PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Effects of Reworking on High-Grade Gneiss Complexes

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Phil. Trans. R. Soc. Lond. A 1973 **273**, 443-455
doi: 10.1098/rsta.1973.0010

Phil. Trans. R. Soc. Lond. A. **273**, 443–455 (1973) [443]
Printed in Great Britain

Effects of reworking on high-grade gneiss complexes

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Polycyclic gneiss complexes in which early rock-assemblages of granulite or high amphibolite facies have been tectonically and metamorphically reworked occur on a regional scale in the crust. The distinctive properties of the dry, structurally isotropic parent-assemblages have played an important part in determining the style of regeneration which was characteristically inhomogeneous. The reintroduction of water and consequent amphibolization of granulites appears to have been associated with increases of ductility and consequent changes in tectonic behaviour. During the early stages of Proterozoic mobility the Archaean crust was traversed by incipient dislocations which developed into 'straight belts' characterized by high strain. Deformation in the mobile provinces as a whole was associated with relative movements of the blocks defined by the straight belts. In these intervening blocks, regeneration was most effective at intermediate depths where pore fluids were available. Many Archaean granulites lying beneath the domain of regeneration remained as closed systems and suffered little tectonic or metamorphic modification.

1. High-grade gneiss complexes in the early crust

The antiquity of much of the continental crust has now been firmly established by geochronological studies allied to regional mapping programmes. It has been estimated that at least 50% of the North American continent was already in existence in late Archaean times, say 2500 Ma ago (Muelberger, Denison & Lidiak 1967), and the proportions were probably even greater in Greenland, India and Africa; indeed, a growing body of evidence suggests that substantial masses of continental crust date back to before 3000 Ma. If we are to judge from the samples which survive, the Archaean continental crust was dominated by two geological assemblages – the granite/greenstone-belt association which is seen, for example, in the Superior province of Canada and the Rhodesian craton of Africa: and the gneiss complexes showing metamorphism of granulite or upper amphibolite facies which are exemplified by the Archaean massif of Greenland.

Although Archaean materials bulk large in the present continental regions, only a comparatively small proportion of them retain the structural and metamorphic patterns which were impressed in Archaean times. Much Archaean material now forms an integral part of younger tectonic provinces in which the structural and metamorphic patterns are of Proterozoic or Phanerozoic age. It is evident, therefore, that Archaean rocks must have been repeatedly reconstituted through the later stages of geological history; the processes of tectonic and metamorphic regeneration at depth, in fact, have allowed the continental crust to adapt itself to changes in geological regime, complementing the recycling of materials by erosion and sedimentation at the surface.

The importance of granulite and gneiss complexes in the early crust has been emphasized by several contributors to the present volume. Such complexes were formed on a regional scale in Greenland, northwest Europe and northeast Canada during events which terminated over the period 2900 to 2700 Ma and in many parts of Africa, India and Siberia at roughly the same time. They were exposed at the surface by late Archaean times in several regions where early Proterozoic successions rest unconformably on granulites, and were considerably more extensive at depth. Windley & Bridgwater (1971) have suggested that the granite/greenstone-belt Archaean assemblages which occupy the Superior province and other comparable massifs may pass downward into granulite complexes, and if this suggestion is accepted one arrives at a picture of the Archaean continental crust in which granulites and their associates underlay very large areas and extended in places even up to the surface. An understanding of the behaviour of these rocks during the subsequent episodes of regeneration at depth must therefore be important for the interpretation of the later evolution of the crust. The object of this paper is to re-examine some aspects of the structure of polycyclic complexes incorporating Archaean granulites with a view to establishing their responses during regeneration.

2. The complexes before regeneration

Most Archaean granulite and gneiss complexes incorporate units of diverse kinds – metamorphosed supracrustal sequences, intrusive igneous bodies, migmatites and older gneisses – and consequently have a wide and varying range of composition. As Heier points out elsewhere in this volume, however (p. 429), many granulite complexes share certain geochemical peculiarities, notably the low contents of H_2O and of U, Th, Rb and K. These peculiarities, thought to be due to the expulsion of mobile elements during metamorphism, are reflected not only in the characteristic dominance of anhydrous minerals but also in the scarcity of pegmatites and coarse segregations. The dryness of the rocks had, as will be seen, profound effects on their response to reworking.

The majority of Archaean granulites show coarse equigranular textures with simple grain boundaries suggestive of post-kinematic crystallization. Fabrics defined by the dimensional preferred orientations of minerals are seldom conspicuous; the strong fabrics and platy partings of the classic Saxon granulites are unusual features possibly resulting from the reworking of older granulites.

The tectonic patterns revealed on the scale of the map are of two main kinds in Archaean (and many post-Archaean) granulite terrains. Predominantly flat layering of secondary origin is seen in the Archaean granulites of Ceylon (the Highland Series), in the Scourian charnockites of the Lewisian complex of northwest Scotland and in parts of the pre-Ketilidian terrain of East Greenland. In West Greenland, in parts of the Limpopo belt of southern Africa and in the Proterozoic Nagssugtoqidian belt of Greenland and Grenville belt of Canada, complex fold-interference patterns are characterized by steep dips and by numerous closed structures spaced at intervals of 5 to 15 km. Neither of these patterns define a well-marked tectonic 'grain' and in this respect they resemble those of the Archaean terrains of granite/greenstone-belt type in which irregular downfolds of low-grade supracrustal rocks are moulded on broad domes of granitic and tonalitic rocks. Taken as a whole, therefore, the continental crust developed in Archaean times would appear to have lacked the strong structural anisotropy built into it during Proterozoic and Phanerozoic epochs.

3. Competence variations and the style of reworking

The reconstitution of older crystalline rocks within the crust has generally been achieved by deformation in association with metamorphism and, on occasion, with partial melting or introduction of granitic material. Deformation of such rocks in a non-metamorphic environment leads to disruption and cataclasis without constructive regeneration. The responses to deformation in many polycyclic complexes appear to have been very closely linked with the effects of metamorphic reactions, especially those accompanying the reintroduction of water into dry rocks, and variations in structural style therefore provide a useful clue to variations in crustal environment.

Where complexes of granulites have been regenerated, the initial dry mineral assemblages are frequently replaced by assemblages carrying hornblende, biotite and other minerals appropriate to the amphibolite facies. In the absence of such retrogressive changes, bending, disruption and cataclastic granulation of the initial minerals or, in some instances, failure along definite shear-zones are commonly seen. Cataclastic granulites produced in this way characterize some of the anorthositic associations of the Grenville belt in North America, for example in the Adirondacks (see, for example, Buddington 1939) and the Mont Laurier area (see, for example, Wynne-Edwards 1969).

Where retrogression to amphibolite facies accompanied deformation or where rocks of differing lithologies are interlayered, the interplay between metamorphism and response to stress is illustrated by variations in extent of deformation (for examples from the Adirondacks, see Buddington, 1963) or in structural style. The incidence of fold-forms resulting from the buckling of competent layers and of boudinage structures resulting from their extension allows one to establish the relative competence of different rock-types at the time of deformation. In the Lewisian complex of northwest Scotland where the effects of early Proterozoic (Laxfordian, *ca.* 1800 Ma) reworking of Archaean gneisses and granulites are seen, criteria of this kind employed especially by Coward (1972), Francis (1972) and Graham (1969) provide a basis for the following generalizations:

(1) Basic pyroxene-granulites and pyroxene-amphibolites acted as competent units with respect to quartzofeldspathic hornblende-gneisses and biotite-gneisses.

(2) Amphibolites generally acted as competent units with respect to similar gneisses but the reverse relationship is occasionally recorded.

(3) Biotite-bearing amphibolites, gneisses and schists behaved as incompetent units with respect to rocks without micas.

(4) Quartzofeldspathic gneisses and pegmatites devoid of ferromagnesian minerals behaved as competent units with respect to almost every other rock-type.

The observed contrasts between rocks carrying pyroxenes and rocks carrying amphiboles or micas are of special interest. Francis (1972) has described from eastern Barra basic dykes in acid gneisses in which pyroxene-bearing and amphibolized portions of the same body appear to have responded differently to Laxfordian deformation; the dykes as a whole retain early two-pyroxene assemblages and are boudinaged; but their marginal parts are amphibolized and are interfolded with the adjacent gneiss in a cuspate pattern which indicates that they were less competent than the gneisses. A difference in competence between amphibolized and unaltered pyroxene-bearing rocks is also suggested by the common development of new fabrics in the amphibolized marginal parts of pods of basic granulite (cf. Sutton & Watson 1951) and in shear-zones traversing such granulites, while older fabrics and structures are preserved with little modification where pyroxenes remain unaltered. Very high local strains are recorded in certain Laxfordian shear-zones where the rocks are wholly amphibolized (see, for example, Ramsay & Graham, 1970).

Evidence relating to structures on various scales suggests that dramatic increases in ductility accompanied the reintroduction of water into granulite complexes subjected to tectonic reworking at depth. Once amphibolization had begun, the relatively ductile zones in which amphibolization was most advanced might be expected to undergo strong deformation while the intervening dryer and less ductile rocks suffered less distortion. Many polycyclic complexes involving granulites or gneisses of high amphibolite grade such as the Laxfordian complex of northwest Scotland do in fact show conspicuous structural inhomogeneity on many scales.

The high relative competence of quartzofeldspathic rocks devoid of ferromagnesian minerals in many parts of the Laxfordian complex is a further illustration of the control exercised by scarcity of water during reworking. Many of the reworked gneisses in the Lewisian complex of the western Hebrides are derived from Scourian (> 2300 Ma) *lit-par-lit* gneisses containing abundant thin pegmatite layers which consist of quartz, plagioclase and potash feldspar. Where these gneisses have been subjected to Laxfordian deformation, the early pegmatites have been buckled and boudinaged in a manner which shows that they were more competent than the associated hornblende or biotite-gneisses. It is clear that these early pegmatites remained essentially solid during reworking in spite of the fact that their composition suggests that they represent a low-melting fraction and in spite of the fact that the Laxfordian mineral assemblages indicate metamorphic temperatures appropriate to the upper amphibolite facies. The generation of a partial melt in the Laxfordian complex, and in other areas where similar features are seen, may have been inhibited by scarcity of water. I believe that many of the 'migmatites' described from polycyclic basement terrains may turn out to be simply old migmatites reworked – their structures are those appropriate to deformation in the solid and not to partial melting.

4. Inhomogeneity in reworked complexes

The occurrence of remnants in which the isotopic clock has not been reset and in which structures and metamorphic assemblages dating from previous cycles have been preserved is almost a hall-mark of polycyclic gneiss complexes – indeed it is by virtue of this feature that the true nature of many complexes has been recognized. The survival of such remnants illustrates a more general characteristic; this is the existence of remarkable lateral variations, exhibited on both local and regional scales, in the style and completeness of the tectonic and metamorphic reconstitution brought about during the period of reworking.

In many polycyclic complexes a distinction can be drawn between two differing styles of reworking. Broad tracts are characterized by complex patterns in which structures dating from the period of reworking are obviously superimposed on and interfere with structures of earlier generations. The extent to which the earlier structural and metamorphic features are modified varies from place to place and is at a minimum in remnant massifs of the type referred to above. These tracts contrast with zones in which a much simpler structural pattern, usually dominated by parallel planar elements, is developed and inherited features are difficult to recognize. The structural simplicity of the 'straight belts' or 'straightening zones' (Hepworth 1967) is clearly not an original feature. Earlier rocks and structures are seen to be distorted and deflected on entering them, early mineral assemblages are lost, new minerals and fabrics appear and apparent ages generally relate only to the period of reworking. The straight belts, therefore, may be thought of as zones in which earlier rocks and structures have been almost completely made over to conform to new patterns, the intervening complex regions as blocks whose structure reflects the interference of earlier and later patterns. The distinction between these domains appears to have been established very early in the period of reworking and to have exerted a long-standing influence on the style and orientation of the structures produced.

The straight belts which traverse polycyclic gneiss complexes are generally characterized by steep and regular dips and by the parallel alinement of lithological boundaries, schistosities, fold axial planes, pegmatites and granites, indeed of all planar elements. In some belts mylonites, mylonite gneisses and tectonic schists are developed on a large scale; in others, the common textures are crystalloblastic and the most distinctive feature of the constituent rocks is a regular striping which, on close inspection, often turns out to have been produced by the flattening or drawing-out of an originally more irregular streaking or banding. Primary structures such as pebbles, lava-pillows or the discordant contacts of intrusive dykes are lacking or strongly distorted. All these features identify the straight belts as zones in which reworking was associated with intense deformation.

When the relationships between the straight belts and the blocks on either side of them are examined, it becomes evident that deformation in the former was connected with relative movements between adjacent blocks. The nature of these movements can be inferred in some areas from observations on structural markers of various kinds. The rotation and thinning of basic dykes at the front of Laxfordian reworking in the Scourie–Laxford area of northwest Scotland suggest flattening in planes parallel to a northwesterly marginal straight belt (Sutton & Watson 1962), perhaps associated with dextral transcurrent displacements. The rotation and thinning of two dyke-swarms at the Nagssugtoqidian front in West Greenland indicates flattening in the marginal straight belt associated with southward overthrusting of the regenerated complex (Escher, Escher & Watterson 1970; Bridgwater, Escher & Watterson 1973). The sense of deflexion of magnetic anomalies at several northeasterly lineaments traversing the Superior and Churchill provinces of Canada suggests sinistral transcurrent displacements (figure 1). Transcurrent movements are also indicated by the deflexion of complex interference-patterns by straight belts parallel to the Limpopo mobile belt of southern Africa (cf. Mason 1973; Coward, in discussion).

The importance of straight belts of the kinds mentioned above is manifold. They form linear zones which extend for distances of hundreds or even thousands of kilometres through provinces in which the regional patterns are structurally almost isotropic. Those mentioned in the preceding paragraph appear to have come into existence at or even before the onset of Proterozoic mobility and must be among the oldest major lineaments developed in the continental

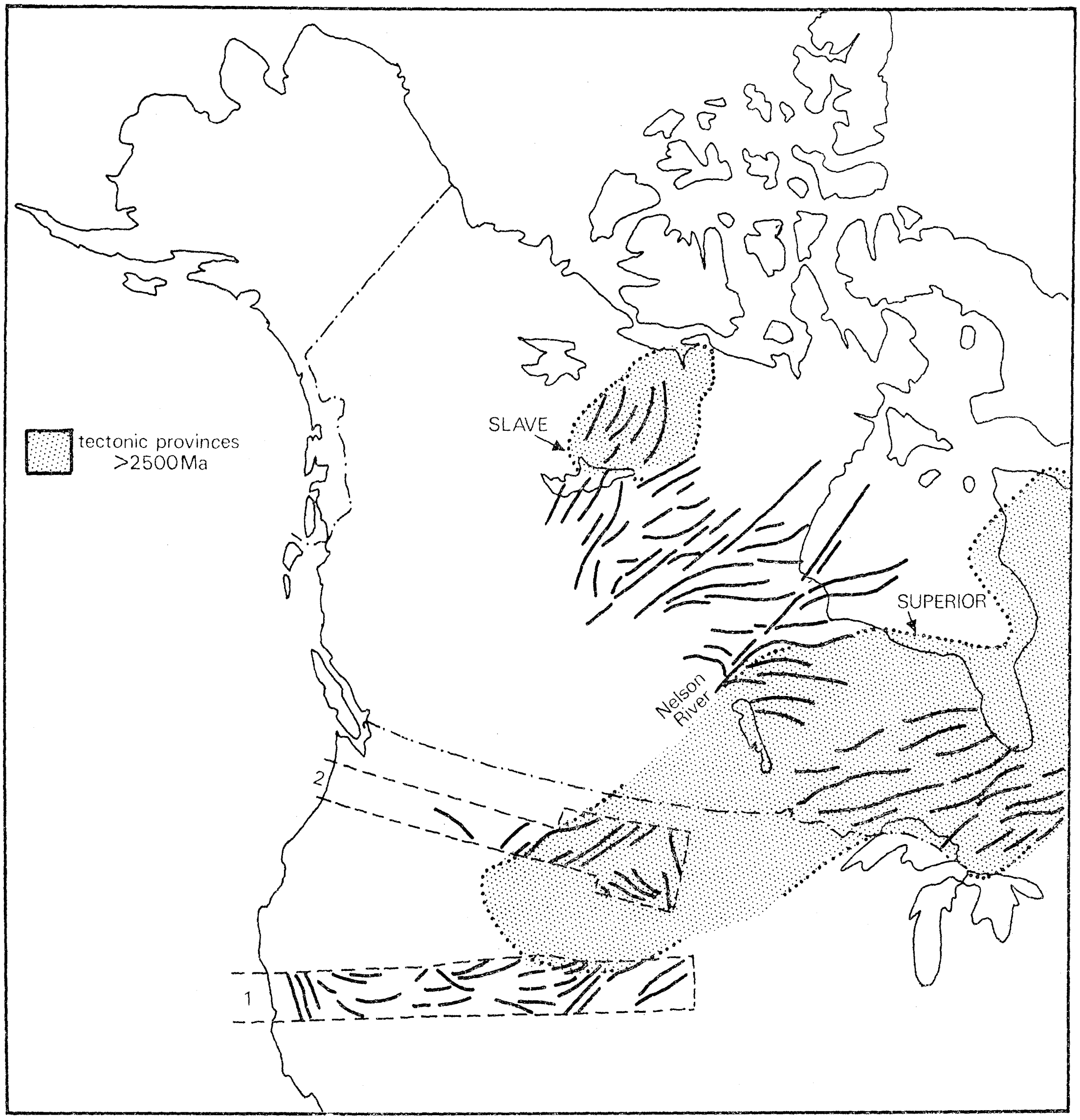

FIGURE 1. Schematic map of Archaean and early Proterozoic provinces of Canada and western U.S.A., showing the tectonic patterns inferred from the arrangement of aeromagnetic anomalies.

crust. Their formation brought about a permanent change in crustal architecture, defining the limits of many blocks which were to behave as structural entities through later cycles.

The scale and relationships of the early straight belts can be illustrated by reference to the Archaean and early Proterozoic tectonic provinces of North America. The deep structure of these provinces as reflected in the arrangement of magnetic anomalies is shown schematically in figure 1 which is based on the Aeromagnetic map of the Canadian shield (Geological Survey of Canada 1968) and two aeromagnetic strips across the western United States (1, Zietz *et al.* 1969; 2, Zietz *et al.* 1971). A pattern of roughly east–west anomalies of broad and irregular form is seen to be deflected into and out of a number of northeasterly lineaments which I interpret as straight belts. The apparent displacements are mostly sinistral (figure 2). The longest straight belt, which extends for not less than 2500 km, coincides for long distances with the front of Proterozoic (Hudsonian) reworking against the Archaean Superior province in the

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Nelson River area of Canada and in Idaho. Other lineaments define the fronts of reworking against the Slave province and the Wyoming massif and still others lie wholly within Proterozoic or Archaean provinces.

It is, I think, reasonable to infer that the anomalies which are deflected into and out of the straight belts (figure 1) are related to an originally unified pattern of structures which was distorted and partly disrupted by the development of the belts. Similar relationships are revealed by tectonic maps of the Nagssugtoqidian province where straight belts intervene between blocks

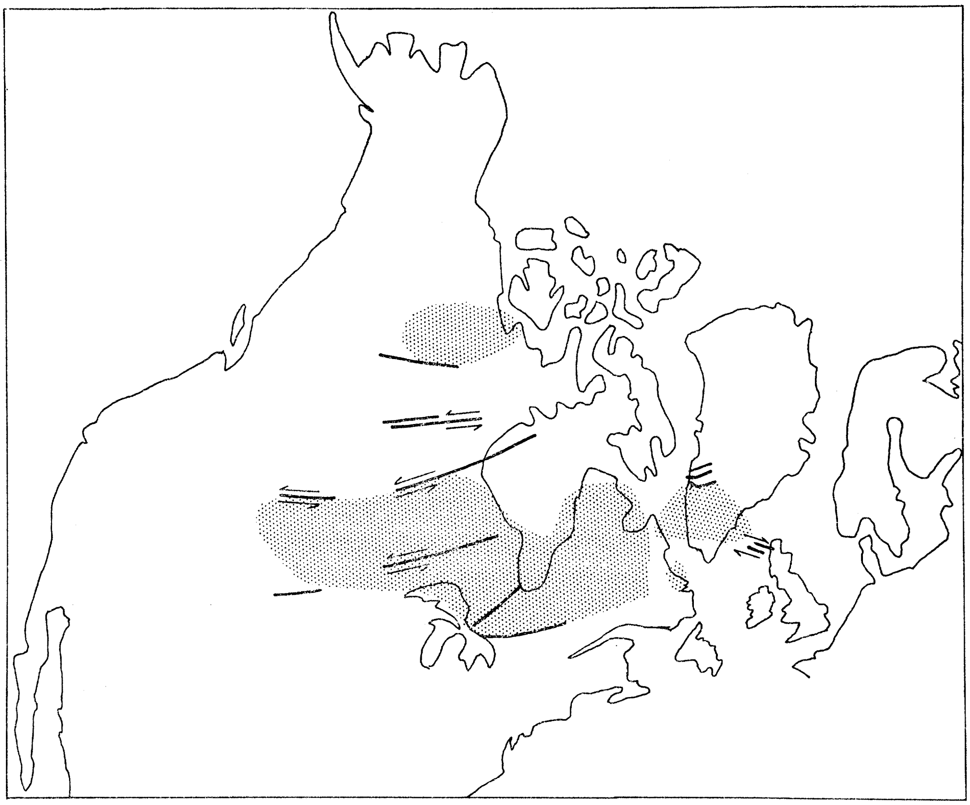

FIGURE 2. Schematic map of the North Atlantic continental regions, reassembled to eliminate the effects of Phanerozoic continental drift and showing the distribution of Archaean cratons (shaded) in relation to that of late Archaean and early Proterozoic straight belts (heavy lines).

which exhibit complex interference-patterns similar in form and scale to those of the unmodified Archaean province south of the Nagssugtoqidian front (Escher 1970; Bondersen 1970) and of the Limpopo belt (Mason 1973). The straight belts, therefore, must be regarded as incipient dislocations developed within large and rather uniform rafts of continental crust; they mark zones of relative motion between neighbouring, formerly continuous blocks and not sutures uniting formerly separated blocks.

Although many of the provinces in which the Archaean crust was reworked in early Proterozoic times include, or are bordered by, straight belts it is clear that the provinces defined by the sum-total of structural, metamorphic and geochronological features are much more extensive than the individual straight belts, often incorporating several such belts as well as the reworked blocks between them. The straight belts, then, are in scale and spacing only indirectly related to the distribution of domains of early Proterozoic reworking. This partial independence, with the fact that they appear to be relatively narrow and clearly defined even at depth, leads

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me to suggest that they were initiated before the rise in geothermal gradients in the Proterozoic mobile provinces had differentiated the latter from the Archaean cratons. Once established, the facilities for the migration of fluids which the structural anisotropy of the straight belts provided would allow dry rocks within them to be rapidly amphibolized. The sharp increases of ductility associated with amphibolization would favour the development of high finite strains. In this way the initial differentiation between straight belts and less strongly deformed blocks might be perpetuated through the period of regional heating and deformation and the contrasting tectonic and metamorphic styles of the two domains might be accounted for. The concentration of effects of stress in domains of high deformation which might be expected to result from the irregular reintroduction of water into dry rocks made it possible for some parts of the intervening blocks to escape deformation entirely and consequently allowed the remnant massifs retaining old rocks and structures to be preserved.

The characteristic inhomogeneity of polycyclic gneiss complexes is thus seen to reflect the nature of the process of early Proterozoic reworking. The first stage in this process, I suggest, was the development of incipient steep dislocations within large masses of Archaean continental crust showing no strong tectonic grain. These dislocations defined a number of blocks between which relative vertical or transcurrent movements took place. At about the same time, temperatures rose in the provinces of Proterozoic mobility and regional tectonic and metamorphic regeneration took place in these provinces. The fact that province boundaries coincide with straight belts over long distances suggests that regeneration was connected with the relative transcurrent or vertical movements of crustal blocks. It is pertinent to recall that the early Proterozoic Ubendian mobile belts of east Africa have for long been considered by McConnell (1951) to have been developed as a result of the incipient break-up of a large crustal block during rotational shear-movements. Some province boundaries, however, appear to be independent of or oblique to major straight belts. The Ketilidian province of South Greenland lacks evidence of marked crustal shortening and is distinguished mainly by exceptional plutonic activity (Bridgwater *et al.* 1972). The Laxfordian province of northwest Britain has an inferred boundary against the Archaean craton of Greenland which must be oblique to the small straight belts within it. Such variations in marginal relationships should have a bearing on the relative motions of the Archaean cratons which border Proterozoic mobile belts and help to illuminate the picture of global tectonics in Proterozoic times.

5. Granulite massifs at depth

The spatial relationships of the remnant massifs which escaped the effects of regeneration in polycyclic provinces have an important bearing on the internal structure of such provinces and, indirectly, on the later evolution of the crust. The upper limit of effective regeneration was controlled by the geothermal gradient. In the cold suprastructure or *Oberbau*, effects of cataclasis, disruption and limited retrogression are seen but no true reconstitution of older rocks took place. The domain of regeneration lay in the hot *Unterbau* which, as Wegmann showed in his classic studies based largely on work in Greenland (1935), is characterized by a fundamentally different tectonic style.

Many remnant massifs, however, appear to have originated at deep levels within or even beneath assemblages of regenerated gneisses. The structure of the Lewisian complex of northwest Scotland illustrates relationships of this type in that a number of small remnant massifs of Archaean rocks, the largest only 60 km in breadth, are enveloped in polycyclic Laxfordian gneisses and migmatites formed by reworking of similar Archaean materials. In the southern parts of the Lewisian outcrop on the Scottish mainland (Sutton & Watson 1969) and the southern islands of the Outer Hebrides (Coward, Francis, Graham & Watson 1971), little-modified Scourian gneisses yielding isotopic ages of up to 2600 Ma and cut by almost undistorted basic

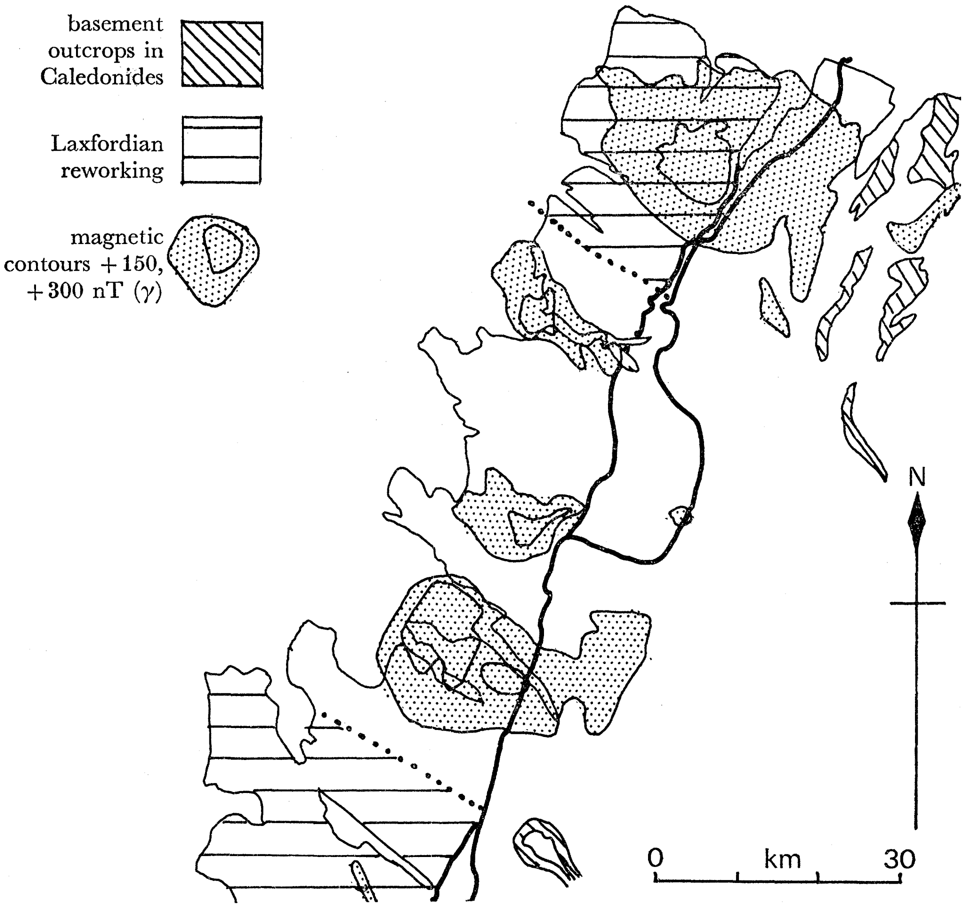

Figure 3. Positive aeromagnetic anomalies believed to indicate the occurrence of Lewisian granulites at depth in northwest Scotland (for discussion see text below).

dykes occupy several antiformal fold-cores which appear to be roofed by regenerated amphibolite-facies gneisses incorporating deformed and metamorphosed dykes. Granulites occur only locally at the present level of erosion, but geophysical evidence shows that dense and highly magnetic rocks interpreted as granulites underlie some of these Scourian massifs. In the northern part of the mainland (figure 3) Scourian granulites intruded by basic dykes form a large massif over which positive aeromagnetic anomalies are recorded. This remnant massif is traversed by narrow zones of late Scourian and Laxfordian deformation and amphibolization and is flanked to the north by a region of Laxfordian regeneration and migmatization with a marginal straight belt. The northern Laxfordian complex consists of amphibolite-facies gneisses, metadolerites, granites and pegmatites and has a broadly antiformal structure (cf. Dearnley 1962). A positive aeromagnetic anomaly (I. G. S. Aeromagnetic Map Sheet 13) and gravity anomalies (Bott, Holland, Storry & Watts 1972) indicate the occurrence of highly magnetic and dense rocks at depth. Several authors have inferred the presence of granulites beneath the reworked complex (Flinn 1969, Bott *et al.* 1972) and analogy with the southern and western areas leads me to suggest that these granulites are little-modified Scourian rocks.

Broadly similar phenomena can be recognized in other provinces. The resemblance between the deep structure of the Churchill province west of the Nelson River lineament and that of the adjacent part of the Superior province as revealed by the aeromagnetic map of the Canadian shield has already been mentioned (figure 1). This resemblance suggests that structures of Archaean age persist at depth in the Churchill province which displays at the surface the effects of reworking at about 1800 Ma. In the Alpine orogenic belt of Europe material from the lower crust associated with the geophysically defined Ivrea body in the region of the Insubric line includes granulites and gneisses which have yielded isotopic ages of up to 800 Ma if not more. These rocks seem to have been little modified during the Hercynian and Alpine orogenic events recorded at higher tectonic levels. Within the European Hercynian belt, granitic and migmatitic materials appear to have been derived from a regenerated basement in parts of the Bohemian massif. Stettner (1971) considers that these materials were mobilized from near-horizontal shear-zones at which moving slabs of the basement were detached from a less mobile lower crust.

Evidence of the kind outlined above shows that in certain areas rocks which lay within or beneath domains subjected to Proterozoic or Phanerozoic regeneration have retained structural patterns, mineral assemblages and apparent ages dating from earlier cycles. It seems unreasonable to suppose that deep-seated remnants of this kind which are roofed over by regenerated rocks did not reach temperatures and pressures at which regeneration was possible and, indeed, several lines of evidence indicate that conditions appropriate to metamorphism of amphibolite or granulite facies were attained. Recrystallization, with the development of high-grade assemblages, may be seen in localized shear-zones traversing remnant granulites, as in the Laxfordian shear-zones which cross the main Scourian massif in Scotland. Furthermore, igneous bodies which intruded the early metamorphic complex prior to the period of regeneration are commonly wholly or partially recrystallized to high-grade metamorphic assemblages. Basic dykes in granulite terrains which exhibit anomalous metamorphic assemblages characterized by pyroxenes, garnets or hornblendes have been described by many authors and have always presented a problem, since they appear to record an episode of metamorphism later than any episode recorded in their country rocks; their characters have been variously ascribed to intrusion into hot host-rocks (by, for example, O'Hara 1961) and to subsequent incipient metamorphism (by, for example, Dearnley 1962, 1972). In the present context their interest lies in the demonstration they provide that temperatures sufficiently high to bring about recrystallization of the dykes had no apparent effect on the granulite country rocks. It appears that the responses of these rocks were inhibited by some factor other than temperature.

6. The *Unterbau* reconsidered

The relationships between metamorphic recrystallization and deformation in reworked terrains and the observed contrasts in tectonic behaviour between granulites and amphibolized granulites suggest that the effective reconstitution of rocks in high-grade terrains has been controlled largely by the availability of water. There are, as has already been noted, indications that even where reworking in amphibolite facies has taken place, the onset of partial melting was inhibited by scarcity of water (p. 446). The Archaean granulites, with their poverty of water and of mobile elements generally, their massive textures and lack of structural anisotropy, were well adapted to resist the influx of pore-fluids and it is not surprising to find that these rocks are represented in many deep-seated remnant massifs. The fact that many rocks in such massifs retain textures and minerals dating from earlier cycles and in some instances yield apparent ages (including mineral ages) appropriate to these cycles indicate that they acted as closed systems during regeneration.

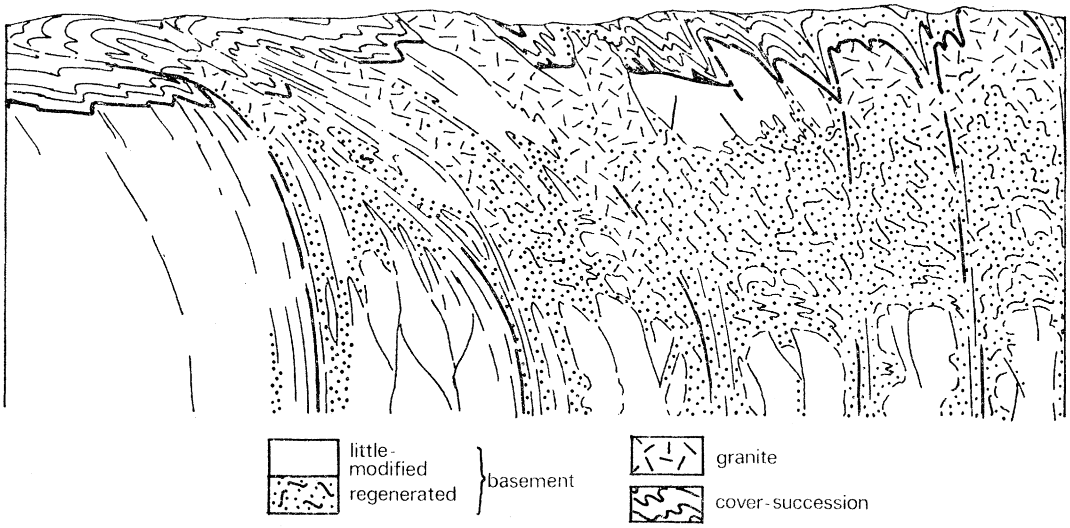

Figure 4. Diagrammatic section of a polycyclic province illustrating the suggested relationships of the domain of regeneration. Remnant massifs in the lower crust consist largely of granulites which resisted regeneration.

The survival of remnant massifs within domains of regeneration is, as I have pointed out, favoured by the inhomogeneous style of regeneration characteristic of dry terrains. The early differentiation of straight belts in which the transport of fluids was facilitated and ductilities were increased allowed portions of the intervening blocks to which water penetrated less easily to remain unmodified and in a broad sense, therefore, the location of the massifs may be said to have been structurally determined. On a smaller scale the local availability of water, the incidence of deformation and the composition of the host rocks might control the extent of modification. Many authors, for example, have described unmodified remnants of basic granulites in acid gneisses which have been strongly deformed and amphibolized; and anorthosites, mangerites and related rocks appear to form nodes in which granulite facies assemblages survive in amphibolite-facies terrains of the Grenville province (see, for example, Wynne-Edwards 1969).

Small massifs, especially those which appear to be both overlain and underlain by reconstituted rocks (cf. Coward 1972), may be written off as incidental products of inhomogeneous reworking. There is, however, a good deal of evidence of the kind mentioned on pp. 450–1 to suggest that the incidence of unmodified remnants in regenerated provinces increases with depth. Many of the granulite complexes which appear in the interior of polycyclic mobile belts such as the Laxfordian complex of Scotland, the Mozambique belt of Africa and the terrains of southeast India and Ceylon have turned out to be occupied by very old rocks in which the radiometric clock has been only partially reset (see, for example, Clifford 1972; Crawford & Oliver 1969).

These indications suggest, in my opinion, that the granulites occurring at deep levels in the crust have remained largely unmodified during the later evolution of the crust. A downward decrease in the extent of reworking appears to be recorded instead of the increase which might be expected to accompany rising temperatures and pressures. This anomalous falling-off of regeneration with depth in polycyclic provinces emphasizes the role of fluids in promoting tectonic and metamorphic activity. It is suggested that the dry granulites formed in the lower crust in Archaean times tended to function as closed systems in which reaction was inhibited and, consequently, retain early structural features and give early dates.

If the suggestions given above are valid, regeneration in the broad Proterozoic mobile provinces should be thought of primarily as an affair of the middle crust, extending to depth mainly in the straight belts. The mobile *Unterbau* was thus confined between the cold and brittle *Oberbau* and the floor of hot but strong and unreactive granulites (figure 4). The lower limit of effective reworking was determined by the depth to which adequate pore-fluids remained under the prevailing temperature conditions; in granulites and gneisses above this level regeneration was possible, in rocks below this level reaction was inhibited. The contrasts in the behaviour of unmodified and amphibolized granulites at higher levels suggest that this lower boundary is likely to be sharp and disharmonic.

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