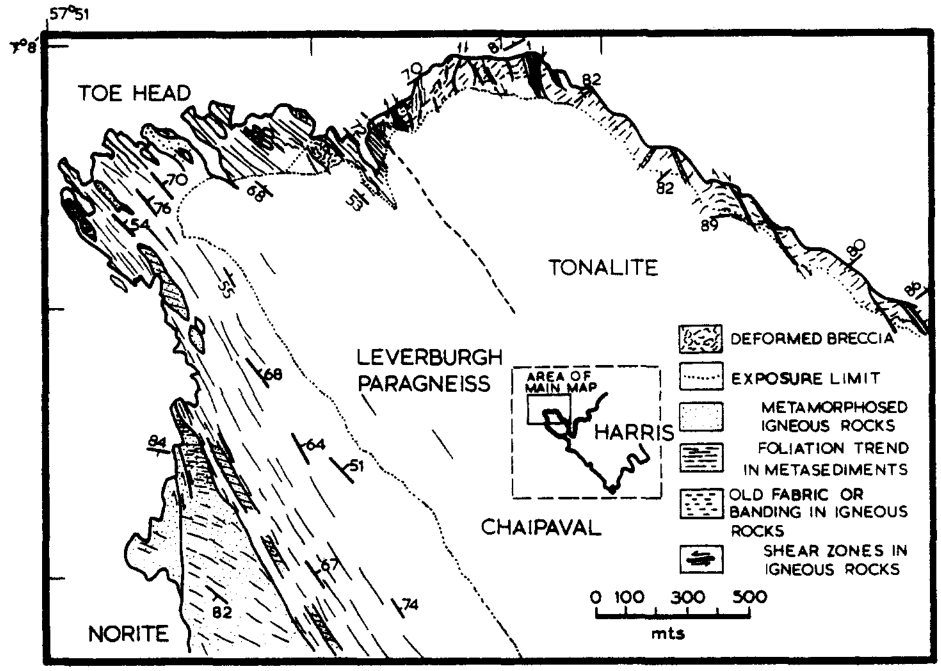

Fig. 4. Map of Toe Head, showing pods of igneous rock within the Leverburgh belt and shear zones in the tonalite and norite.

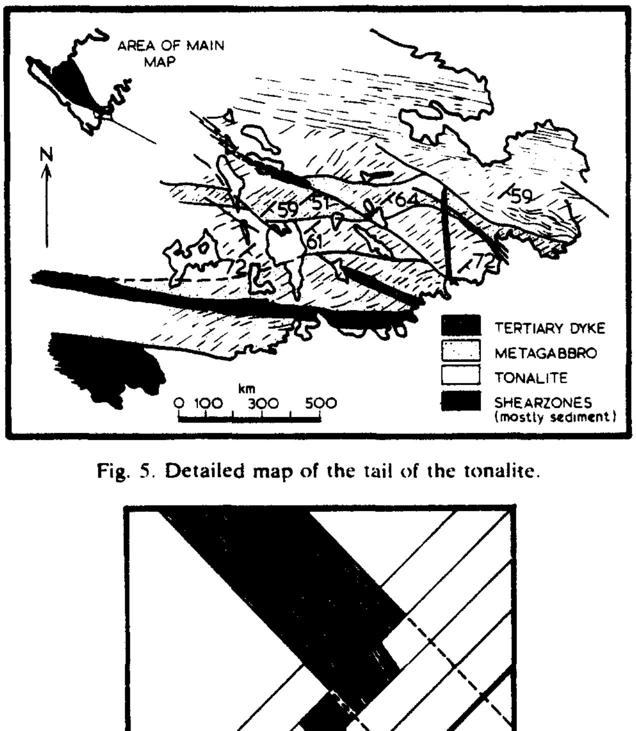

Fig. 5. Detailed map of the tail of the tonalite.

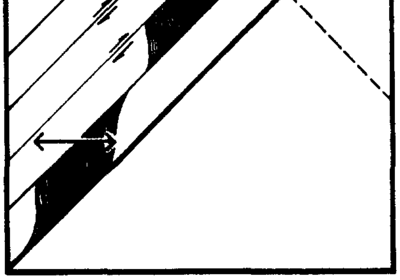

Fig. 6. Schematic representation of the formation of sheared pods (after Palmer 1970). The distance normal to the internal structure of the pods is an indication of the minimum thickness of the body from which the pod is derived.

THE STRUCTURE OF THE TONALITE

The Tonalite is the largest of the South Harris igneous masses. Its shape is comparable with that of some of the smaller scale metagabbro pods in South Harris, i.e. it seems to be part of a less deformed lozenge lying between two shear belts with the same sense of movement. The coast of Harris cuts off the northern end of the lozenge (Fig. 6). The belt of strong deformation which represents the northern bounding shear belt is about 2 km wide of which about 0.5 km is deformed tonalite, and the rest is the Langavat paragneiss belt. The Leverburgh belt represents the southern bounding shear belt, though at the contact deformation of the tonalite itself is restricted in a zone only a metre or so wide. The early penetrative fabric curves gradually into the northern zone, but is deflected sharply into the southern one. Smaller scale shear zones cut the tonalite for some distance north of the southern boundary, but are not so frequent in the north. These differences probably relate to more extensive amphibolitization in the north. The northern shear zone shows a displacement of at least 14 km if one assumes simple shear, a width of 2 km and chooses the shear direction and angular relationships shown in Fig. 8. Since both the early fabric and the shear zone are vertical, this figure is unaffected by problems of oblique section, and the movement is assumed to be pure strike-slip.

However, it is unlikely that the tonalite has been deformed by simple shear only. Regional flattening seems to have modified angular relationships (see later), though clearly the effect is limited to the marginal zone since the centre of the tonalite is very weakly deformed (see below). A reconstruction of the original rectangle assuming simple shear gives a strain (γ) of 1.4 unevenly spread through the tonalite. The total amount which the

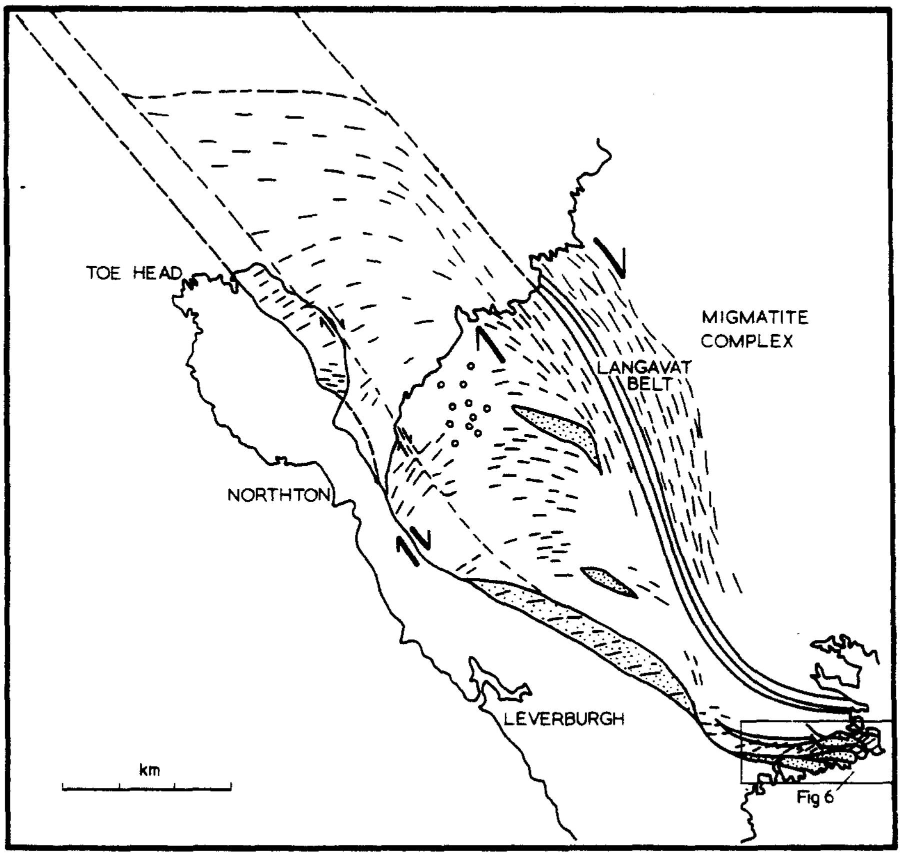

Fig. 7. Reconstruction of the tonalite, interpreting it as a large sheared pod.

lozenge has been translated on its bounding shear zones is impossible to assess because of uncertainties about the width of the bounding shear zones, the amount of flattening and the magnitude of any brittle movement. The reconstruction (Fig. 11) implies that it is the furthest travelled of the igneous masses.

The early fabric of the tonalite has been deflected into a highly asymmetrical 'S' shape sympathetic with the shape of the tonalite lozenge itself. Where least intense, inland from Scaraster and north of Northon, it trends NE–SW. Here, in the central part of the igneous mass, the fabric is defined by minerals of the granulite facies and later strain is absent. Assuming that the main zones of translation are straight and regional rotation unimportant this fabric cannot have been deflected from its original orientation. Fabrics with E–W or NW–SE orientation have been deflected by ductile strain associated with the shearing of the whole tonalite body. The deflection is usually associated with some degree of retrogression to amphibolite facies.

THE NORTHERN MARGIN OF THE TONALITE

Late igneous feldspathic veins, themselves of at least two ages are more or less random in undeformed parts of the Tonalite (Fig. 9A) but have been deformed by both the early fabric and by the marginal shear zone. In the shear zone some are folded and some extended, depending on their original orientation (Fig. 9A and D).

Given the more or less random original distribution,

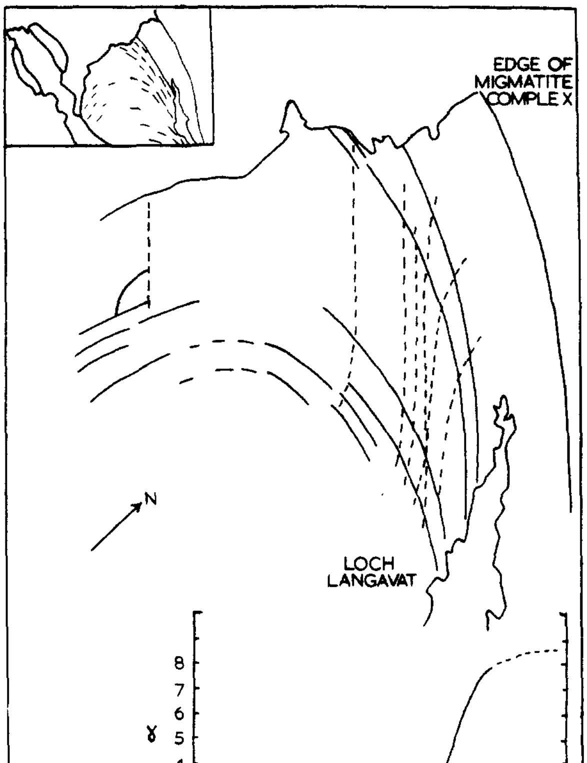

Fig. 8. Simple shear construction on the northern margin of the tonalite. A maximum strain of about 7.5 is indicated by the deflection of the old fabric.

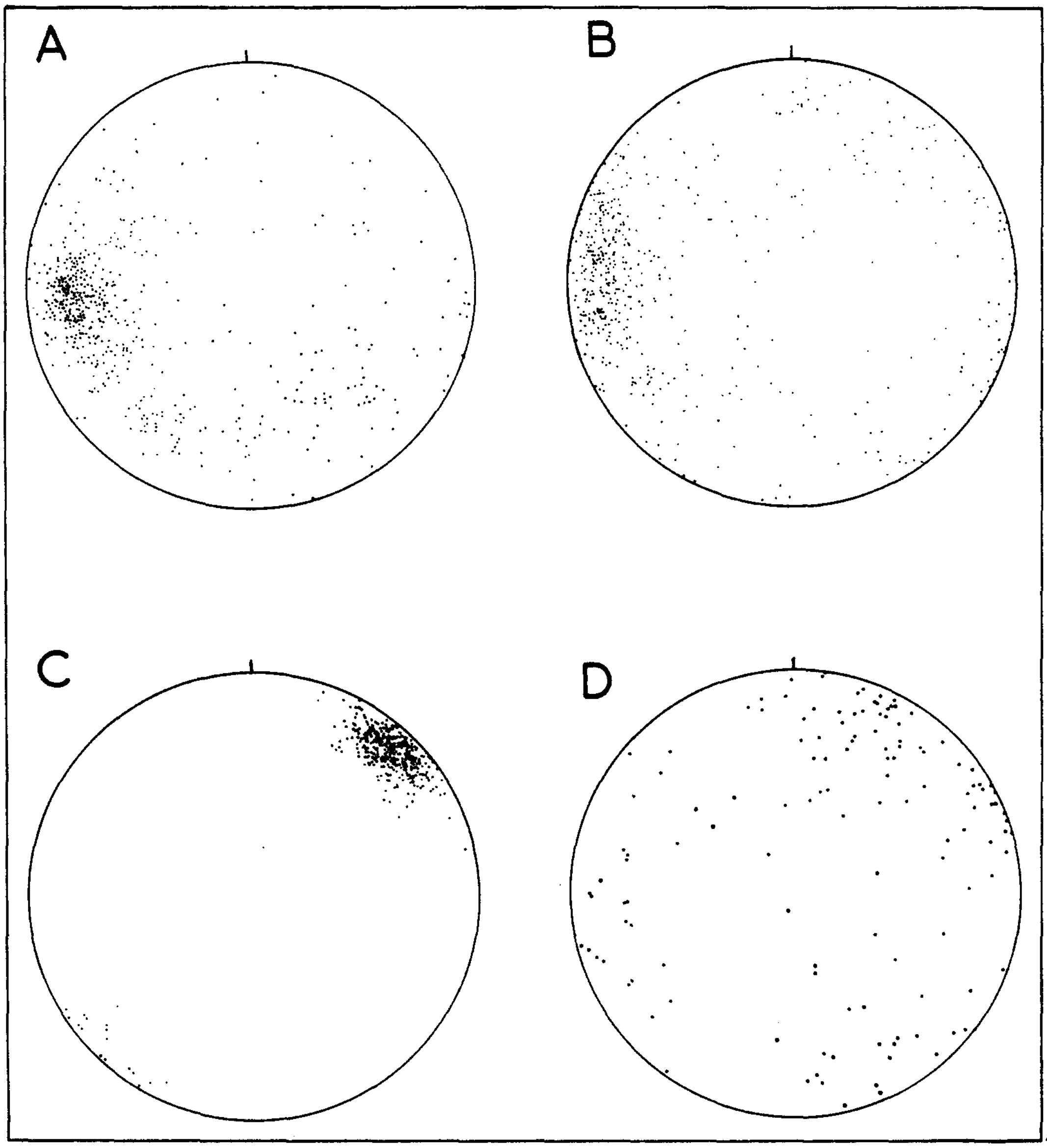

Fig. 9. Stereograms of poles to pegmatite veins in the tonalite. A in the undeformed centre of the mass; B in areas showing early fabric; C in the northern marginal shear zone; D Poles to inflexion surfaces of folded veins in the northern marginal shear zone.

the surface separating veins which have been shortened (folded) from those which have been extended Figs. 10A and C are the projections of the surface of no finite longitudinal strain of the finite strain ellipsoid and from its angular dimensions one can calculate the strain ratios (Flinn 1962, Talbot 1970). In fact, the veins within the tonalite provide almost ideal material for this particular method of strain determination since it relies upon an originally random family of veins. Normally this must be assumed; here it can be demonstrated. The surface of no finite longitudinal strain between the shortened and elongated elements on the stereonet was drawn by contouring poles to the enveloping surfaces of folded layers and poles to extended veins, superposing diagrams for equal percentage concentrations, and drawing a dividing line through the areas of overlap. Overlaps of concentrations of 0.5, 1, 2, 3, 4 and 5% are shown in Fig. 10C. A spread of shapes and orientations of strain ellipsoids is evident but the average area of elongation shows angular dimensions indicative of a flattening type strain ellipsoid with ratios of 10:6:1. Slight horizontal stretching is indicated by the elongation of the plot (pure oblate ellipsoids give circular plots, ellipsoids $1>k>O$ give elliptical cones elongated in XZ towards X (Flinn 1962, Ramsay 1967, p. 164, Talbot 1970). This horizontal stretching might be thought compatible with the essentially transcurrent nature of the shear zone at the northern margin of the tonalite. However, the ellipsoid is not the plane-strain type associated with simple shear deformation, and the strain ratios given by the deformed veins (more or less 10:1 in the horizontal plane) are hardly compatible with the extreme ratios implied by shear strains of more than 7 gamma given by constructions assuming simple shear (Fig. 8).

A component of flattening with consequent angular changes presumably accounts for the discrepancy between the strain values from the veins and those from simple shear constructions and renders the construction invalid.

The shape fabric of the rocks is virtually totally planar,

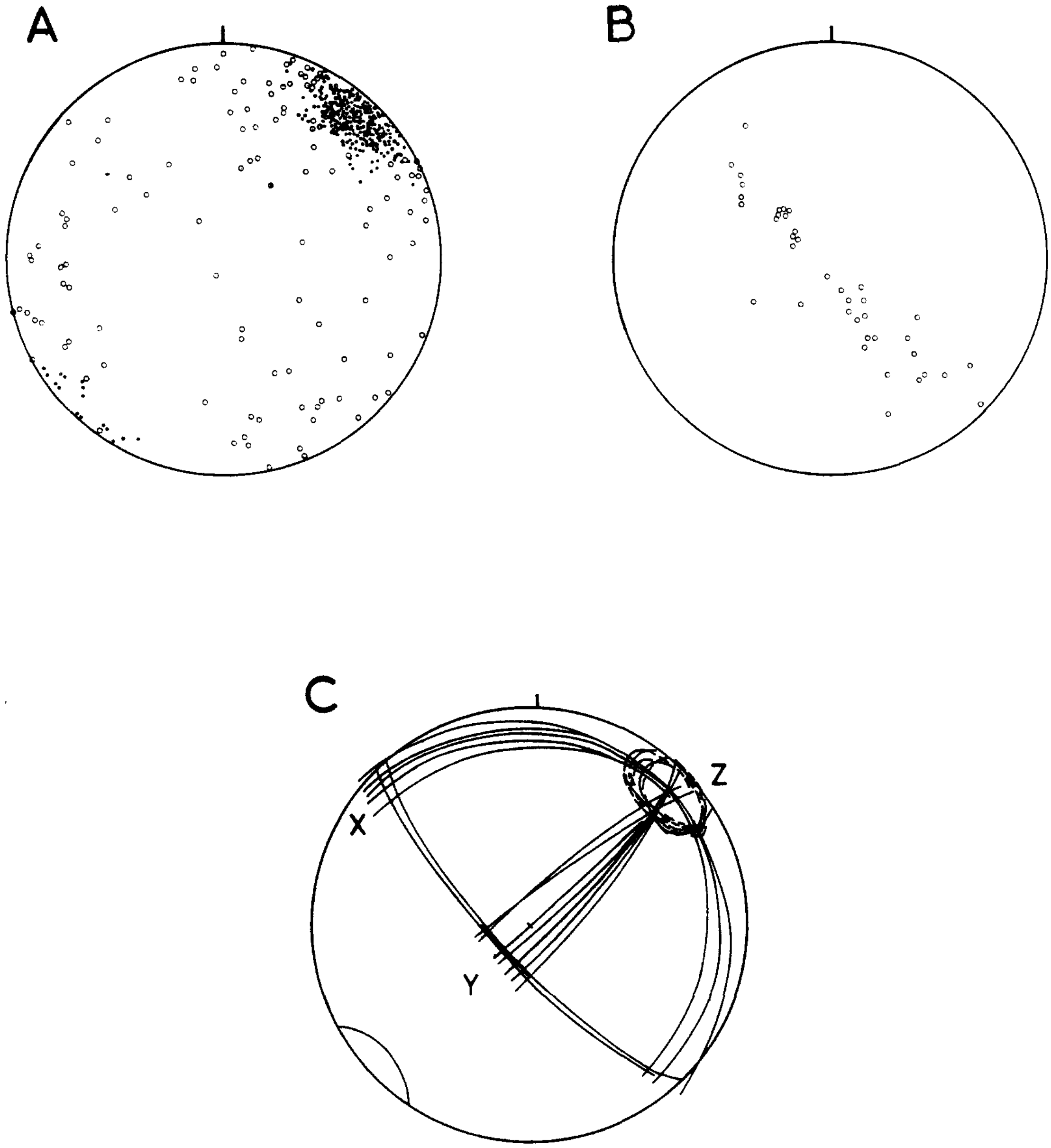

Fig. 10. Data from the northern marginal shear zone of the tonalite. A Poles to extended veins superimposed on poles to the inflexion surfaces of folded veins; B Hinges of folded veins; and C Constructions of the surface of no finite longitudinal strain using the overlaps of contours for 0.5, 1, 2, 3, 4 and 5%. The range of orientation for the three principal planes of the finite strain ellipsoid is shown.

fold hinges and an early finite stretching direction vary in the plane of the foliation, and there is a late subhorizontal linear mineral growth on some foliation surfaces in the Langavat belt. These features fit with the vein plots, imply polyphase deformation and once again are incompatible with an assumption of simple shear alone.

Polyphase deformation in the shear belt is also indicated by the fact that highly deformed Scourie-dyke amphibolites are slightly discordant against even more highly deformed flaggy gneisses, suggesting that the Langavat belt was a highly strained zone before the emplacement of the dykes (the bulk of the deformation is probably pre-dyke, as on the Laxford Front of the Scottish mainland).

The gradual northward decrease in strain, coincident with decreasing dip from the deformation belt into the less deformed migmatite complex (Fig. 2) suggests a more or less vertical shear direction—perhaps associated with the diapiric rise of the migmatites. Such deformation, superposed on the essentially transcurrent deformation indicated by the foliation swing in the tonalite might have helped create a flattening type finite strain. Certainly the northern margin of the Tonalite is a complex deformation zone.

THE STRUCTURE OF THE NORITE

Norite outcrops all along the South Harris coast between Toe Head and Renish point and is also exposed in northeast Ensay and on Coppay. Because the structural patterns on Ensay and the mainland can be linked, the norite body is assumed to be continuous between these rather isolated outcrops, unexposed beneath the South of Harris.

The northeastern contact of the norite is sub-

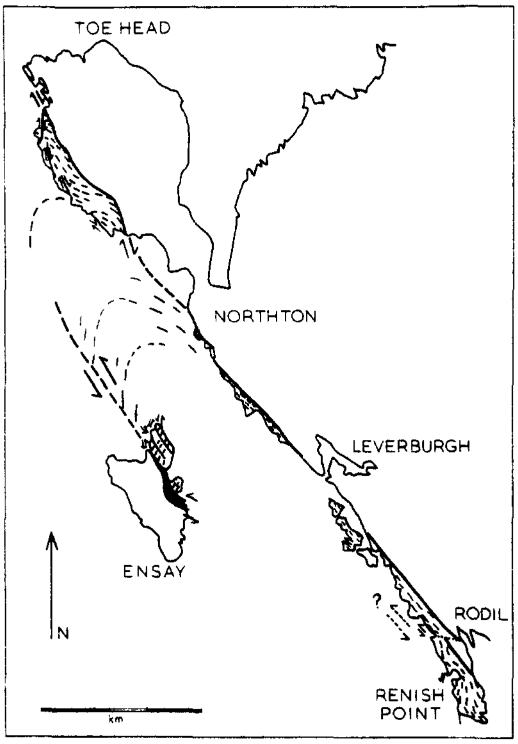

Fig. 11. Reconstruction of the norite.

vertical ductile shear zone in which there is retrogression of the granulite facies assemblage of both the norite and the Leverburgh supracrustals to amphibolite facies. The southern contact (on Ensay) is a ductile shear belt which dips northwards at about 50°. Thus the norite body seems to be wedge-shaped, thinning downwards.

The early penetrative fabric of the norite trends E–W on the Toe Head peninsula, NNE on Ensay and NW-SE through the exposures southeast of Leverburgh. The sense of the shear zones on Ensay is sinistral, while on the Toe Head peninsula it is dominantly dextral. The early fabric therefore seems to be deformed into a vertical neutral fold between Toe Head and Ensay. Presumably its original trend was NE–SW. Near Leverburgh there are no shear zones, and the fabric trends parallel to the margin of the body. On Renish Point near Rodel, many, but by no means all the shear zones are sinistral.

The degree of retrogression varies. It is most extensive near Leverburgh and entirely confined to shear zones on Ensay and in parts of the Toe Head peninsula.

The structure of the norite implies gross flattening rather than shear, though the presence of a fabric originally running at such a high angle to the length of the body suggests that like the other igneous bodies of South Harris it is a shear zone-bounded slice. It may be that an original slice was modified by later flattening.

THE DEFORMATION OF THE METASEDIMENTS

The configuration of pods of igneous rock, preserving old oblique internal foliations, and paragneiss belts, showing intense homogeneous strain, clearly suggests that the paragneisses were relatively incompetent during the shearing deformation, that they coincide with shear zones and have to some extent accommodated themselves around the igneous rocks.

It is easy to understand how the Langavat and Sound of Harris gneisses, in amphibolite facies and biotite rich, have been less competent than the basic pods. It is less easy to understand why the Leverburgh gneisses, dominantly in granulite facies like the igneous rocks, also seem to have behaved in a relatively more ductile fashion. The answer presumably is that most of the shearing deformation which displaced the igneous rock, (the deformation which imparted a NW–SE strike on the Leverburgh paragneisses) was, in fact a syn- or pre-granulite facies phenomenon which took place while a marked ductility contrast existed between igneous rocks and sediments. Small scale structural relationships in isolated pods bear this out. Pods of metamorphosed igneous rock within Leverburgh paragneisses preserve an old fabric and are less deformed than the gneisses, but granulite facies assemblages are late or post tectonic in both the pods and the paragneisses.

In general it seems that Laxfordian shearing and retrogression have hardly done more than rejuvenate existing structures. Locally however, their effects are profound. The asymmetry of the curve of the early fabric of the tonalite—sharp into the southern shear zones, gently curving into the nothern marginal deformation zone—is presumably connected with the extent of Laxfordian amphibolization, and the nearness of the migmatite complex.

CONCLUSIONS AND SPECULATIONS

Figure 12 uses the ideas expressed above to make a cartoon reconstruction of the igneous mass from which the Harris pods were derived. The displacements shown on the figure probably have little validity because of the difficulty of estimating amounts of movement on the shear zones. However one or two points seem clear. The igneous mass must have been very large (on the scale of the layered Archaean gabbro–anorthosite complexes of Greenland or the Limpopo belt) and the shear zone translations of considerable magnitude. There must have been several sheets of metagabbro interlayered with metasediment. One of them was at least 3 km thick. The tonalite and metagabbro were intimately associated before shearing (probably xenoliths of the latter within the former). Igneous rocks were disrupted into pods while metasediments were sheared out in a more ductile fashion, and now effectively form the most important shear belts. Most of the fundamental shearing and displacement pre-dated or was synchronous with granulite facies metamorphism. The structure was modified during later amphibolite facies Laxfordian metamorphism. Simple shear must have been complicated by flattening, and polyphase deformation.

The reconstructed rock assemblage of gabbro–anorthosites interlayered with sediments, and introduced by tonalite is typical of Archaean high grade ter-

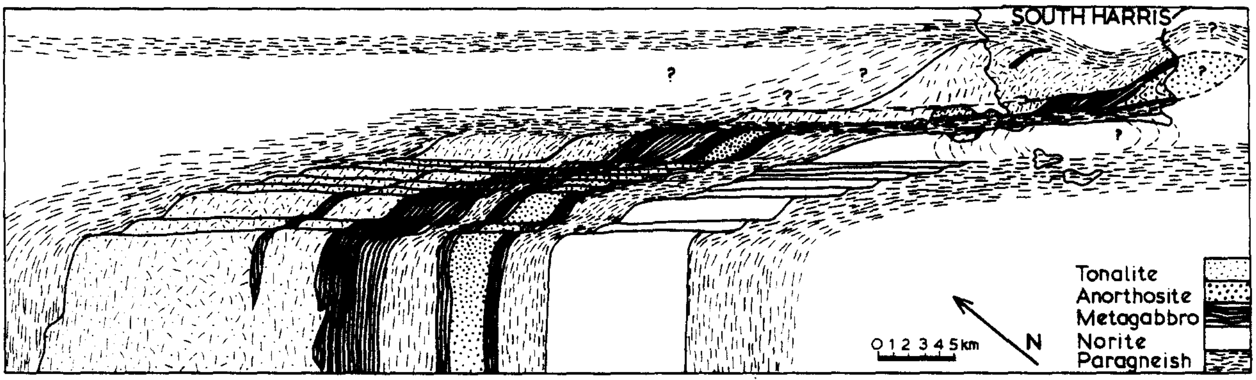

Fig. 12. Cartoon showing the derivation of the South Harris Igneous Complex by the slicing up of an original layered complex.

rains (Windley & Bridgwater 1971). Its significance and meaning—whether or not South Harris is a greenstone belt later metamorphosed in granulite facies, or whether the igneous rocks represent obducted oceanic crust (Garson & Livingstone 1973)—are problems of Archaean geology, not particularly relevant to a conference on shear zones. The original orientation of the complex (including the problem that it was probably sub-vertical rather than flat before the development of the shear zones) is something of local rather than general interest. Appreciation of processes taking place in shear zones has helped specify these problems. It might eventually help solve some of them.

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