acta
geologica
polonica

Vol. 26, No. 1 Warszawa 1976

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Significance of structural trend in Precambrian terrain

ABSTRACT: The development of the concept of structural trend and its use both in the study of Precambrian shields and intercontinental Precambrian correlations are examined. On the basis of examples from Scotland, Fennoscandia, East Africa, India and Western Australia it is shown that the concept has been useful where applied to regions in which a single feature, such as lithological layering, foliation, upright folds or major fault lineaments, dominates the structural regime. However, its unqualified use in regions of polyphase deformed rocks has often been misleading and resulted in erroneous correlations. This is particularly the case where the nature and origin of the particular trend is unspecified, where differences between cover tectonics and tectonic overprinting of basement are not demonstrated, or where the relationship of trend to a polyphase deformational sequence is not determined. Repeated reference in the literature to trends which are ill-defined or not representative of a structural regime often leads to their unquestioned acceptance. With the framework of Precambrian shields being important in atempts to reconstruct previous configurations of continental masses, assessment is necessary of any structural trend used as a basis of correlation.

INTRODUCTION

The use of "trend" has for long been commonplace in the literature of structural geology, particularly in accounts summarizing regional information for Precambrian shield areas. As early as the beginning of the second quarter of the 19th century, Élie de Beaumont (1829, 1830) set out theories concerning the origin of mountain ranges and tried to demonstrate that parallelism of ranges was indicative of similarity in age. The genetic considerations on which this idea was based were later shown to be erroneous. However, the general trend shown by granitic masses forming the central axis of a mountain range was recognized, as was the structural pattern of bedded rocks on either side of the central axis. Initially Élie de Beaumont postulated twelve mountain systems with parallel trends, a number that was increased to twenty-one by the middle of the 19th century (Adams 1954, p. 394—395).

By this time field observations in some metamorphic terrains, notably in Scotland, had demonstrated the existence of regions with different structural trends as well as the "want of parallelism between the lines of perpendicular foliation and cleavage, forming the boundaries of the great arches of gneisses, schist and slate which traverse Scotland" (Sharpe 1852, p. 454). Sharpe (p. 455) pointed out that "the divergence above pointed out militates strongly against M. Élie de Beaumont's favourite theory of the parallelism of contemporary mountain chains". He also showed that the north-western part of the mainland of Scotland, together with Lewis in the Outer Hebrides, had a prominent N.W.–S.E. strike of foliation and cleavage while in the eastern part of Northern Scotland the foliation and cleavage generally had a N.E.–S.W. strike (Fig. 1). This separation was subsequently shown to be that between the Precambrian Lewisian complex making up the foreland of the Caledonian mountain belt and the main Caledonian fold belt itself. This divergence in strike between the foliation of the "Laurentian gneiss" in the west and the "eastern schists" was also pointed out by Murchison (1860) who had previously recorded that the two terrains showed different structural patterns with the rocks of the western part being highly contorted with abundant granitic veins, features not characteristic of the eastern part of the region (Murchison 1859).

The composite structure of present day mountain ranges was discussed by Dana in his *Manual of Geology* (1871, p. 19—21). Dana's exposition of the arrangement of parallel-trending individual parts, such as ridges, into overall trends that were straight or curved, or of the complex (interference) patterns where there were transverse ridges, was later to be taken up by Precambrian workers in the development of the idea of structural trend in Precambrian orogenic belts. Dana (p. 37) also showed that individual mountain chains could show marked differences in trend in different places with some trends curving through 90° between regions where the trend was linear.

The recognition of correspondence between "axes of disturbance" and the direction of a mountain belt made up of rocks of "great antiquity" came in the last quarter of the 19th century from work in the Precambrian shield of Peninsular India (Meldicott & Blanford 1879, p.vi, vii). These two aspects of (*i*) trend and (*ii*) age (relative or absolute) of belts with particular trends appear time after time in subsequent Precambrian studies not only in India, but also elsewhere. There, as in Scotland earlier on, varying trends of foliation in metamorphic rocks (Fig. 2) were recorded (Lake 1890, Pl. 2, p. 211—212) and subsequently the different trends interpreted as being indicative of different ages (Oldham 1893, p. 37).

The latter part of the 19th century and the first few years of the 20th century saw a great surge forward in the mapping of large areas of Precambrian terrain, mapping which provided a solid basis on which to discuss the nature and significance of structural trend on a crustal scale as well as a regional scale. In Scotland this period culminated, in 1907, with the publication of *The Geological Structure of the North-West Highlands of Scotland* by Peach, Horne, Gunn, Clough & Hinxman, while in Fennoscandia Ramsay published his *Geologins grunder* in 1909. In Scotland it was demonstrated that the N.W.–S.E. strike, previously recorded by Sharpe (1852) and Murchison (1860), was dominant over considerable areas of the Lewisian complex and that this trend was a composite feature made up of (*i*) strike of lithological units (Fig. 6*a*), (*ii*) strike of metamorphic foliation (Fig. 5*a*), (*iii*) trend of fold axes, (*iv*) strike of axial planes of folds with highly variable interlimb angles (Fig. 6), (*v*) trend of granitic and pegmatitic veins and sheets (Figs. 5*b*, 6*a*), (*vi*) the trend of lines of shear (Fig. 5*a*) and thrust planes and (*vii*) the trend of fold-crush zones (Fig. 5*b*) — "the pre-Torridonian lines of movement" (Peach & al., 1907; Peach & Horne 1930). Subsequent geochronological investigations have shown that this N.W.–S.E. trend is related to a particular orogenic episode (*see* Laxfordian orogen) and subsequent structural work has shown that while other trends do occur in the polyphase deformed rocks of this orogen, the N.W.–S.E. trend is dominant over considerable areas (*cf.* Fig. 7*a*). For other parts of the North-West Highlands of Scotland an entirely different structural pattern with a different structural trend, or trends, was demonstrated by Peach & al. (1907), with much later investigations using isotopic data showing that these were related to a much older orogenic episode (*see* Scourian orogen). However, for Fennoscandia, recent investigations using isotopic data have

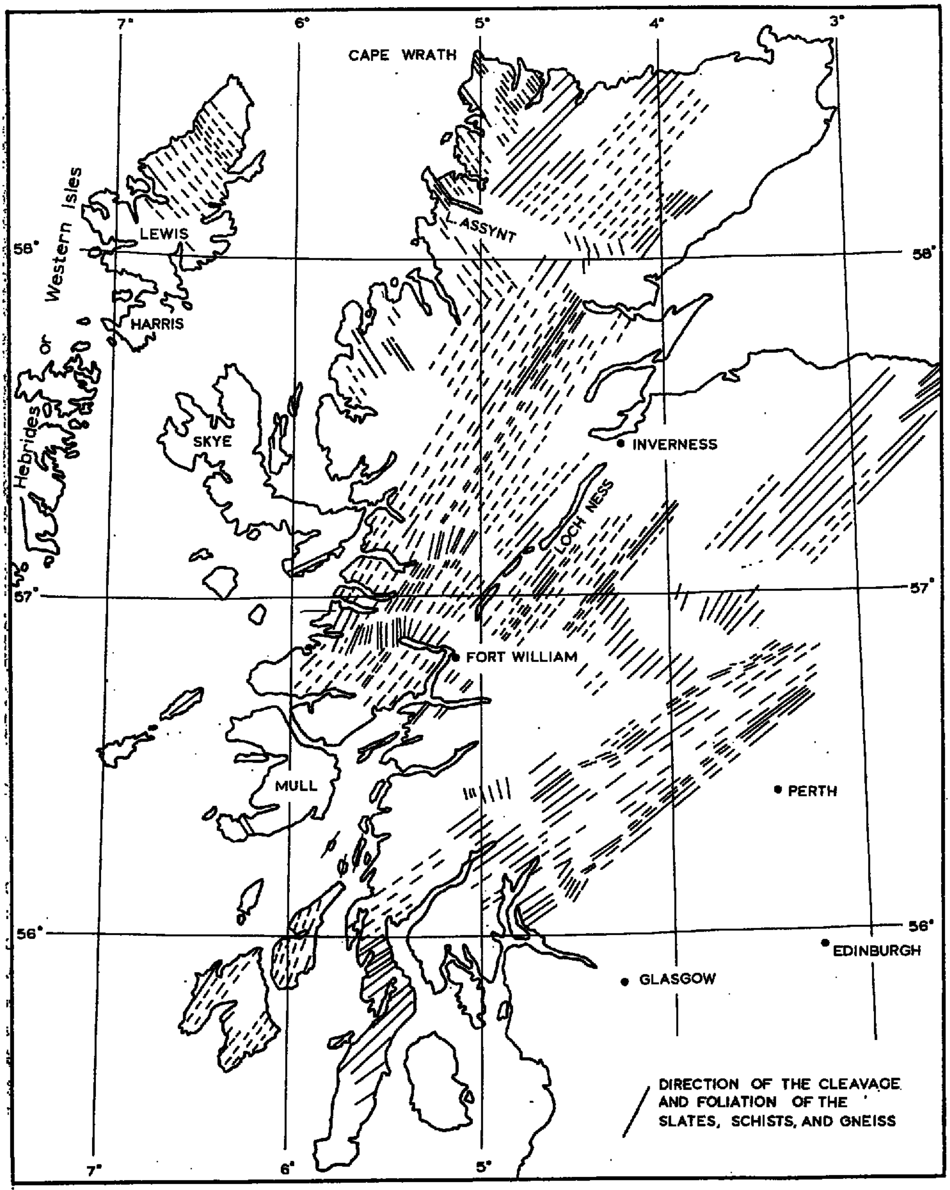

Fig. 1. Map of Scotland showing the direction of the cleavage and foliation of the slates, schists and gneiss (*after* Sharpe 1852, Pl. 24)

shown that the two different belts with different trends demonstrated by Ramsay (1909) — the generally E.–W. trending Svecofennian belt and the N.W.–S.E. -trending Karelian belt (Fig. 8) — are not of different age, but have been formed during one major crustal episode (*see* Fennoscandia).

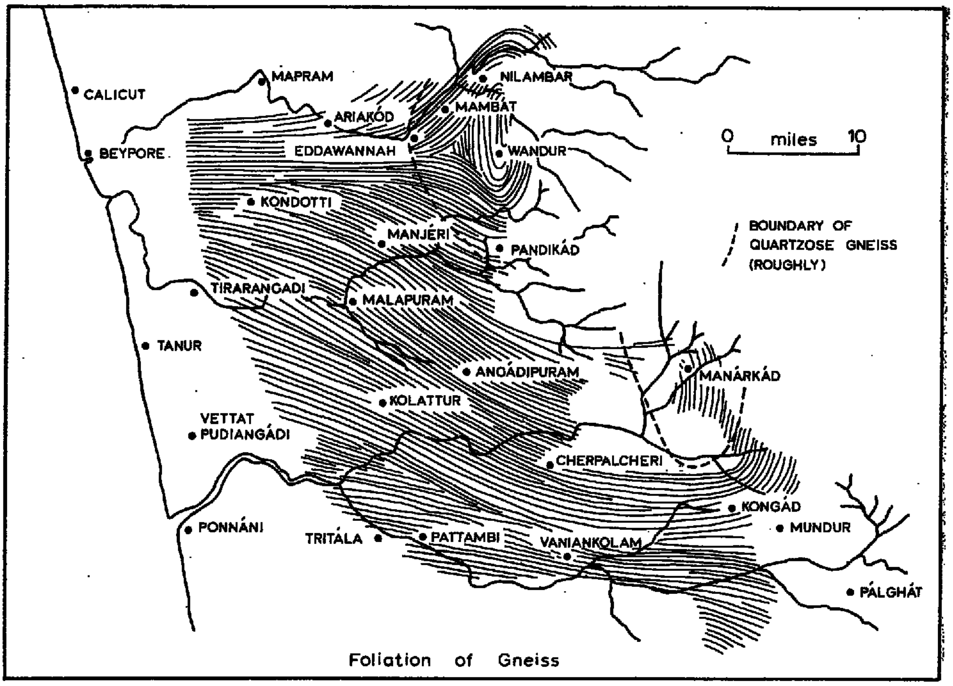

Fig. 2. Variations in trend of foliation of Precambrian gneiss, South Malabar, Peninsular India (*after* Lake 1890, Pl. 2)

The remaining part of the first half of the 20th century saw a great expansion in the understanding of Precambrian geology associated with the documentation of the nature and attitudes of structural features. There was progressive elaboration of the concept that each "of the old shields has an ingrained pattern of successive orogenic belts and each continent appears to be an integration of many such belts" (Holmes 1948, p. 254). Out of the mass of data collected came syntheses of structural trends in Precambrian terrain such as that of Krishnan (1953) for the Indian subcontinent (Fig. 12*a*). However it was Holmes in 1948, who established the study of orogenic belts on a firm quantitative footing by assigning radiometric ages to Precambrian orogenic belts with known trends (Fig. 3). This work relating to southern and central Africa set the pattern for the beginning of the second half of the 20th century with Precambrian structural trends being linked to absolute ages based on isotopic data. With increasing availability of isotopic data, and the greater reliability of this data, successive revised compilations have been possible for the African continent (*e.g.* Holmes 1965, Fig. 823; Clifford, 1970). For India, Pichamuthu (1967) has related absolute ages and the main trends of Archaean orogenic belts (Fig. 12*b*), while for Australia the progressive use of isotopic data related to structural trends is illustrated by Wilson & al. (1960) and Wilson (1969a). Corresponding work for other shield areas has also been carried out.

A recent development in the understanding of the significance of structural trend in Precambrian terrain is related to the increasing awareness of the extensive structural sequences shown by polyphase deformed rocks (Hopgood 1973) and of

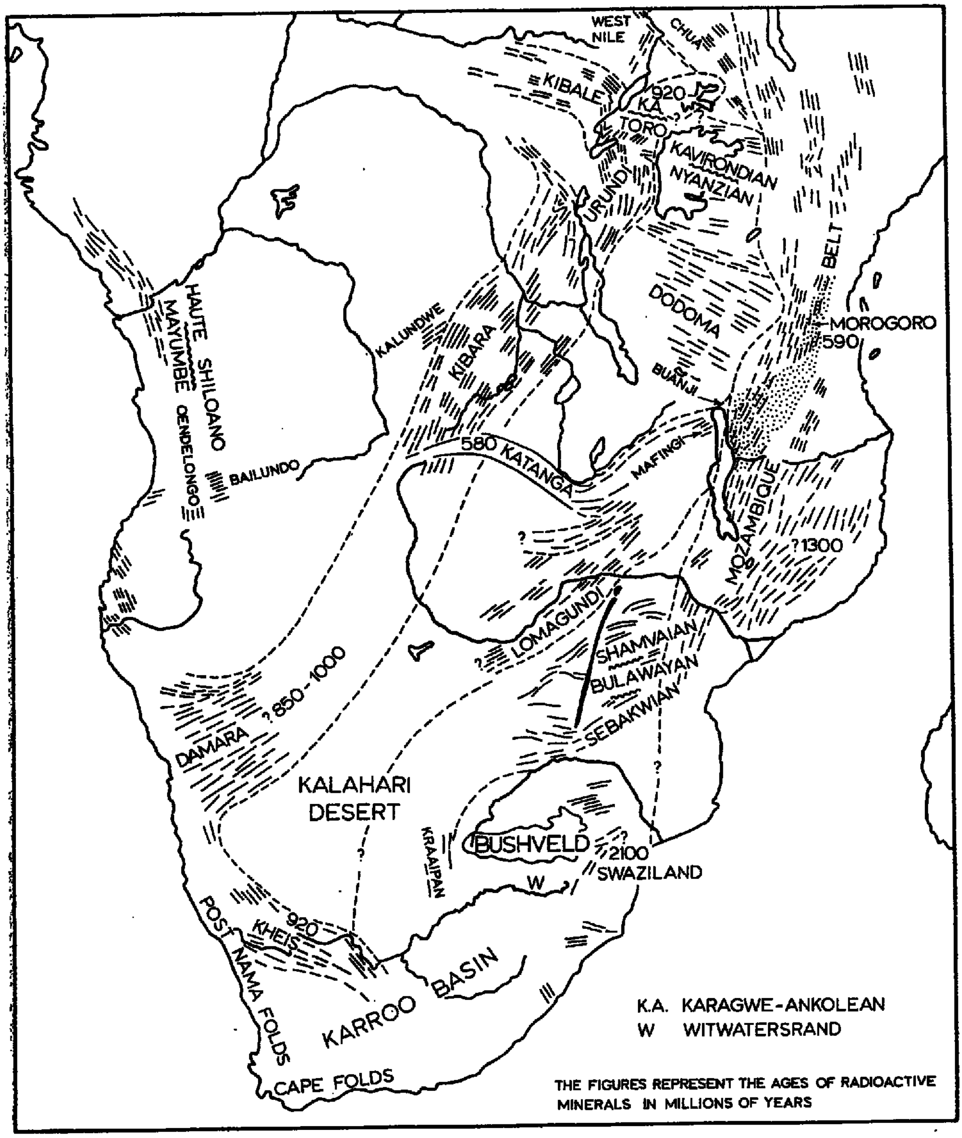

Fig. 3. Provisional map of Precambrian orogenic belts of South and Central Africa (*after* Holmes 1948, Fig. 1)

the variety of trends present within one belt (Hopgood & Bowes 1972a). While the resultant structural data is far more extensive and far more complex than previously envisaged (*cf.* Fig. 7), it provides a much more exacting framework for using structural trend as a basis for correlation than that provided by the previously used simple structural trend maps. In addition, dating by isotopic methods of metamorphic and/or igneous events associated with, or between, particular structural phases (Bowes, Hopgood & Taft 1971; Lyon & al. 1973) means that the two factors of trend and age can be used with far greater precision than previously.

The structural features defining structural trends vary. Trends of the "Svecofennian and Karelian folding" are referred to by Eskola (1963, Fig. 28). In the Precambrian rocks of Peninsular India, Krishnan (1953, Fig. 1) refers to "trend lines in the Archean rocks" and Pichamuthu (1967, Fig. 9) refers to the "main trends of the Archaean orogenic belts". In the granulite terrain of south-western Australia, Wilson (1969a, Fig. 1; 1969b, Fig. 1) refers to both "fold trends" and "planar trends" while Sutton & Watson (1951, p. 293) refer to the trend of "the dominant foliation" and the trend of a "complex" in Precambrian rocks of Scotland. Examination of these, and the very many other examples available, shows that the structural elements used to designate trend vary from example to example. These elements are rarely precisely defined, in many cases they are composite and, in the majority of instances, their relative time of formation in polyphase deformational sequences is not given, or even determined.

That the concept of structural trend and summaries of regional structural information (*e.g.* Dearnley 1966, p. 20, Fig. 8; Stockwell & al. 1970, Fig. IV-2) have been, and are, of value in the elucidation of Precambrian geological history cannot be doubted. However, with their increasing use as bases for correlation within continental masses, and from continent to continent in attempts to establish previous configurations of continents, critical review and assessment is necessary. In this way the possibility of serious mismatching based on erroneous correlation of trends whose nature has not been specified, and corresponding positions in structural sequences not demonstrated, can be avoided, or at least minimised.

The following discussion of the significance of structural trend is confined to some of the Precambrian terrain in which the authors have carried out structural studies, *viz.* Scotland, Fennoscandia, East Africa, eastern Peninsular India and south-western Australia.

NORTH-WESTERN SCOTLAND

SCOURIAN OROGEN

Reference is made to the "formation of the north-easterly trending Scourian complex" in the Lewisian of the North-West Highlands of Scotland by Sutton & Watson (1951, p. 293; *cf.* Peach & Horne 1930, p. 26). The postulation of a regional trend is based on attitudes of structures shown by quartzofeldspathic and hornblendic gneisses north of Loch Torridon and by banded pyroxene granulites south of Scourie, more than 100 km to the north (Fig. 7*a*).

In part of the Torridon district the dominant strike of both the foliation of the gneisses and the lithological units is N.E., with local variations to E. and S. E. trends (Sutton & Watson 1951, p. 244). However, neither the geometry of the folds or fold sets responsible for these attitudes, nor the relationship of the N.E. -trending foliation to fold hinges or limbs, is given for rocks which show evidence of polyphase deformation. The quartzofeldspathic gneisses of the nearby island of Rona (Fig. 7*a*) show the development of seven successive fold phases (Hopgood 1971b; Lyon & al. 1973) and the isotopic data indicates that while the dominant foliation of the gneisses was developed during the Scourian orogenic episode (*c* 2700 m.y. ago), its present attitude is, at least in large part, determined by tectonic overprinting during the latter phases of the much younger Laxfordian orogenic episode, *c* 1740—1700 m.y. ago. Elsewhere in the Lewisian a north-easterly trend of foliation in quartzofeldspathic and hornblendic gneisses demonstrably represents the middle limb of a steeply plunging large asymmetrical fold, with N.W. -trending long limbs and a N. N. E. -trending subvertical axial plane (Bhattacharjee 1963, Pl. 1).

In the district south of Scourie the strike of the banding shown by pyroxene granulites swings from N. E. through N.—S. to S. E. (Sutton & Watson 1951, p. 267). This change of trend (Fig. 4) is consistent with the existence of parasitic folds on the south-western limb of an open, upright, N. W. -plunging antiform, the Kylesku fold (Khoury 1968). The presence of broad gentle arches and troughs, irregular and isoclinal contortions of banding and of an irregular attitude of fold axes were also recorded by Sutton & Watson (1951, p. 267—268). Subsequent investigations (Barooah 1967; Bowes & al. 1971) have shown that the rocks of the district have been affected by five phases of deformation during the Scourian orogenic episode. The granulite facies metamorphism, dated at 2700 ± 20 m.y. (Pidgeon & Bowes 1972, Fig. 2) is associated with the second phase of deformation. The prominent N. E. trend of the banding in the granulites, used as evidence that "the structural pattern" is "marked everywhere by a dominant north-easterly trend" (Sutton & Watson 1951, p. 293) represents the trend of one limb of a large fourth phase fold in the region south of Scourie (Fig. 4). The other limb trends N. W. to W. N. W., the latter direction being considered by Dearnley (1966, p. 10) to be the regional trend of the Scourian orogen. Elsewhere in the same structural block, the form lines of banding or foliation are so variable that establishing a structural trend on more than a local scale does not appear possible (Sheraton & al. 1973, Fig. 1).

In the absence of information to indicate which set or sets of folds form extensive and prominent structural features on a regional scale, neither the present attitude of the banding nor the trend of the axes and axial planes for any one set of folds provides a satisfactory basis for postulating the regional structural trend of the Scourian orogen. Accordingly use of a single structural trend for this orogen as evidence for correlation with rocks of corresponding age in other shield areas is not legitimate even after necessary corrections in orientation. Even the use of the pattern of "trend-lines of gneissic foliation" (Dearnley 1962, Pl. 9) in this belt in the North-West Highlands has led to erroneous correlation with polyphase deformed Lewisian gneisses in the Outer Hebrides (Fig. 7*a*; *cf.* Hopgood & Bowes 1972a, b). However correspondence in orienta-

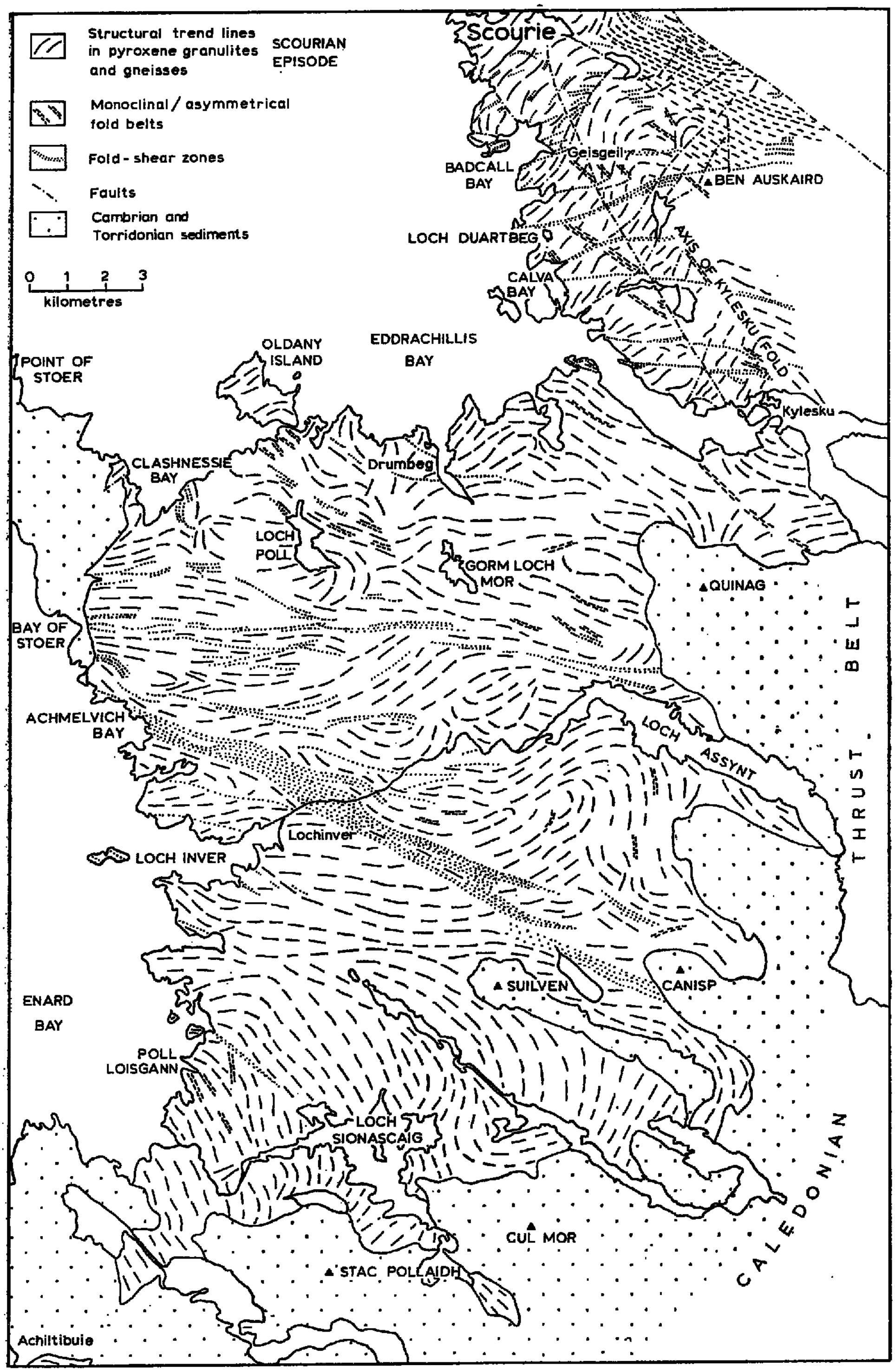

Fig. 4. Structural trends in pyroxene granulites and gneisses in the Precambrian Scourian orogen in the district south of Scourie, Northwest Highlands of Scotland (*after* Bowes 1969, Fig. 2 and Sheraton & al. 1973, Fig. 1)

tions of successively formed structural elements in extensive polyphase deformational sequences provides a basis for correlation of the Scourian orogen with the Presvecokarelian orogen of Finland (Bowes 1975).

LAXFORDIAN OROGEN

The "north-westerly strike of the Laxfordian complex" (Sutton & Watson 1951, p. 293) is dependent upon the existence of "structures with a north-west to south-east trend" (p. 276), structures which include both foliation and folds (*cf.* Fig. 6). The dominant N. W.–S. E. trend of gneissose foliation in the type locality around Loch Laxford results from the deformation of the foliation and the generally parallel lithological layering by a large, tight fold (Chowdhary & Bowes 1972, Pl. 1; Gillen 1975, Fig. 2) with a N. W.–S. E. -trending axial plane that dips c 50° S. W. and an axis that pluges c 20° S. E. (Fig. 5*a*). Hinge zones of parasitic folds have a new axial planar mineral growth. The large fold is one of a series of such folds (Fig. 6*a;* Bowes 1969, Fig. 6), with sub-parallel axial planes, formed during the Dionard phase of deformation (Dash 1969), c 1750 m.y. ago (Lyon & al. 1975). The dominant foliation in the quartzofeldspathic gneisses (Fig. 6b) was formed c 1000 m.y. earlier than these folds (Lyon & Bowes, *in press*). Hence the structural trend of the Laxfordian orogen, in its type area, is partly expressed by the attitude of foliation and lithology in basement, not cover, rocks, resulting from tectonic overprinting. The existence of any structural trend in cover rocks of the orogen must be demonstrated elsewhere (Bikerman & al. 1975; Keppie 1969).

Abundance of granitic and pegmatitic veins, which in places generally parallel the axial planes or limbs of Dionard phase folds (Figs 5*b*, 6*a*), enhances the general N. W.–S. E. trend of lithological units in the type locality. Also imparting a N.W. trend are open folds which plunge S. E. at angles dependent upon the pre-existing attitude of the dominant foliation and have axial planes, with some new axial planar mineral growth, which strike N. W. and dip either N. E. or S. W. (Gillen 1975). Even later-formed crush-zone of extensively fractured rock with pseudotachylite (Fig. 5*a*) trend N. W.–S. E. (Chowdhary & Bowes 1972). Hence the "structural trend" of the Laxfordian orogen, in its type locality, results from general parallelism of a whole series of structural elements and of lithological units resulting from tectonic overprinting of basement rocks. This parallelism is reinforced by an abundance of sheet-like structurally controlled granitic and pegmatitic intrusions (Figs 5–6).

The N. W.–S. E. trend of lithological units and of axial planes of large folds is shown in other parts of the Lewisian of the North-West Highlands of Scotland (*e.g.* Bhattacharjee 1968, Fig. 1; Bowes 1969, Figs 4–5). Support for interpreting this trend in regions considerable distances from the type area (*cf.* Hopgood & Bowes 1972a) as resulting from deformation during the Laxfordian orogenic episode is given by isotopic data

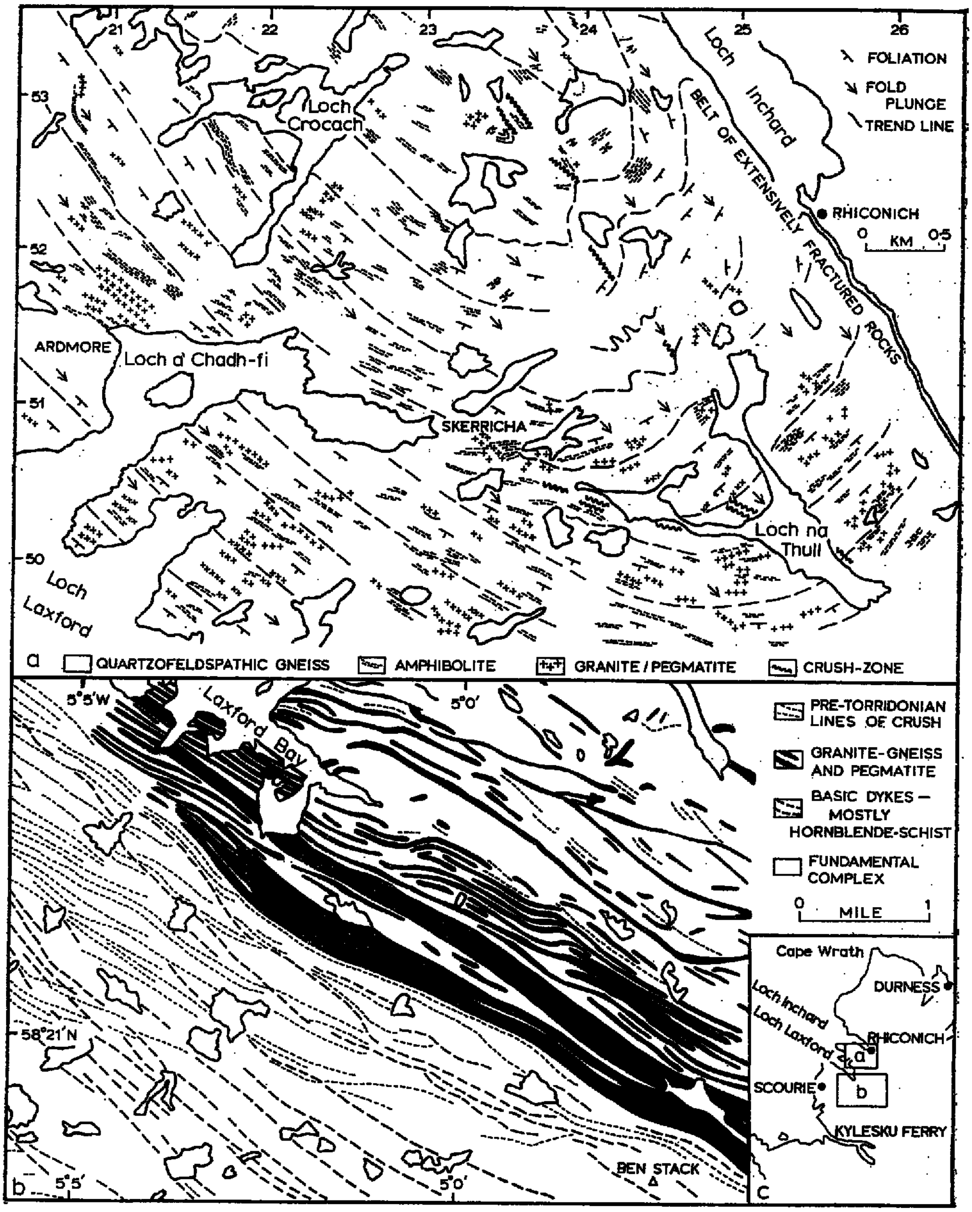

Fig. 5. Lithological and fabric elements making up the N.W.–S. E. trend of the Precambrian Laxfordian orogen in the Loch Laxford district, Northwest Highlands of Scotland

(a) Geological map of the Loch Inchard — Loch Laxford area (*after* Chowdhary & Bowes 1972, Pl. 1)

(b) Map of the Lewisian in the Laxford district, north of Loch Glencoul (*after* Peach & Horne 1930, Fig. 2)

(c) Outline locality map of part of northwestern Scotland

(Lyon & al. 1973; Lyon & Bowes, *in press*). Marked deviations from the dominant N. W.—S. E. trend are related to deformation during a late phase of this episode (Bhattacharjee 1963, Pl. 1) while marked accentuation of the dominant trend occurs where there are long, narow zones of strongly

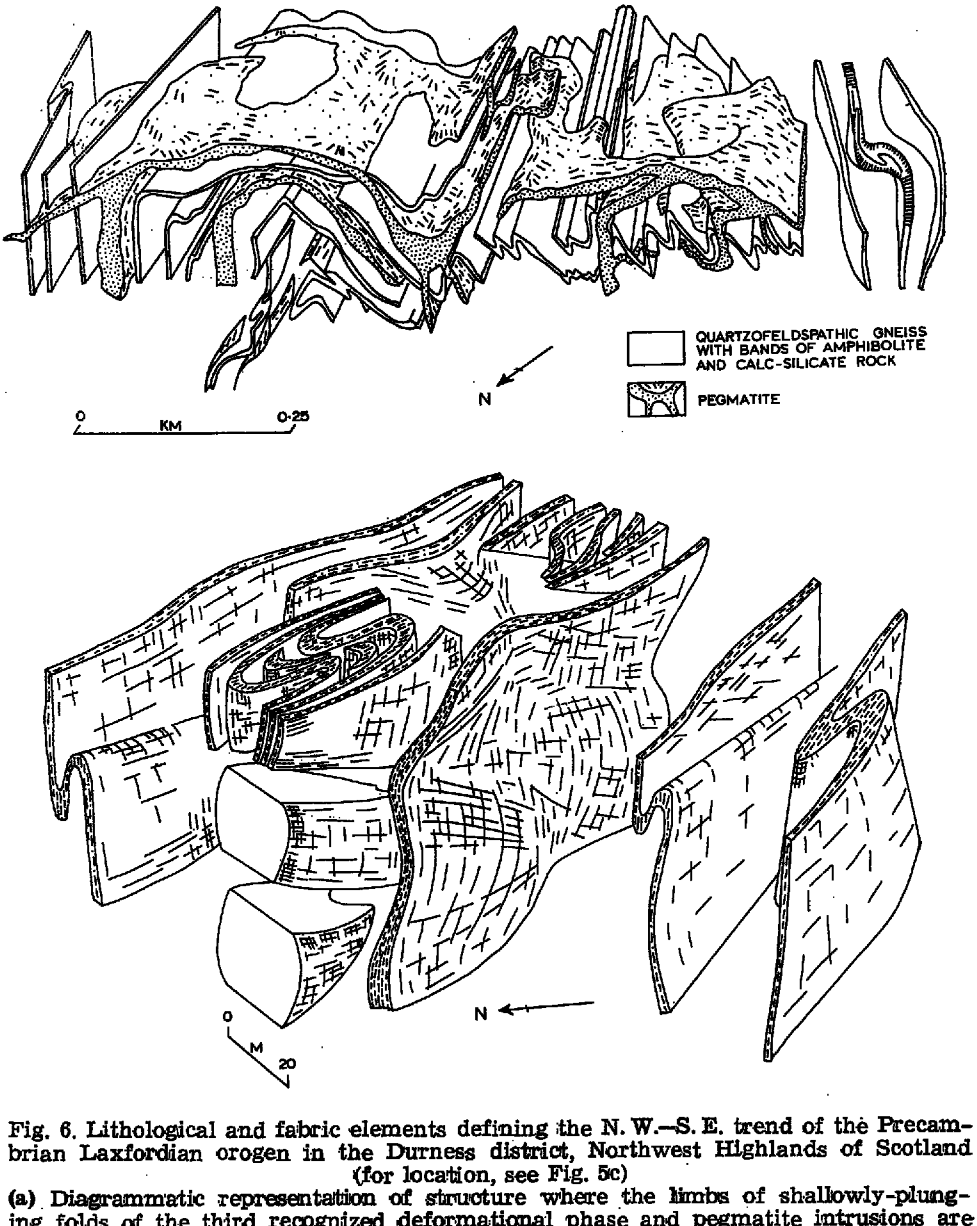

Fig. 6. Lithological and fabric elements defining the N. W.—S. E. trend of the Precambrian Laxfordian orogen in the Durness district, Northwest Highlands of Scotland (for location, see Fig. 5c)

(a) Diagrammatic representation of structure where the limbs of shallowly-plunging folds of the third recognized deformational phase and pegmatite intrusions are the dominant features expressing the trend (*after* Findlay 1970, Fig. 5—1)

(b) Diagrammatic representation of structure where folds of more than one phase together with long axes of boudins and the strike of foliation reinforce the strike of lithology in the expression of a strong trend (*after* Findlay, 1970, Fig. 4—8) foliated rocks which form tight synformal zones between large antiforms of the third deformational phase (Bhattacharjee 1968, Fig. 12).

The occurrence of broad, open antiforms and complementary tight synforms with N. W. axial traces and steeply-inclined or upright axial planes has been described for the Lewisian of the Outer Hebrides (Coward & al. 1970, Fig. 1) and the folds considered to be equivalent to the Dionard (third) phase folds of the mainland north of Loch Laxford (*cf.* Fig. 5*a*). However, over large areas of the Outer Hebrides the third phase folds have near-horizontal to shallowly-dipping axial planes (F_3, S_3 — Fig. 7*d*, *e*) and a considerable spread of axial plunge directions (Hopgood & Bowes 1972b; Bowes & Hopgood 1975). In this region the broad, open upright folds with N. W. -trending axial traces (F_4 — Fig. 7*e*) were formed during the fourth recognized deformational phase (Hopgood 1971a, p. 42; Hopgood & Bowes 1972b); *i.e.* in successive deformational phases folds were formed that were of generally similar style, co-axial but not co-axial planar. In parts the large folds are of one set, in other parts the large folds, of similar style, are of the other set. Correlation of such folds of comparable dimensions and axial trends, but which are in different positions in the structural sequence (Taft 1971), has resulted in mis-matching and the postulation of a very large wrench fault (Dearnley 1962, Pl. 9) subsequently discounted on the basis of geophysical studies (Smythe & al. 1972).

Not only have corresponding structural trends in different parts of the Laxfordian orogen resulted from more than one phase of deformation, but other phases in the polyphase sequence produced different structural trends which are prominent over considerable areas (Fig. 7*a*). The most obvious structural feature in one part of the Outer Hebrides is not N. W. -trending but approximately E.—W. -trending (*cf.* Fig. 7*f*) and the result of deformation during the fifth fold phase (Hopgood 1971a, p. 45 and Fig. 1). In another part of the Outer Hebrides deformation during the sixth fold phase resulted in the formation of a large, open, upright shallowly N. N. E. -plunging fold (Fig. 7*h*) with the trend of foliation, on the fold limbs, being both N.—S. and E.—W. (Bowes & Hopgood 1969, Fig. 2; Hopgood 1971b, Table II).

The Laxfordian orogen illustrates the complexity that can exist in relation to the number of structural elements expressing trends and in the variation in intensity of expression of these elements. While much of the orogen is characterized by a N. W. trend due to the expression of a number of structural elements, some formed coevally and others not, correlation throughout the belt solely on the basis of this trend is unreliable. Only as the various structural elements are related to one another in a sequence of polyphase deformation can different trends arising from variations in strength of expression of any one element be recognized (Hopgood & Bowes 1972b). This data (Fig. 7), together with information concerning metamorphic and igneous histories in relation to the structural sequence and with confirmatory geochronological evidence (Hopgood & Bowes 1972a; Lyon & al. 1973) does provide a rigorous method for correlation in gneissose terrain, such as that represented by the Laxfordian orogen. Then as a result of correlation using many separate and interrelated parameters, rather than just a single parameter, the regional extent of a particular structural trend can be deduced and a strong basis established for correlation with other regions (*cf.* Bowes 1975).

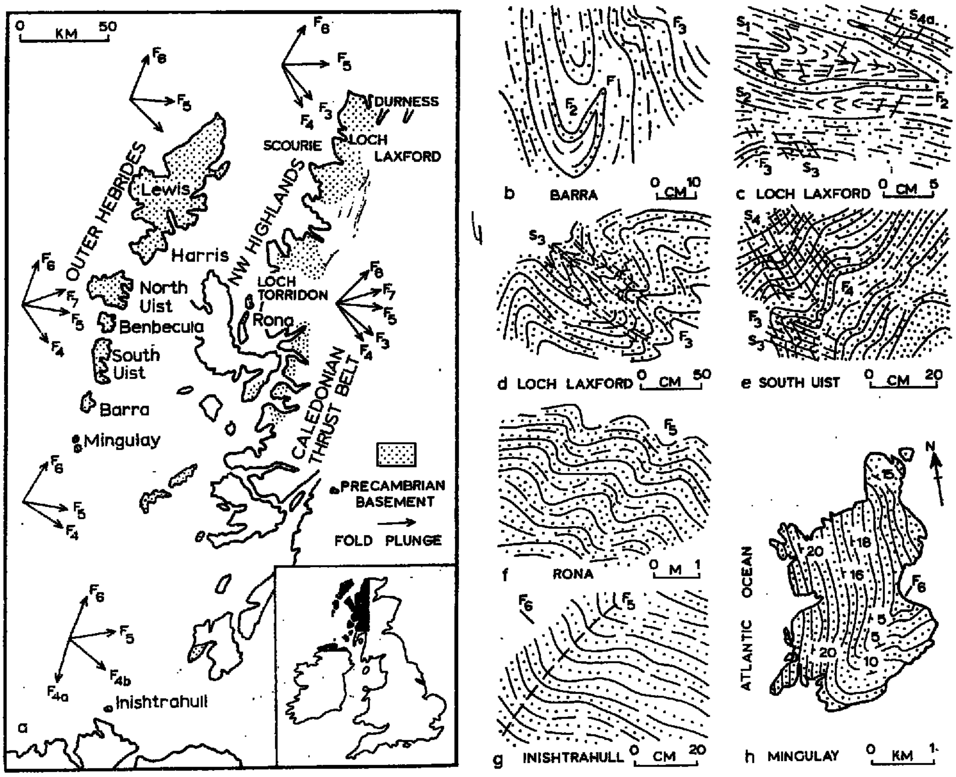

Fig. 7. Structural sequence in Precambrian gneisses of northwestern British Isles
(a) Orientations of fold axes formed during successive deformational phases showing marked correspondence over considerable distances (*after* Hopgood & Bowes 1972a, Fig. 1)
(b-h) Nature of structures formed during the successive deformational phases (*b-g* after Hopgood & Bowes 1972a, Figs. 2–3 and 5–7; *h* after Bowes & Hopgood 1969, Fig. 2)

FENNOSCANDIA

The main structural trend of the Karelian zone of eastern, central and northern Finland is N. W. to N. N. W. (Fig. 8; *cf.* Eskola 1963, Fig. 1). However in parts of Karelia it is N. E. (Fig. 9*a*) with regions where an "axial trend" almost perpendicular to the main Karelian trend swings into this trend. Further north and west an approximately E.—W. trend over considerable regions was considered by Väyrynen (1954) to be representative of an orogenic episode younger than the Karelian episode.

An E.—W. to E. N. E. "general strike of the folding axes" characterizes much of the Svecofennian zone south of the central granite of Finland (Eskola 1963, p. 189) as well as large parts of Sweden (Fig. 8). The suggestion that the intrusive rocks related to the generally E.—W. -trending zone were related to a different and older orogenic episode than the intrusive rocks of the generally N. N. W. -trending Karelian zone was made by Eskola (1961). This hypothesis involved the "folded Svecofennian formations" being "partly refolded and reoriented in the Karelidic N. N. W.—S. S. E. direction" (Eskola 1963, p. 234). However, the isotopic data indicates general equivalence in age of the Karelian and Svecofennian intrusions (Polkanov & Gerling 1960; Kouvo & Tilton 1966; Simonen 1971). Thus the N. N. W. trend of the Karelian zone and the E.—W. trend of the Svecofennian zone must be considered as different expressions of the deformation of one orogenic belt.

Both the Karelian and Svecofennian zones show evidence of poly-

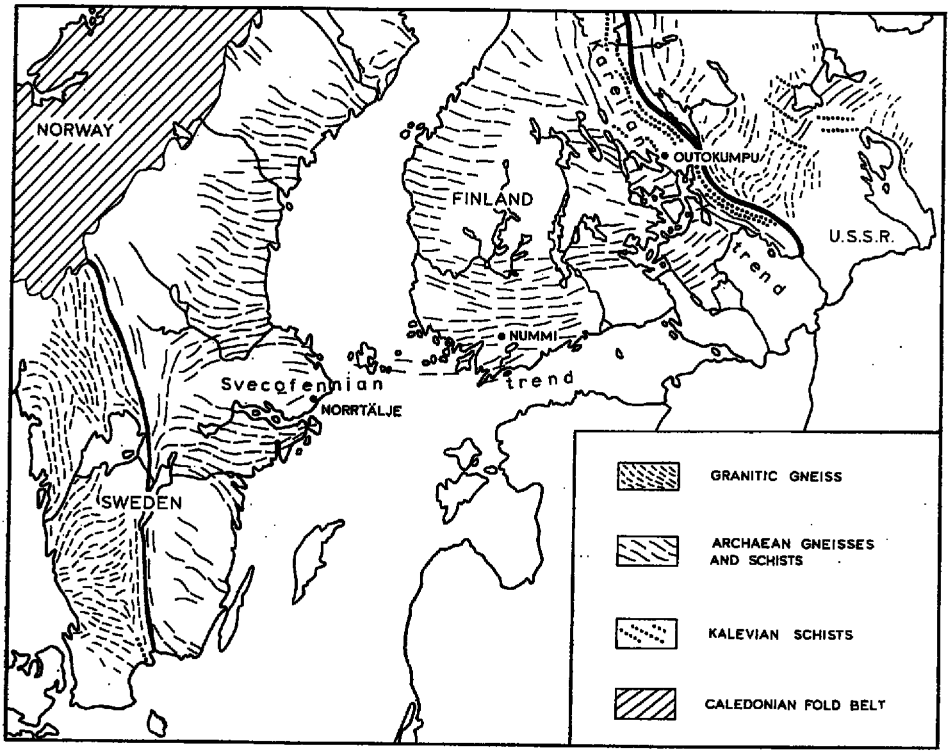

Fig. 8. Structural trends in the Precambrian Svecofennian — Karelian belt of Fennoscandia (*after* Ramsay 1909)

phase deformation (Figs 9*b*, 10) and in both there are folds with axial planes that trend N. N. W. to N. W. paralleled by mineral growth, and folds that trend E.—W. Seven phases of deformation have been identified in Karelia (Fig. 9*b*) and there are at least six phases in southern Finland and eastern Sweden (Fig. 10). In Karelia large asymmetrical folds are the major structures over considerable areas. They were formed after the development of the gneissose foliation and schistosity which took place in the early deformational phases (Gillen & Macdonald 1971; Bowes 1975; Gaál & al. 1975). The general N. N. W. strike of both the metamorphic planar fabric elements and lithology on the long limbs of these asymmetrical folds is reflected by a strong N. N. W. trend on the magnetic anomaly maps of the region (*cf.* Gaál & Rauhamäki 1971, Map 1). This trend is reinforced by the existence of long narrow zones in which there has been intense development of new axial planar foliation. Hence the dominant Karelian trend

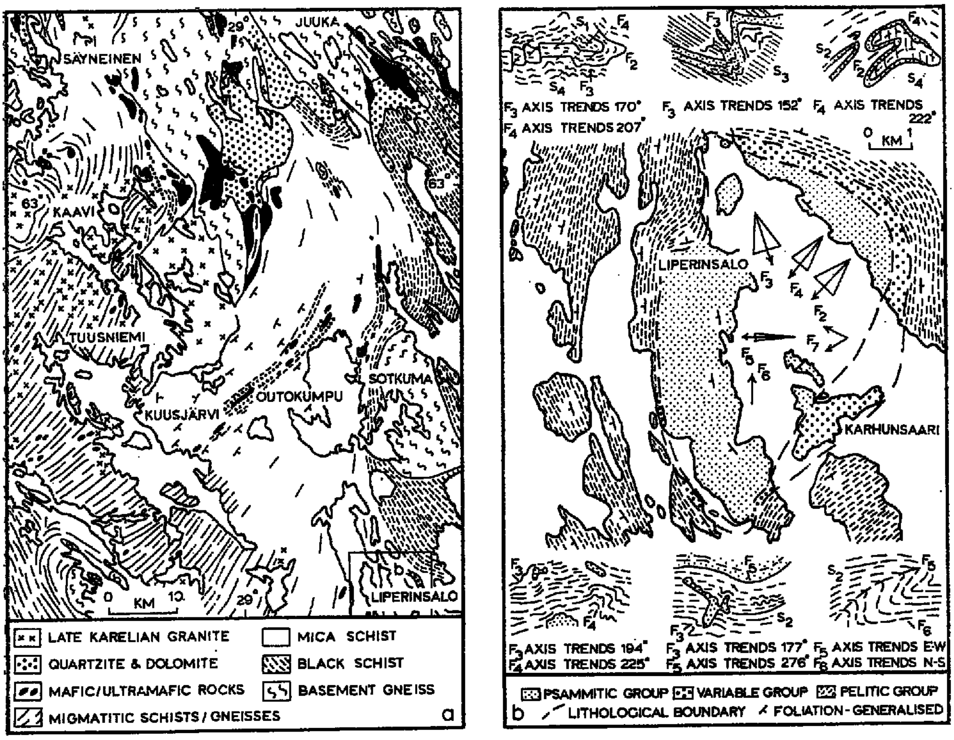

Fig. 9. Structural trends and structural elements in the Precambrian Karelian belt, eastern Finland
(a) Outline geological map of the Outokumpu region (*after* Väyrynen 1939)
(b) Map of the fold interference Karhunsaari dome showing the dominant fold plunge, with variations, of the successively formed structures and examples of small-scale structures illustrative of the polyphase deformational history of this part of the Karelian belt (*after* Gillen & MacDonald 1971, Figs 4—5)

results from the parallel expression of a number of structural features. Other trends occur, some regionally and others locally, *e.g.* the strong N. E. trend in the vicinity of Outokumpu (Fig. 9*a*) is the expression of large refolded first deformational phase folds (Gaál & al. 1975), while the fold interference dome and variable trends in the Liperinsalo district (Fig. 9*b*) expresses the existence of different fold sets making up a polyphase deformational sequence. Locally one fold set is sufficiently strongly expressed to control the structural trend so that E.—W., N. E.—S. W. and N.—S. trends occur as well as the dominant N. N. W.—S. S. E. trend.

The region between that with a strong N. N. W. Karelian trend and that with a strong E.—W. Svecofennian trend (Fig. 8) shows many fold interference structures. Some of these interference structures are generally symmetrical or elongate domes and basins, but where more than two fold sets have interfered, the interference structures have complex shapes. Even in those parts of the Svecofennian zone where E.—W. disposition of foliation predominates there are other trends shown by both the disposition of foliation (Härme 1965, Appendix 1; Kouvo & Tilton 1966, Fig. 3) and by attitudes of fold axial planes and axes. The observed polyphase deformational sequence shows general correspondence with that recognized in the Karelian zone (Fig. 10), with E.—W. -trending upright folds formed late in the sequence. Where complex structural patterns are shown in the Svecofennian zone (Fig. 11), these reflect the superimposition of successively formed fold structures with the intensity of expression of the deformational phases varying from place to place. However, regionally

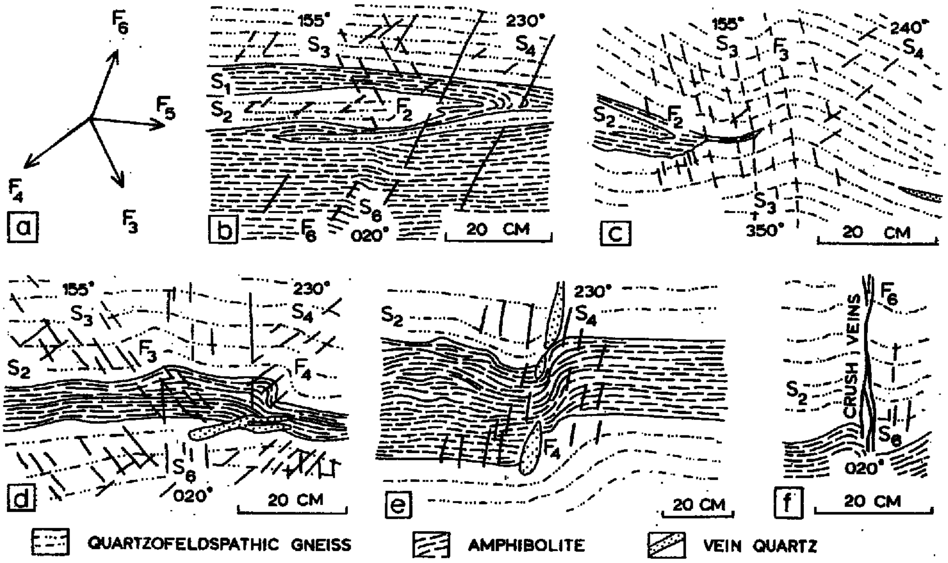

Fig. 10. Trends of folds and nature of small-scale structures illustrative of the polyphase deformation history of the Precambrian Svecofennian belt, Norrtälje district, eastern Sweden

an overall E.—W. to E. N. E. trend of the major axes of fold interference structures is evident (*cf*. Eskola 1963, Fig. 11).

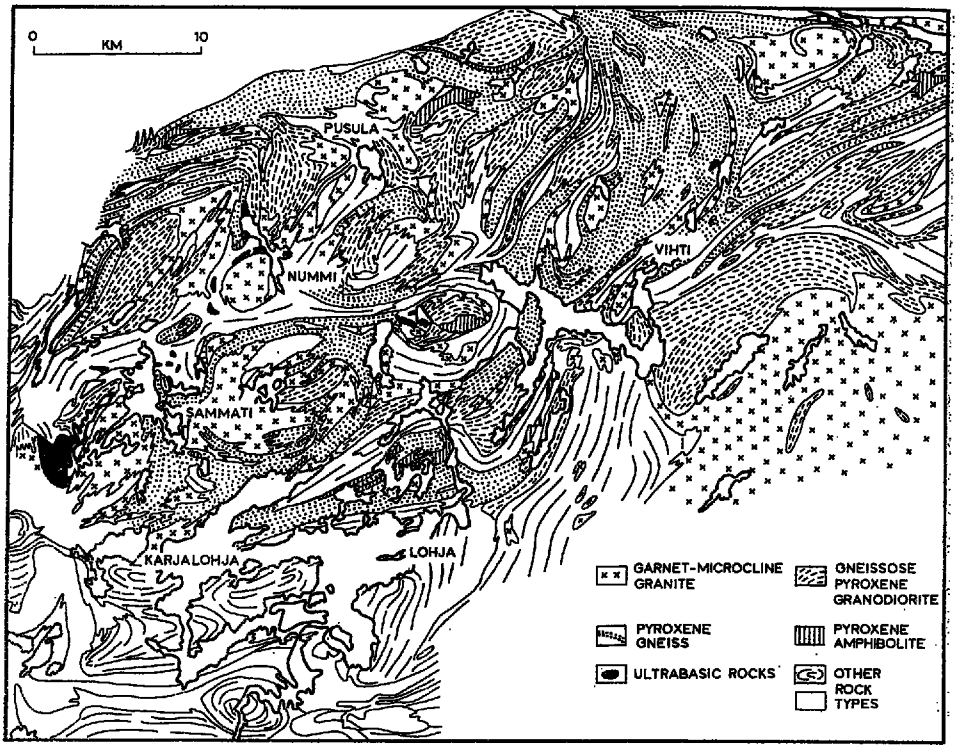

Fig. 11. Map of the Nummi district and adjacent areas, southwestern Finland showing the major structural trends in part of the Precambrian Svecofennian belt (*after* Parras 1958)

Hence while the consideration of structural trends out of a context of polyphase deformation led to the postulation of three separate episodes, *viz*. Svecofennian, Karelian and "Lappidic" (Väyrynen 1954) each expressed by individual trends, integration of information relating to trends and polyphase deformation permits determination of both structural pattern and tectonic evolution of the belt as a whole. In this way isotopic and structural data can be reconciled and the intensity of expression of different structural trends representing different deformational phases of the one orogenic episode can be determined in various parts of the belt.

SOUTH-WESTERN UGANDA, EAST AFRICA

Precambrian basement rocks of the Ankole District bordering the Western Rift Valley in south-western Uganda belong predominantly to the Karagwe-Ankolean System (Fig. 3). The presence in these rocks of two predominant axial planar directions, trending N. W. and N. E., was pointed out by Macdonald (1966) while subsequent detailed structural investigations disclosed an extensive sequence of polyphase deformation, of Kibaran age, with four sets of folds having strongly expressed axial planar trends, *viz.* F_2: E.–W., F_3: N.–S., F_4: 120°, F_5: 160° (Hopgood 1970). Of these, either the E. S. E. -trending axial planes of the fourth phase of folds or the S. S. E.-trending axial planes of the fifth phase of folds could be related to the N. W.–S. E. direction of Macdonald (1966) although in the region where detailed work has been carried out, the E. S. E. (F_4) trend is the more strongly expressed of the two sets. Here the N. E. trend of the Karagwe-Ankolean System does not appear to be significantly developed, possibly as a result of the suppression of the N. E. -trending fold set by the local intense development of the E. S. E. -trending and S. S. E. -trending sets.

Basement trends in this particular setting are subject to a certain amount of reorientation due to basement warping preceding and accompanying the dominant regional lineament of this part of south-western Uganda, the N. N. E. -trending Western Rift Valley. The extent of this reorientation varies dependent upon both the nature and the initial orientation of the structure responsible for the basement trend. Where the resultant variations in orientation of a clearly identified single structural element in the basement rocks can be determined with certainty, this can be used as a means of determining the axis of basement warping (Hopgood 1970).

EASTERN ANDHRA PRADESH, INDIA

The "trend lines" in the Archaean rocks of India shown by Krishnan (1953, Fig. 1) include the "Eastern Ghats strike" (p. 6) which is mainly N. E. with a bifurcation in eastern Andhra Pradesh to the N. W. "Mahanadi Strike" (p. 8). These and other strikes described (Fig. 12*a*) represent the elongation of orogenic belts, the distribution of lithological units and the attitudes of some structures in these belts. They correspond to large scale crustal features and may also designate the areal distribution of igneous masses confined to the particular orogenic belt. The structural elements which contribute to these composite trend lines include limbs, axes and axial planes of folds, planar and linear metamorphic mineral growths, shear zones and faults. Isotopic dating has established absolute ages for the various component features (Fig. 12*b*) and has thus imbued them with considerably more significance.

In the region of the N. W. Mahanadi structural trend, near the intersection with the N. E. Eastern Ghats trend (lat. 17°42′ N. long 80°37′ E.) the rocks, which are *c* 1500 m.y. old (Fig. 12*b*), are complexly folded and deformed by a polyphase sequence (Hopgood 1968). Because of the complexity of the structural evolution, the strike of the dominant foliation formed early in the deformational history, varies considerably with major swings from S. to S. E. The strongest influence on the attitude of the foliation is exercised by a series of open folds, of the fifth fold phase, which have axial planes striking approximately E.—W. Many of these folds have wavelengths of the order of a km. Their axial surfaces are paralleled by a strong fracture cleavage and this, together with a related intersection lineation imparts an E.—W. structural trend to the rocks.

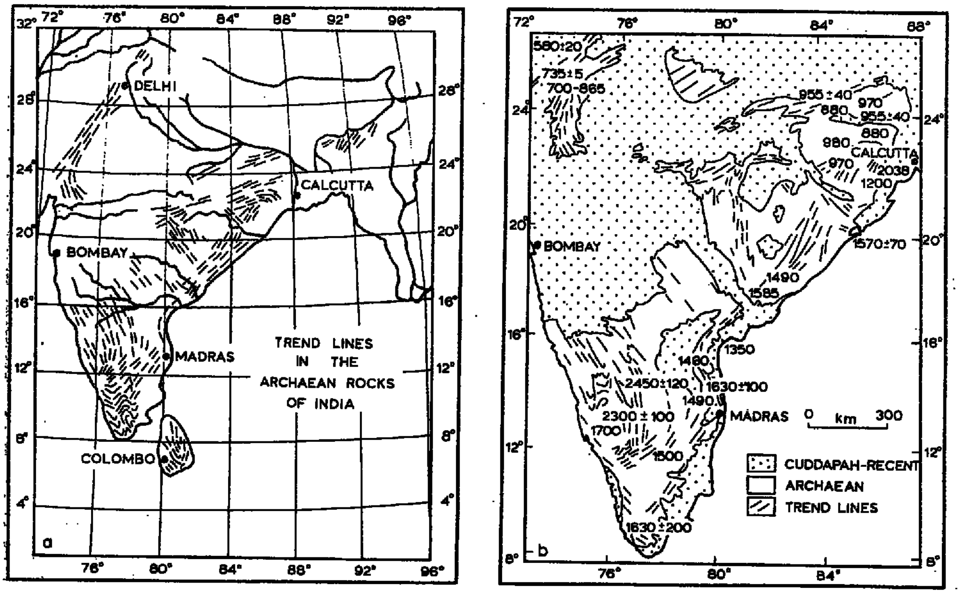

Fig. 12. Trend lines and ages of Precambrian rocks of India
(a) Trend lines of Archaean rocks of India (*after* Krishnan 1953, Fig. 1)
(b) Structural map of Peninsular India showing the main trends of the Archaean orogenic belts; the figures indicate radiometric ages in millions of years (*after* Pichamuthu 1967, Fig. 9)

The S. E.— and N. N. E. to N. E. -trending, strongly developed linear structures also inpart strong trends on a regional scale. The S. E. -trending structures parallel axial planar foliation associated with tight to chevron folds of the second fold phase. The later-formed N. N. E. to N. E. -trending structures are discrete zones in which the rocks are intensely sheared. Both sets of structures were formed sometime between the development of folds of the second and third phases and both are exposed as prominent elongate ridges of hard rocks cutting across other structures. The earlier of the two groups (expressed by S. E. -trending fold axial planes) parallels the Mahanadi strike and the other (expressed by N. E. -trending zones of sheared rocks) parallels the Eastern Ghats structure.

The average S. to S. E. trend of the foliation and the S. E. -trending shear structures together probably constitute the N. W.—S. E. "Mahanadi Strike" while the N. E. -trending zones of intense shearing may well represent the local effects of the N. E. "Eastern Ghats strike". Thus it can be shown that although in one part of a belt the "strike" may be expressed by shear zones, in other parts it may be expressed by the attitude of foliation and in yet other parts by axial planar structural features. However, the extent to which each of these structural features contributes to, or predominates within the overall "strike", can be resolved by detailed mapping and structural studies to relate the small scale to the large scale structures. This aspect has been very adequately treated by Naha (1964) in his discussion of "orogenic trends" in the Archaean rocks of India.

SOUTH-WESTERN WESTERN AUSTRALIA

"Fold trends" in granulite terrain in Australia have been given by Wilson (1969a, Fig. 1). In the *c* 2700 m.y. old "Wheat Belt" of south-western Australia, the trend is generally N. W. (Wilson 1969a, Fig. 2; *cf.* Wilson 1958) and is based, at least in part, on the attitudes of "keels of synclinoria or other relics of folds now enclosed in granitic material" (p. 243). In the younger (c 1300 m.y.) granulites further east in the Fraser Range, a N. E. to N. N. E. "fold trend" is based on the trend of a major fault zone in which there is extensive development of mylonite, the trend of strongly-developed transcurrent structures, the distribution of major lithological units, and on folds with "almost horizontal axes which trend N. E. or N. N. E." (p. 247, Fig. 3; Wilson 1969b, p. 48). In the even younger (c 650 m.y.) granulites exposed on the coast west of the "Wheat Belt", a northerly trend is shown with the rocks in many places exhibiting "rigid banding ... of the type common near ... deepseated fault zones" (Wilson 1969a, p. 249).

The "structural trends" in the Precambrian rocks of south-western Western Australia are thus expressions of disparate structural elements, or combinations of structural elements. Representation of these various features either as "fold trends" (Wilson 1969a, Fig. 1), or as "planar trends" (Wilson 1969b, Fig. 1) may be misleading and could be used as a basis for sweeping and possibly erroneous comparisons. Now with the determination of extensive sequences of polyphase deformation in both the *c* 2700 m.y. old granulites of the "Wheat Belt" and the *c* 650 m.y. old rocks exposed on the coast (Hopgood 1973), a necessary prerequisite to any use of structural trend for correlation is demonstration of its relationship to the overall structural sequence. In both regions a N. W. to N. N. W. trend is prominent where the axial planes of upright, open folds, formed late in the structural sequence, correspond in strike with the axial planes and limbs of earlier-

-formed close, tight or isoclinal folds. However, as in the other areas considered in this discussion, other fold sets, with different attitudes of axes, axial planes and limbs, may be locally prominent and influence both igneous emplacement and the development of faults.

DISCUSSION AND CONCLUSIONS

Structural trend has been used in the literature of the Precambrian not only to refer to the orientation of orogenic belts, but also to the distribution of lithological units as well as to a variety of tectonic structures. Because of this the term has had different meanings for different authors. Nevertheless, the concept of trend is a useful one provided its usage is clearly defined. Its unqualified use in regions of rocks which have been subjected to polyphase deformation can be misleading and result in erroneous division of cognate units or erroneous correlation. This is particularly the case where the nature and origin of a particular trend is unspecified or not fully understood and where its relationship to the overall deformational sequence has not been established. However, where the significance of each structural element is determined and a complex pattern of trend variation resulting from successively formed deformational phases is determined, the pattern provides a refined basis for correlation. This stems from the demonstration that structural sequences and trends in polyphase deformed metamorphic terrain are characteristic of the individual terrains and indicative of the distinctive tectonic histories of the orogens in which the rocks developed (Hopgood & Bowes 1972b; Hopgood 1973).

Where the structural evidence is associated with geochronological evidence permitting absolute correlation to be made between particular events in a sequence, then adjacent segments of metamorphic rocks from various parts of one mobile belt can be correlated with one another with considerable certainty. Such correlations can be extended, step by step, over large distances as illustrated by the Karelian—Svecofennian belt. Here the geochronological evidence indicates correspondence in the age of Precambrian rocks showing marked variations in attitude of trend of the most strongly expressed structures (Fig. 8). The structural evidence shows that these variations in structural trend represent differences in the intensity of development and expression of the variously trending structural elements in similar polyphase deformational structural sequences in the rocks of eastern Finland (Fig. 9*b*), south-western Finland and eastern Sweden (Fig. 10). Whether the variable structural trends in the Precambrian granitic gneisses of south-western Sweden (Fig. 8) can be correlated, by these means, with those of the Karelian — Svecofennian belt, or distinguished from this belt, must await detailed investigations. However, the polyphase deformational sequence and the trends of the variously distinguished structural elements in the *c* 1970—1700 m.y. Laxfordian orogen of north-western Britain (Fig. 7) correspond with those found in various parts of the Karelian — Svecofennian belt which is of the same age. This suggests a Karelian — Svecofennian — Laxfordian correlation not only in time, but also in place (Bowes 1975). Such an implied westward continuation of the Fennoscandian shield to north-western Britain has important implications not only in reconstructions of Precambrian history, but also in the crustal environment of the Caledonian mobile belt which now separates the Precambrian rocks of Fennoscandia from the Precambrian rocks of north-western Britain.

Correlation of Precambrian terrains using structural trend in the context of structural sequence, and in conjunction with geochronology, appears to be of fundamental importance in (*1*) the reassembly of fragmented basement complexes, e.g. the linking of the Owl Mts (Góry Sowie) block of polyphase deformed gneisses and migmatites in the Sudeten Mountains of Poland (Grocholski 1964; Teisseyre 1964, 1968) with the main part of the Bohemian (Moldanubian) basement and (*2*) the matching of the margins of continents and the reconstruction of pre-drift configurations, *e.g.* the linking, or separation of Canada, Greenland, Scotland and Fennoscandia. If further detailed structural and geochronological data permits such large scale matching to be demonstrated, then the past one hundred and fifty years of study of structural trend in Precambrian terrains may emerge as a very significant factor in the reconstruction of past environments over the *c* 3500 m.y. of known Precambrian time.

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