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Tectonics in the Baltic Shield in the period 2000–1500 million years ago

ABSTRACT: The effects of deformation during the Svecokarelian orogenic episode on pre-2000 m.y. sedimentary and volcanic assemblages, developed in contrasted crustal environments, are compared and related to the effects of coeval deformation on older crystalline basement. Comparability in both the polyphase structural sequences and the orientations of successively formed structural elements in schistose and gneissose cover rocks indicate an overall unity of the complex framework from eastern Finland to Sweden. Correspondence of this framework with that resulting from deformation of 2200–2000 m.y. cover rocks during the Laxfordian orogenic episode in northwestern Britain, together with comparison with the effects of coeval deformation of crystalline basement, suggest a unity of structural framework from Finland to Scotland c 2000–1700 m.y. ago.

Epeirogenic movements in the post-orogenic cratonic stage of the orogenic cycle c 1700–1500 m.y. ago, or even younger, were associated with granite emplacement, sedimentation, extrusive volcanism and faulting. The fault patterns developed in the lower crust had a marked effect on the geological evolution of the region during the remainder of Proterozoic and Phanerozoic times.

INTRODUCTION

The effects of the Proterozoic crustal event referred to as the Svecokarelian episode are widespread, being expressed mainly in southern, central and northwestern Finland and northern, central and eastern Sweden (Fig. 1). From isotopic evidence, gneisses in Norway, both occurring as basement in the Scandinavian Caledonides and making up the western foreland of this belt, also record ages in the Svecokarelian episode (Heier & Compston 1969; Wilson & Nicholson 1973). The continuity of crystalline basement from northwestern Norway to northwestern Britain (Fig. 8; Talwani & Eldholm 1972), and the marked similarities in both age and tectonic expression of the Laxfordian episode there with the Svecokarelian episode of Fennoscandia (Bowes 1975) suggest an extension of the Baltic Shield in early Proterozoic times beyond the general region of western U.S.S.R. and Fennoscandia. A correspondingly large, or even larger crustal segment, including the regions of southern Ireland and western France as well as northwestern U.S.S.R. appears to have been the site of considerable crustal addition in the c 3000—2700 m.y. period and to have become a large stable crustal area by the end of Archaean times (Bowes 1976a).

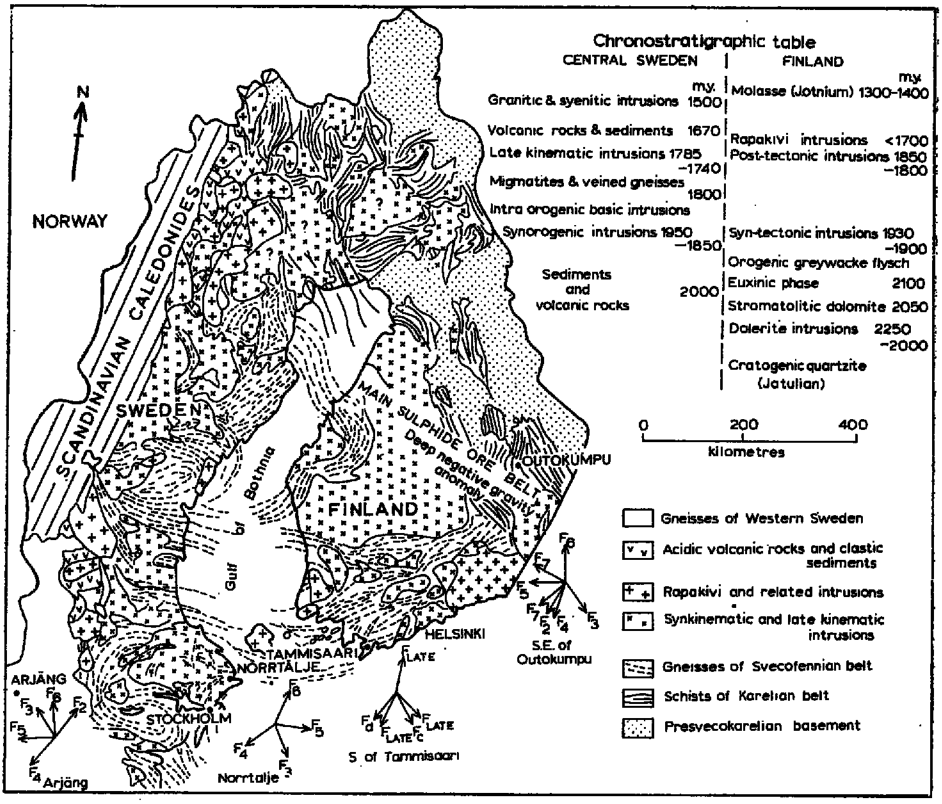


Fig. 1. Geological map of Finland and Sweden (*after* Welin 1970) with chronostratigraphic table (*after* Stephansson 1975; Kouvo 1975) and axial trends of successively formed folds

The crystalline products of the c 2800—2600 m.y. Presvecokarelian and related orogenic episodes formed the major part of a basement on which extensive sedimentary deposits, with associated products of igneous activity, were developed in the early part of Proterozoic times. The unconformable relations are clearly seen in parts of Finland where the basement is overlain by a thin veneer of epicontinental deposits consisting of the products of in situ weathering, breccias with fragments of the underlying basement and satrolites together with semipelitic and thin pelitic units, now seen as micaceous schists (Pl. 1*b*, *c*). In many places the succession is continued by glassy orthoquartzites and calcsilicate rocks. Micaceous schists, some graphite-bearing and some sulphid-bearing (Pl. 1*a*), occur above the epicontinental rocks and are interpreted as metamorphosed sapropelites. These rocks form the transition to a geosynclinal facies now mainly micaceous and siliceous schists or gneissose and migmatitic equivalents. Amongst the geosynclinal rocks are many igneous masses, including amphibolites, with serpentinites regarded as ophiolites by Huhma and Huhma (1970). Metaturbidites indicative of rapid flysch-type deposition represent the youngest sedimentary rocks (Gaál 1972). The overall period of sedimentation began about 2300 m.y. ago, the model lead age of sulphides at Outokumpu (Kouvo & Kulp 1961), with syn-sedimentary volcanism dated at 2150 m.y. (Sakko 1971), and must have ended *c* 2000 m.y. ago (Fig. 1). A generally corresponding period of sedimentation and volcanism has been determined for central Sweden (Stephansson 1975) while in Scotland the Loch Maree Group of micaceous schists with graphite-bearing rocks, banded ironstones and associated igneous masses developed *c* 2.2—2.0 b.y. ago (Bikerman & al. 1975). This means that about 2000 m.y. ago when the depositional part of the cycle was succeeded by the orogenic part of the cycle, a thick lithologically layered supracrustal pile, with marked internal competence differences, overlay a generally much more competent crystalline basement. Within the basement itself there were also competence differences, the most gross being between lithologically layered amphibolite facies quartzofeldspathic and related gneisses and more competent granulite facies rocks of deeper crustal levels (Bowes 1976b).

It is this type of crustal segment which *c* 1950 m.y. ago was subjected to deformation, metamorphism and, successively, to syntectonic and post-tectonic igneous activity. The emplacement of the rapakivi-type intrusions in Finland after 1700 m.y., the development of sediments and volcanic rocks in Sweden *c* 1670 m.y. ago and the abundant emplacement of granitic masses during the latter parts of an extensive polyphase deformational sequence *c* 1750—1700 m.y. ago in Scotland (van Breemen & al. 1971; Bowes & Hopgood 1975a), all indicate the transition from the orogenic to the post-orogenic cratonic stage. The major crustal cycle ended in Finland before the deposition of the Jotnium sandstones 1300—1400 m.y. ago. This, together with the emplacement of granitic and syenitic intrusions 1500 m.y. ago in parts of Sweden (Stephansson 1975) and the evidence of extensive epeirogenic movements related to crustal uplift in Scotland also *c* 1500 m.y. ago (Bikerman & al. 1975) means that the 500 m.y., ending 1500 m.y. ago, is a cognate time span for considering the nature of tectonics in Proterozoic times in the Baltic Shield.

Extensive and complex deformational, metamorphic and igneous histories have been established in various parts of Finland, Sweden, Scotland and Ireland on the basis of the relationships of small-scale structures to one another and to metamorphic and igneous features. Using isotopic data for rocks and minerals whose relative times of formation by metamorphic activity or igneous crystallization have been determined in relation to the overall structural sequence, time spans for the established sequences have been determined and the validity of correlations based mainly on structural criteria checked. In this way the various phases, or cognate groups of phases, of structural, metamorphic and igneous activity can be assigned to, or correlated with, major episodes of crustal history established on geological criteria in other regions.

The approach employs techniques previously used successfully in highly deformed Precambrian rocks in Scotland (Hopgood & Bowes 1972 a, b) and in other parts of the world (*cf.* Bowes & Hopgood 1976, and references therein). The erection of sequences is based on two fundamental principles of geology, namely that (*1*) deformed structures are older than those which deform them and (*2*) cross-cutting features are later than those which they cut. Structures and igneous intrusions so found to post-date others can be traced, using a combination of characteristics including orientation, mineral growth and style, to places where they, in turn, are affected by later structures or cross-cut by later intrusions. The orientation of component structures is, to a large extent, controlled by the orientation of the stress field producing them. The more extensive the orogen, the greater is the likely variation in orientation of the stress field during a particular phase of deformation with additional variations imprinted as the result of local internal differences of stress orientation. Consequently structures formed in the same segment of an orogen, and in regions where competence contrasts are comparable, are more likely to be identical in terms of orientation and style than those originating in widely separated areas. However the demonstration of comparability of structural features, including orientations, over large areas suggests little variation in stress field orientations.

While fold style may change from layer to layer, and from outcrop to outcrop, and axial attitudes vary dependent upon attitudes of pre-existing surfaces, close matching of orientations together with styles of a given pair of structures suggests they have a common origin. Where matching can be accomplished between groups of sequential structural elements, particularly away from complex interference patterns resulting from superimposition of fold hinge zone on fold hinge zone, the likelihood of common origin is greatly enhanced. The more complex the structural, metamorphic and igneous histories of the rocks, the larger are the number of independent and related factors that can be used for correlation and the stronger is the basis for correlation. Where the number of parameters is large, the likelihood of random matching is small and variations of expression of a particular structural, metamorphic or igneous event can be separated from expressions of only locally developed events. The linking of isotopic data to particular events not only provides a means of correlation but, if there is sufficient data, may permit assessment of the possibility of diachronous rather than coeval development throughout the orogen.

BASEMENT DEFORMATION IN FENNOSCANDIA

The structural pattern resulting from polyphase deformation in the *c* 2800—2600 m.y. Presvecokarelian orogenic episode in Finland is markedly different from that resulting from polyphase deformation of the younger supracrustal assemblage in the Svecokarelian episode. Over large areas, rocks fabrics formed in Archaean times remain extant with fine cleavages as well as prominent foliations recognizable (Bowes 1976 a, Pl. 1). The various fabric elements can, in places, be traced into the zone of in situ weathering at the unconformity with the overlying supracrustal group while the orientations of the successively formed planar and linear features can be matched from the isolated masses of basement occurring as cores of domes in the Svecokarelian belt to the main, essentialy undisturbed basement region. The concept of wholesale 'reworking' or 'reactivation' suggested to have been operative in Proterozoic times in other shield areas (Watson 1973) is not applicable except in particular situations. These are in the region of the medium-pressure granulites of Lapland, formed *c* 2100 m.y. ago (Meriläinen 1976) in association with anorthosite emplacement (Bowes *in press*), and in narrow elongate ductile shear zones in which there has been considerable retrogression (Lestinen 1969). From field observations such zones make up a very minor proportion of the exposed basement, although they could have provided loci for ice movement and glacial deposition.

In some of the gneisses of the basement masses occurring within the younger orogenic belt, the U-Pb isotopic systems of zircons remained undisturbed and show ages of 2800 m.y. U-Pb zircon ages of the basement complex in part of Lapland are 2800 m.y. to 2500 m.y. analogous to the whole rock Rb-Sr isochron age, while 1900 m.y. ages shown by mineral isochrons and sphene point to the very limited scale of subsequent disturbance (Kouvo & Sakko 1974). Some limited disturbance is also shown in the U-Pb isotopic systems of zircons in basement gneisses forming the cores of fold interference structures formed during the Svecokarelian episode (Fig. 3*a*). Generally, the mica ages of 1900—1700 m.y. show the effects of reheating of the products of the Presvecokarelian episode during the Svecokarelian episode (Kouvo & Tilton 1966; Bowes 1976a).

This combination of structural and isotopic evidence shows that basement tectonics in Proterozoic times in this part of the Baltic Shield was not associated with remobilization of crystalline basement in the manner described by Eskola (1948) for the formation of mantled gneiss domes or with the formation of gneisses with new fabrics at the expense of pre-existing gneisses. Rather the evidence suggests very limited effects in the basement, except associated with the emplacement of large masses of high temperature magma, or the development of major tectonic slices or ductile shear zones and faults. However there is a possibility that the formation of the domes with cores of basement is related, at least in part, to movement of material at greater depth following melting or partial melting over rising heat sources.

COVER DEFORMATION IN FENNOSCANDIA

In places the unconformity between the basement and cover rocks is represented by a zone of in situ weathering which passes down to the basement rocks with their characteristic structural framework and passes up into fossil subsoil or fossil soil, now composed of amphibolite facies mineral assemblages. There, and where there are beds of breccia and conglomerate containing pebbles of basement rocks, an essentially undeformed stratigraphic succession remains, even with sedimentation features indicative of environment of deposition (Nykänen 1971). Like the immediately underlying basement, these rocks show no obvious effects of the penetrative deformation that generally characterizes the cover rocks affected during the Svecokarelian episode. However the first incompetent unit above the unconformity, which may only be a few metres, and at the most a few tens of metres away, shows the effects of penetrative deformation, new metamorphic fabrics and folds formed in a regime dominated by horizontal-type tectonics (Pl. 1*b*, *c*). Competent beds of meta-conglomerate, apparently in a simple stratigraphic succession, may separate the incompetent units showing the intense deformation and amphibolite facies mineral assemblages. Further from the unconformity all units, except later intrusive masses, exhibit the new penetrative metamorphic fabric and are seen as schists and gneisses showing the effects of polyphase deformation. This marked change in tectonic response indicates largely independent movement of much of the cover and the basement, at least in the early stages of the orogenic episode, a feature that is not uncommon in mobile regions.

The dominance of an E—W to ENE—WSW regional structural trend in the gneisses of southwestern Finland and parts of Sweden and of a NW—SE to NNW—SSE regional structural trend in the schists of Karelia (Fig. 1) was used as evidence for the development of the Svecofennian gneisses and Karelian schists during separate orogenic episodes. The E—W trend of the schists in parts of northern Finland was also used as evidence for suggesting the existence of an even younger orogenic episode (Eskola 1963; Bowes & Hopgood 1976). However isotopic data has demonstrated the overall correspondence of ages throughout Finland and Sweden (Welin 1970; Kouvo 1975), but with some diachronism (van Breeman & Bowes, *in press*). In addition structural studies have shown that more than one structural trend is expressed within areas and regions (Fig. 3a). This feature and the common occurrence of fold interference structures (Gaál & Rauhamäki 1971) is related to polyphase deformation and the variations in intensity of expression of the successively formed sets of folds. The occurrence of structural domes is unrelated to and precedes the uprise of granitic diapirs which are abundant in parts (Fig. 1). The situation and limits of the various batholithic masses appear to be controlled by the pre-existing structural pattern rather than being its cause. This is illustrated by the change from dominantly E—W structures to dominantly NE—SW structures controlling the limit of the Dala batholith in central Sweden (Stephansson 1975).

The NW—SE-trending zone which contains about 90% of the sulphide deposits and ore reserves of Finland (Fig. 1; Kahma 1973) generally separates the region of mainly sedimentary schists of the Karelian belt from the region of the Svecofennian belt in which gneisses and granites are common and in parts of which domains of metaturbitites alternate with domains of the metamorphosed products of basic igneous volcanism and plutonism. The elongate zone is the locus of a major wrench fault system (Gaál 1972) operative during the third deformational phase of the Svecokarelian episode and which may correspond to or parallel a major lineament formed in Archaean times (Bowes *in press*).

KARELIAN BELT

The polyphase deformational sequence shown by the siliceous and micaceous schists and amphibolites of the Karhunsaari dome, near Liperinsalo 40 km SE of Outokumpu (Fig. 3*a*), illustrates the tectonic development of the Karelian belt. There the effects of seven successive phases of deformation are shown with the dominant rock fabric being the result of the first and second phases. The major structure of the area resulted from folding in the third phase, and superimposed folding during the fourth and fifth phases. However these features are on the limbs of much larger and earlier formed structures whose closures are seen in the adjacent region (Gaál & al. 1975).

Both the development and expression of the various structural elements are related to the competence of the lithological layers in which they are found and to the heterogeneities produced during deformation.

Hence while a consistent structural sequence can be determined throughout the area on the basis of refolding of folds, foliations and lineations or of new structural elements cutting across deformed ones, there is a patchy development of structural elements (Pl. 1*f*; Text-fig. 2b). Later formed folds are generally most strongly expressed on the limbs of earlier formed structures and except in some of their hinge zones, where there was new penetrative mineral growth (Pl. 1*d*), it is possible to elucidate the effects of earlier structural and metamorphic events. Subject to unfolding, the various fold sets have consistent attitudes throughout the area with the trends, and variations from these trends resulting from superimposed deformation (*cf*. Fig. 3*a*).

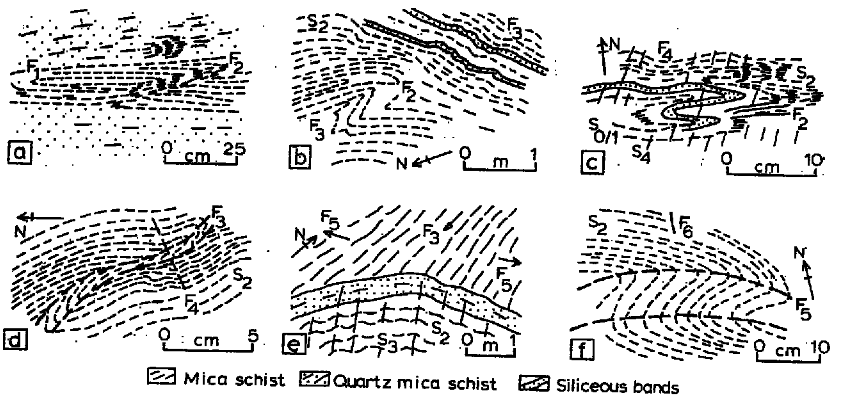
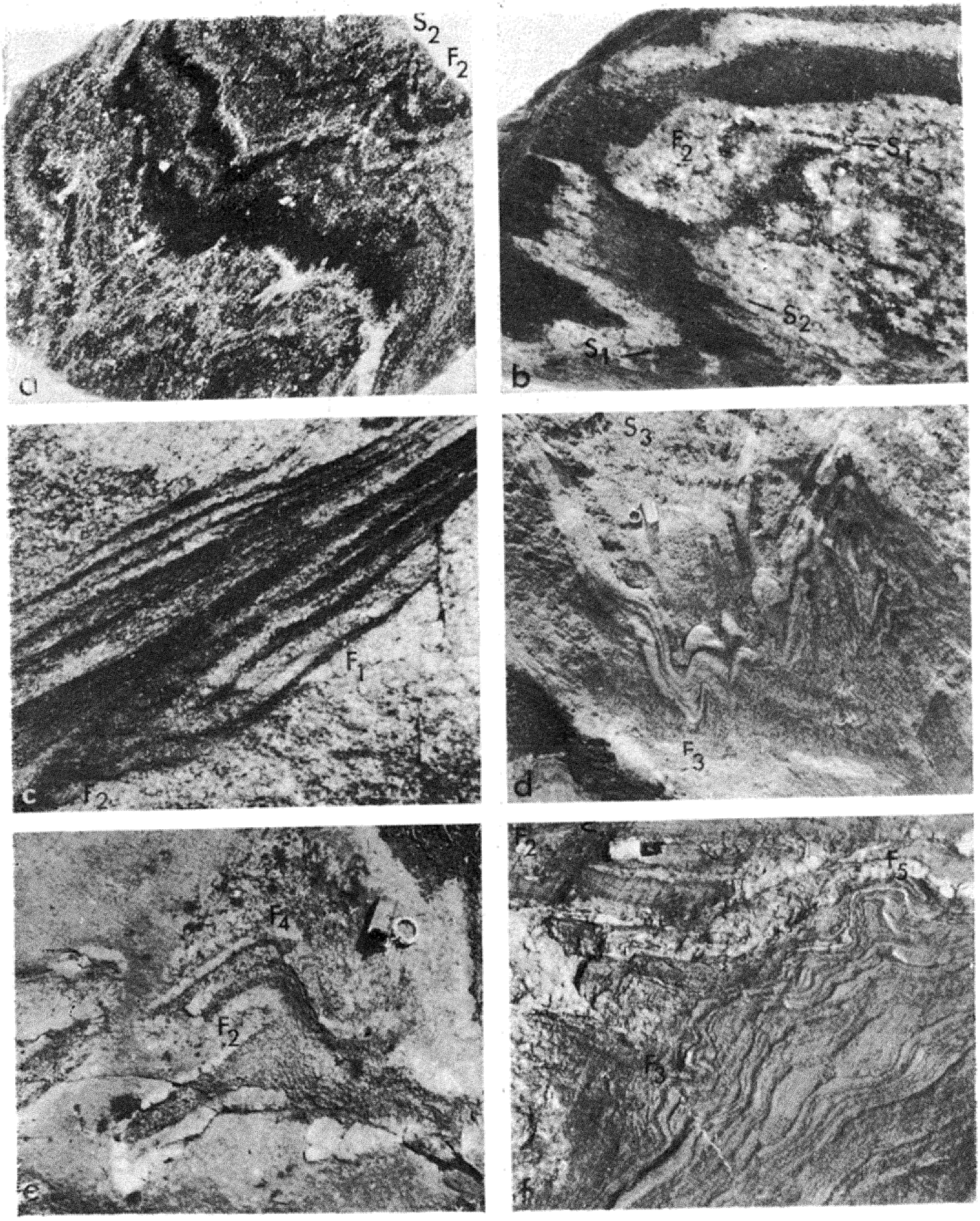


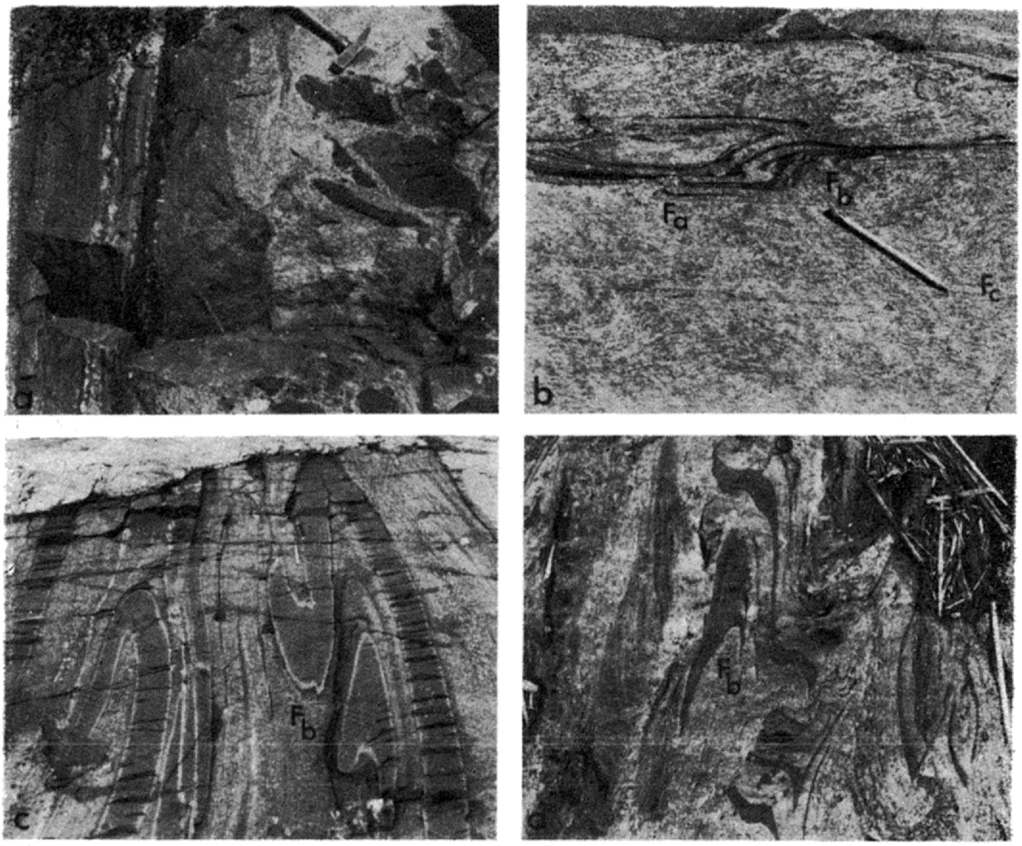
Fig. 2. Nature, mutual relations and attitudes of successively formed structural elements in micaceous and siliceous schists; Karhunsaari dome, near Liperinsalo, northern Karelia (*cf*. Text-fig. 3*a*)

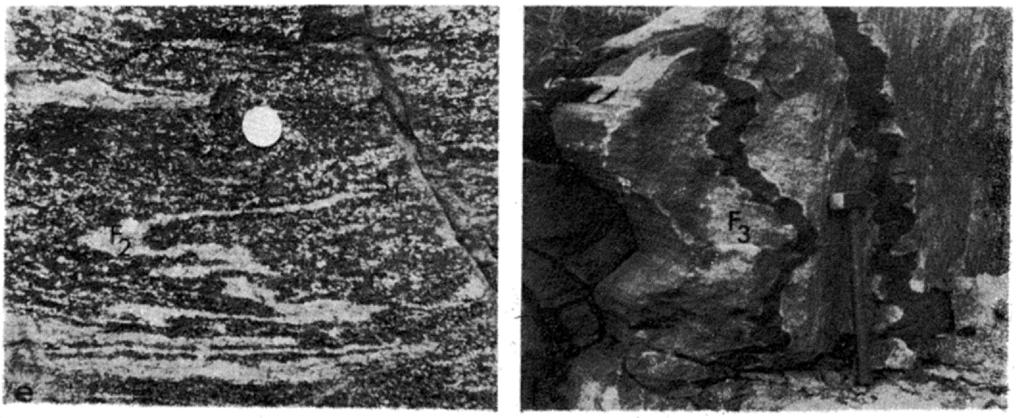
Folds of the first deformational phase are consistently isoclinal (Pl. 1*c*; Text-fig. 2*a*) and related to the formation of an amphibolite facies foliation. All observed F_1 structures are small but are presumed to be parasitic on large folds (*cf*. Gaál & al. 1975). Both folds and foliation, which mainly parallels lithological layering, are deformed by F_2 folds which are close, tight or isoclinal (Pl. 1*c*, *e*; Text-fig. 2*a*, *b*, *c*) and have SW—NE axial trends. On the island west of Liperinsalo some of these folds have wavelengths and amplitudes in the order of 0.5 and 1 km, respectively. The S_2 foliation, developed under lower amphibolite — upper greenschist facies conditions, is expressed as an axial planar alignment of minerals, particularly micas, in fold hinge zones. On fold limbs most of the foliation appears to be composite $S_{1/2}$ Dimensional alignment of minerals and quartz rodding parallels the hinge direction of F_2 folds while quartz boudins, which lie in S_2, were deformed by F_3 as are the other structural elements of the second deformational phase. The F_3 folds are moderately open and commonly asymmetrical particularly in the more pelitic units (Pl. 1*d*; Text-fig. 2*d*) in which axial planar S_3 is developed,



Structures in schists in northern Karelia formed during the Svecokarelian episode (*cf.* Text-fig. 3)

a — With axial planar sulphides, Outokumpu; **b** — West of Sotkuma dome; **c—f** — Karhunsaari dome, Liperinsalo





Structures formed during Svecokarelian episode; Skåldö, south of Tammisaari, southwestern Finland (*cf.* Text-fig. 1)

a — Agmatite showing little flattening adjacent to strongly foliated gneiss; **b—d** — Folds in gneiss

Structures in rocks affected by Sveconorwegian event with correspondence in axial trend with structures formed in the Svecokarelian episode; Arjäng, western Sweden

e — In amphibolite; **f** — In banded gneiss and amphibolite locally becoming the dominant planar fabric element. In some adjacent lithological layers F_3 is expressed as small crenulations and open folds (Fig. 2*e*) with prominent L_3 rods and mullion. The trend of fold axes varies from 145° to 195°, due to later deformation, with an average attitude of 25/170° *i.e.* corresponding to the regional 'Karelian trend'. The fold axial planes generally dip at moderate angles. They and the earlier formed structural elements are deformed about moderately open upright F_4 folds (Pl. 1*e*, Text-fig. 2c, *d*) with axes that trend SW to SSW and are paralleled by a strong quartz rodding and intersection lineation. New axial planar mineral growth indicates maintenance of elevated temperatures. Over considerable areas where F_3 folds are strongly developed there is little evidence of F_4, but some S_4. Where F_4 folds occur close to hinge zones of F_3 folds the resultant composite structures have the appearance of box folds. Both F_5 and F_6 folds are very open or open and upright, with E—W and N—S axial trends, respectively (Fig. 2*f*). Some axial planar cleavage is associated with F_5 but apparently not with F_6 or F_7, the latter being a conjugate set of very open, upright folds that pass into fractures. Various combinations of folds make up fold interference structures which are expressed regionally (Fig. 3*a*) as well as locally (Pl. 1*f*).

The structural elements of the first six deformational phases have been recognized regionally where the sequence of development, general expression in comparable lithological assemblages, mutual relations and orientations correspond with those determined in the area of the Karhunsaari dome. This correspondence is illustrated in Fig. 3 for the area near Sivakkavaara, east of Kaavi (*b*—*e*) and the area east and south of the dome of Presvecokarelian gneissose basement at Sotkuma (*f*—*j*; Pl. 1*b*). The isotopic data of van Breeman & Bowes (*in press*) for the former area suggests that temperatures remained elevated for c 120 m.y. after the emplacement of pegmatites between F_3 and F_4 at least 1880 m.y. ago. This combined with the petrographic data, and the isotopic data of Gaál (1972) indicating that synorogenic intrusive masses affected by F_3 deformation were emplaced c 1925 m.y. ago, indicates an extended period (> 150 m.y.) of elevated temperatures after the main fabric forming first two deformational events.

In the vicinity of the Outokumpu ore deposit, folds not yet identified regionally are seen, possibly because of competence contrasts resulting from the presence of the large mass of sulphides. The first deformational phase produced NE—SW trending large recumbent F_1 folds whose co-axial refolding by upright structures (Gaál & al. 1975) caused the major structural trend of this part of the region (Fig. 3*a*). As elsewhere the dominant rock fabric was developed under amphibolite facies conditions early in the polyphase deformational sequence with sulphides making up an axial planar foliation in some folds (Pl. 1*a*). Before or coeval with the

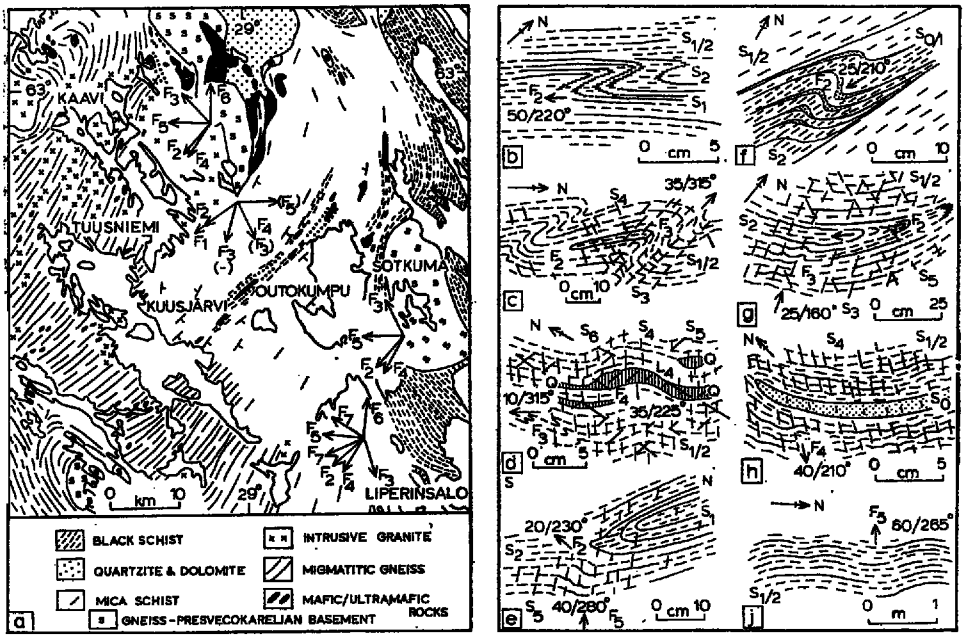


Fig. 3

a — Outline geological map of part of northern Karelia and adjacent regions (*after* Väyrynen 1939) showing axial trends of successively formed folds; trends for the Outokumpu district after Gaál & al. (1975) with those in brackets indicating suggested correspondence with those elsewhere

b—j — Nature, mutual relations and attitudes of successively formed structural elements near Sivakkavaara, east of Kaavi (*b—e*), and near the southern and eastern margins of the Sotkuma dome of basement gneiss (*f—j*), respectively

development of the SSE-trending folds which control the structural trend of the eastern and northern parts of the region (F_3 regionally — Fig. 3*a*), 015° to N—S-trending folds developed and these are related by Gaál & al. (1975) to the development of the Sotkuma dome. Part of the major deep-seated wrench fault system which characterizes much of the main sulphide ore belt (Fig. 1; Gaál 1972) occurs 30 km SW of Outokumpu. There is subparallelism of shear zones associated with ductile deformation and complex folding and correspondence in the overall sequence with the F_3 folds which control the 'Karelian trend'. This major crustal lineament generally separates the Karelian schists to the northeast from the Svecofennian gneisses and related rocks to the southwest.

SVECOFENNIAN BELT

Despite the repeated emplacement of ultrabasic, basic, intermediate and acidic igneous masses which has compounded the complexity of the rocks, an extensive polyphase deformational sequence has been established for the migmatites and related rocks of the Skåldö area, south of Tammisaari (Fig. 1). Their history illustrates the tectonic development of at least part of the Svecofennian belt with the effects of at least seven deformational phases recognized. Amphibolite facies metasediments and gneisses occur together with the wide variety of igneous rocks which include the host parts of agmatites (Pl. 2*a*) intruded at varying stages during the deformational history. As it is likely that the association of much flattened and little flattened zones may occur regionally, with the possibility of evidence of additional early deformational phases being found in the surrounding region, letters rather than numbers have been used to designate events in the structural sequence (Figs 1 and 4; Hopgood & al. 1976).

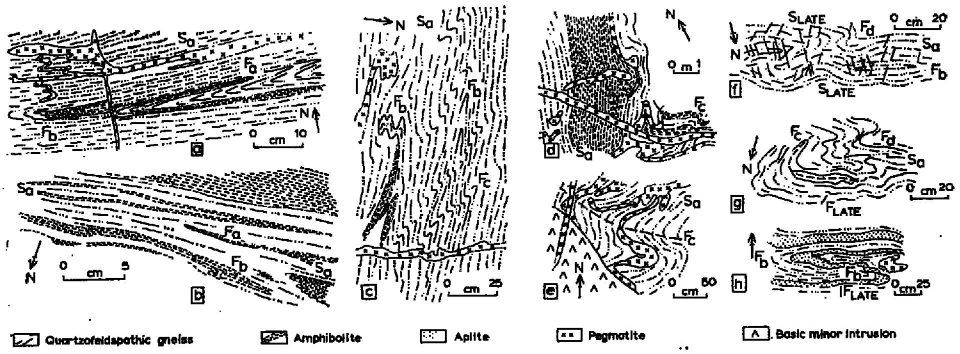


Fig. 4. Nature, mutual relations and attitudes of successively formed structural elements; Skåldö, south of Tammisaari, southwestern Finland

The earliest folds identified (F_a) lie wholly within the amphibolite facies foliation except at the sharp hinges where the foliation is axial planar. They are isoclinal with attenuated limbs (Pl. 2*b*; Text-fig. 4*a*, *b*), have subhorizontal axes and while only small scale folds have been recognized, these are probably parasitic on large scale structures. The F_a folds are seen to have been folded around generally tight and sometimes almost symmetrical folds (F_b) whose axial planes are largely parallel to the foliation (Pl. 2c; Text-fig. 4*a*, *c*) but sometimes are paralleled by a weakly developed mineral growth. Some of the F_b folds are asymmetrical and vary from tight to open (Pl. 2*d*; Text-fig. 4). Autochthonous and parautochthonous granite development was associated with their formation (Pl. 2*d*) which, at least in part, was due to slip. This deformational phase appears to have ushered in an extensive period during which there was folding by inclined slip parallel to the foliation direction resulting in the relatively common occurrence of co-axial planar folds of the F_b and later generations. In addition successive generations of igneous minor intrusions emplaced at high angles to the foliation became folded while earlier formed folds were progressively modified.

The F_c folds, and those formed during subsequent deformational phases are more open than is generally the case for F_a and F_b folds, with both F_c and F_d folds asymmetrical (Pl. 2*b*; Text-fig. 4c, *f*), sometimes with quartzofeldspathic veining parallel to their axial traces or, in the case of F_3 folds, a plexus of veins in their hinge zones (Fig. 4*d*). Generally they have rounded, lobate hinges with weakly developed axial planar mineral growth in parts. The F_c axial traces commonly trend SE but are curved by F_d and later formed folds (Fig. 4*f*, *g*) and cross-cut by basic minor intrusions (Fig. 4*e*). The axial traces of F_d folds, which trend SW are, like those of the F_c folds, inclined to the foliation trend.

Subsequent deformation became progressively more brittle. The F_e folds are represented by a conjugate set of open folds that trend NNE and SE and produce highly irregular interference patterns. They have incipient shears parallel to their limbs and axial planes that rarely continue for more than a few centimetres. Even later formed folds are generally only locally expressed apart from very open to moderately tight structures with N—S- to NNE-trending axial planes (F_{late} — Fig. 4*f*, *g*, *h*), which are common. They are flexural folds that impart a wavy effect to the banding and to F_b axial planes (Pl. 2c) and are probably related to a N-trending fracture cleavage seen particularly in the amphibolites. Conjugate shears trending NNE and SSE affect the N-trending late folds, but the shears themselves are offset by shears parallel to the foliation. This appears to represent a continuation of the foliation shear that began at least as far back as the formation of F_b folds and which has resulted in the marked flattening seen in parts.

Further west in the gneisses of the Svecofennian belt, near Norrtälje on the western coast of central Sweden, an extensive polyphase deformational sequence also begins with two phases associated with amphibolite facies mineral growth (Bowes & Hopgood 1976, Fig. 10). In some of the amphibolites the dominant growth is S_1, but in the quartzofeldspathic gneisses and in some amphibolites, S_2, which is axial planar to generally tight to isoclinal folds, predominates. Asymmetrical folds (F_3), with some new axial planar mineral growth particularly in fold hinge zones, are prominent expressions of the third deformational phase. However, fold style varies from place to place but the axial trace trends SSE unless it is curved about later formed structures. Of these, the F_4 folds vary from open and symmetrical to asymmetrical. Axial planar cleavage, in places concentrated in hinge zones, occurs related to very open, upright warps of the foliation as well as to tighter folds and like the axial traces, trends SW. Some E—W-trending F_5 crenulations occur while open, symmetrical NNE- to N-trending folds pass into brittle crush zones.

DISCUSSION

There are marked similarities in the structural sequences determined in various parts of the Karelian belt with those determined in parts of the Svecofennian belt. Such similarities as correspondence of metamorphic intensity with time and of expressions and styles of the various structural elements through the sequences could be matched with features of other orogenic belts and be accounted for in terms of changing response of rocks to an orogenic environment. However the correspondence from place to place of the attitudes of the successively formed structures, particularly those developed in the latter parts of the sequence and not subject to significant reorientation, suggests a unity of tectonic evolution in rocks that have been shown to have formed coevally. This is instanced by the consistent expression of the late N—S- to NNE-trending open folds passing into fractures (F_6, F_{late} — Figs 1—4), the SW-trending F_4—F_d symmetrical to asymmetrical folds and their reorientation of SE- to SSE-trending F_3—F_c folds which are commonly asymmetrical and associated with the development and emplacement of quartzofeldspathic vein material. Thus the combination of correspondence of the fold geometries of the structures formed in successive phases, together with other structural as well as igneous and metamorphic features, serves to characterize the Svecokarelian orogenic regime. The variations from the cognate structural development that do exist are explicable in terms of the nature of the rock assemblages affected which themselves reflect the overall crustal environment of formation, *e.g.* the volcanogenic assemblage in a very mobile part of the belt in southwestern Finland shows a much more extensive igneous history and a more complex late structural history than the epicontinental assemblage deposited on competent basement in Karelia.

Isotopic data indicates that the orogenic stage of the Svecokarelian orogenic cycle lasted in the order of 200 m.y. (Fig. 1; Welin 1970; Kouvo 1975; van Breemen & Bowes, *in press*) while the structural and metamorphic evidence points to a change over this period from major recumbent fold formation with associated penetrative metamorphism at considerably elevated temperatures to a regime of major wrench fault tectonics and subsequently to a regime in which dominantly flexural folding passed into brittle fracture. The subsequent post orogenic cratonic stage of the cycle, represented by the emplacement of rapakivi intrusions, volcanic eruptions and sedimentation, even later emplacement of granitic and syenitic masses (Stephansson 1975) and much faulting, also lasted in the order of 200—250 m.y. When taken together with the initial sedimentation stage, the length of this cycle of earth history was in the order of 750—800 m.y.

The shape of the Svecokarelian mobile belt, as represented in Finland and Sweden (Fig. 1), does not correspond with that of a Phanerozoic linear mobile belt. However neither its total dimensions nor its overall shape have been determined and both isotopic and structural data suggest it extends over a much larger crustal segment than the confines of Fennoscandia. Ages corresponding with those of the Svecokarelian episode have been recorded in Norway in basement rocks that have been traced by geophysical means to northwestern Britain (Fig. 8), while some gneisses showing isotopic evidence of the effects of the c 1200 m.y. Sveconorwegian event have polyphase deformation sequences corresponding with those shown in the Svecokarelian belt. For example quartzofeldspathic gneisses and amphibolites in the vicinity of Arjäng in eastern Sweden show the effects of six deformational phases with orientations of the successively formed F_2, F_3, F_4, F_5 and F_6 fold sets showing general correspondence with folds in corresponding positions in the structural sequence in Karelia (Figs 1 and 5*k*). There is also general correspondence in the expression of the structural elements expressing the various deformational phases (Fig. 5). The peak of metamorphic recrystallization and the imposition of the major part of the rock fabric was associated with the first deformational phase, with S_1 and L_1 prominently developed in some lithological units. The F_2 folds, which are generally tight to isoclinal, deform both siliceous bands (Fig. 5a) and foliation in amphibolite (Pl. 2*e*) but are intrafolial in the gneisses (Fig. 5*b*, *c*). They and the foliation are deformed by asymmetrical to symmetrical F_3 folds (Fig. 5*c*) with parautochthonous or intrusive quartzofeldspathic material common in hinge zones (Fig. 5*d*, *e*). In places the axial planes are subhorizontal (Pl. 2*f*; Text-fig. 5*f*). They, the fold limbs and the earlier formed structures are affected by upright open F_4 folds (Fig. 5*g*, *h*) which in places are represented by a conjugate set (Fig. 5*j*). The F_5 and F_6 folds are mainly represented by open warps.

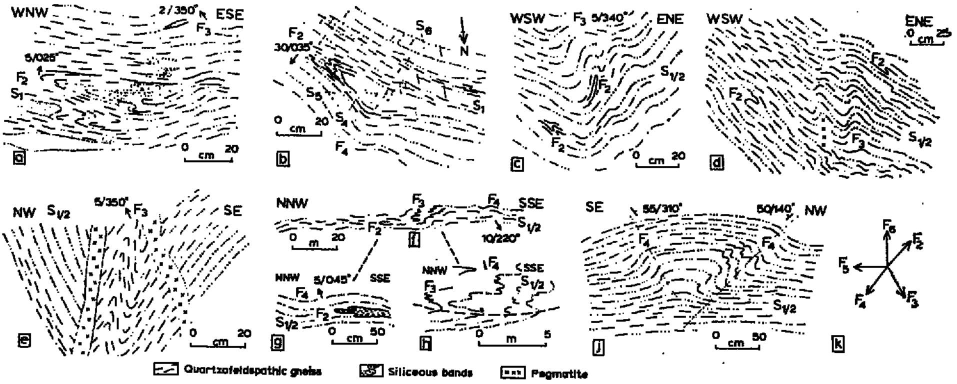


Fig. 5. Nature, mutual relations and attitudes of successively formed structural elements; Arjäng, western Sweden

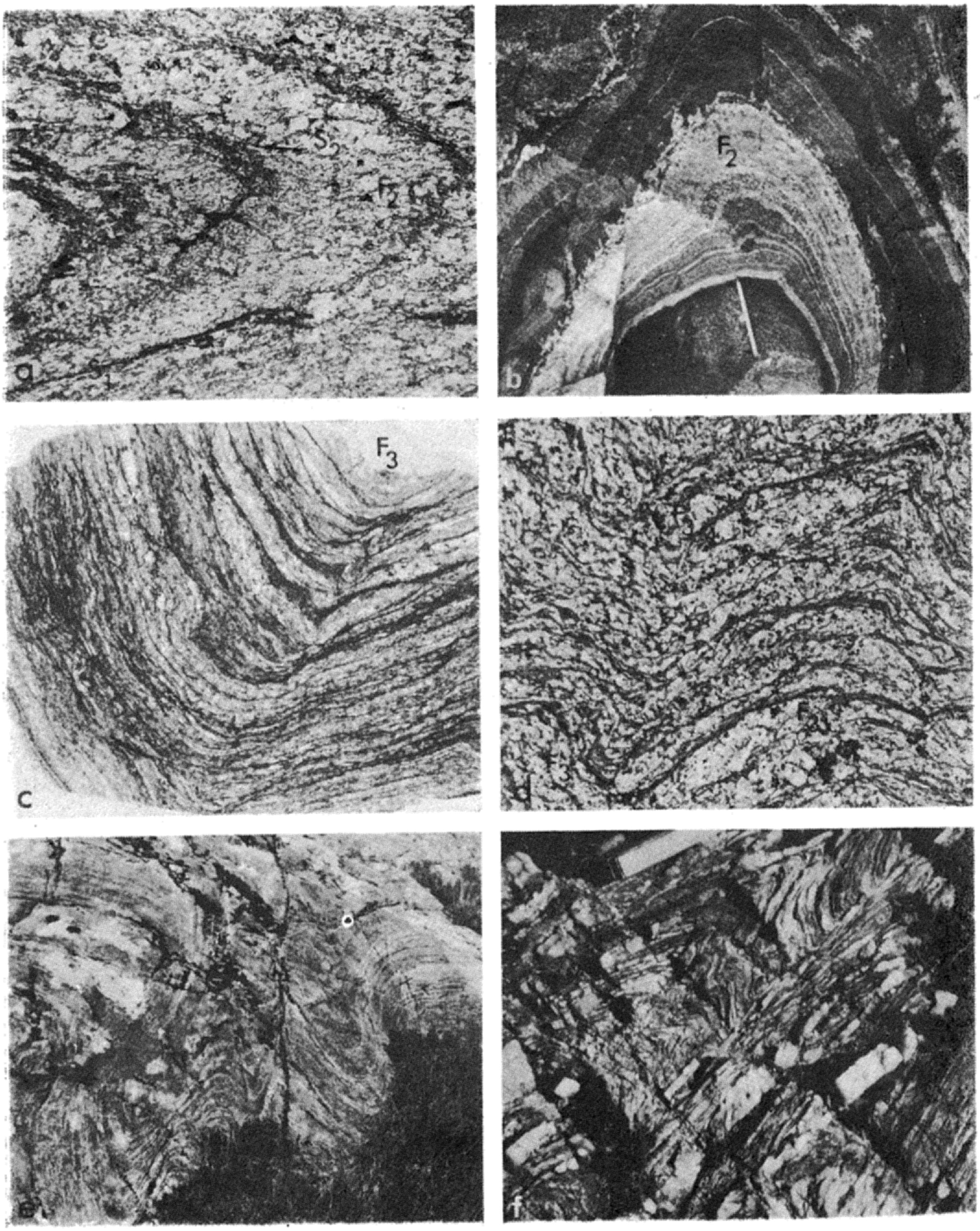
A continuation of the Svecokarelian belt not only into parts of Sweden and Norway that have undergone subsequent deformation, but also into Britain is suggested by the correspondence of structural sequences and orientations of successively formed structures in rocks that are generally coeval (Bowes 1975). Much of the deformation there represents tectonic overprinting, during the Laxfordian episode, of crystalline basement rocks, but cover deformation is shown in the metasediments of the Loch Maree Group (Bikerman & al. 1975).

BASEMENT DEFORMATION IN NORTHWESTERN BRITAIN

Tectonic overprinting during the *c* 1950–1700 m.y. Laxfordian episode of granulites, gneisses and amphibolites formed during the *c* 2800–2600 m.y. Scourian episode is widespread in the Lewisian complex of northwestern Britain (Fig. 6*a*). The rock fabrics mainly reflect the effects of polyphase deformation and metamorphism during the Scourian episode (Bowes 1976b) except in elongate ductile shear zones (fold-crush belts — Fig. 7*a;* zones of pre-Torridonian movements — Peach & al. 1907, Sutton & Watson 1951) which affect the granulite facies rocks in the region south of Scourie (*II* in Fig. 6*a*). In these generally narrow zones that correspond to the 'steep structures' described elsewhere (Pl. 3*e;* Benedict & al. 1964), tight to isoclinal folds of variable plunge occur between strongly refoliated bands in which localized retrogression to greenschist facies schists is associated with formation of axial planar foliation (Pl. 3*f;* Text-fig. 6*f*). Locally upper amhibolite facies assemblages occur, associated with the adiabatic transport of water upwards through the crust (Beach 1973, 1976). The widest of the shear zones separates the granulite facies rocks of the Scourie district from the amphibolite facies gneisses north of Loch Laxford (Fig. 6*a;* Sutton & Watson 1962). Isotopic data indicates its development *c* 1750 m.y. ago, *i.e.* during the Dionard phase of the Laxfordian episode (F_3 in Fig. 6*a;* Lyon & al. 1975).

Small asymmetrical folds deform the foliation in these zones and they and the earlier folded structures are deformed by a conjugate set of open, steeply plunging folds which are generally small and show some weakly developed axial planar cleavage (Khoury 1968; Bowes 1969). While direct correlation with the structures formed elsewhere in the latter part of the Laxfordian episode is not yet possible, their time of formation must correspond generally with that of F_4–F_5–F_6 recognized elsewhere. They and the shear zones are displaced by two prominent sets of faults. One set is almost straight and trends NW–SE to NNW–SSE (Fig. 7*a*). This trend is approximately parallel to the axial trace of the Kylesku fold which was formed in the later stages of the Scourian episode and with which are associated a very strongly developed set of axial planar joints. The other set, which consists of smaller but more abundant faults, is generally arcuate with a trend from NNE–SSW to NE–SW. The faults are related to the epeirogenic uplift stage of the Laxfordian episode that took place in the *c* 1700–1500 m.y. period (Bikerman & al. 1975). They apparently represent the first formed set of major faults in this crustal segment and a strong influence on the subsequent geological development of the region is suggested by correspondence of the fault directions with those of later formed features (Fig. 7*b*). The line of the Arran, Mull, Ardnamurchan and Rhum Tertiary igneous centres and that of the large magnetic anomaly in the Minch corresponds with that of the NNW–trending fault set in the basement as do a number of fault bounded masses of Triassic sediments in western Scotland. Both the arcuate nature and trend of the Minch Fault, which has actively controlled sedimentation since Precambrian times (Smythe & al. 1972) correspond with features of the other fault set in the basement. Corresponding features are shown by the margins of masses of Precambrian basement off the northern coast of Scotland while the line joining the Blackstones, Rhum and Skye Tertiary igneous centres also trends NNE. While there are many other factors that controlled the subsequent geological development of northwestern Britain (*cf.* Hall & Smythe 1973), the reactivation of major faults formed during middle Proterozoic times appears to have played a significant role.

The tectonic overprinting during the Laxfordian episode of the amphibolite facies gneisses of both the southern and northern regions of the Northwest Highlands (*I* and *IV* of Fig. 6*a*), the Outer Hebrides and Inishtrahull has been well documented. The deformational sequence recognized in Mingulay and Barra (*VI*; Bowes & Hopgood 1969; Hopgood 1971) has been recorded throughout other parts of the Outer Hebrides (Hopgood & Bowes 1972a; Bowes & Hopgood 1975a) and correlated with that of the Durness — Loch Laxford district, Rona and Inishtrahull (Hopgood & Bowes 1972b; Bowes & Hopgood 1975b). The overall correspondence in structural sequence can be established despite the complexity of some of the structural framework developed (Fig. 6*e*), while there is marked correspondence in orientations of the later formed structures. In places the abundance of F_3 folds and the amount of igneous material emplaced means that few of the structural elements formed in the much older Scourian episode can be recognized, apart from the very strongly developed dominant foliation (Pl. 3*d*). Both regionally (Fig. 6*e*; Findlay 1970) and locally (Pl. 3*d*) these F_3 folds are generally the most prominently expressed structures with flexural-slip playing an important role in their formation. Development *c* 1750 m.y. ago is shown by isotopic data for quartzofeldspathic material concentrated in their hinge zones (Lyon & al. 1973; Lyon & Bowes, *in press*), *i.e.* much of the tectonic overprinting took place in the last 50 m.y. years of the Laxfordian orogenic episode. Earlier formed (F_2) folds which deform the *c* 1000 m.y. older foliation (Pl. 2*b*) are interpreted as representing deformation between the *c* 1970 m.y. imposition of the dominant metamorphic fabric of the cover rocks (Bikerman & al. 1975) and the development of the F_3 folds. During this interval there were major thrusting movements involving both cover and basement. Large scale horizontal movements within the upper part of the basement at this stage (*cf.* Coward 1975) could account for the marked differences in response of the higher level quartzofeldspathic gneisses and the lower level granulites during subsequent deformation. It could also account for the present occurrence north of Loch Laxford of granulites apparently



Structures formed during Laxfordian episode in northwestern Britain (*cf.* Text-fig. 6)
a, c — In metasedimentary cover rocks; southwest of Loch Maree (*a* magn. x18); **b, d** — In basement gneisses; Harris (*b*), Inishtrahull (*d* magn. x 7.5); **e, f** — In basement pyroxene granulites (*e*) with retrogression to schists (*f*); south of Scourie

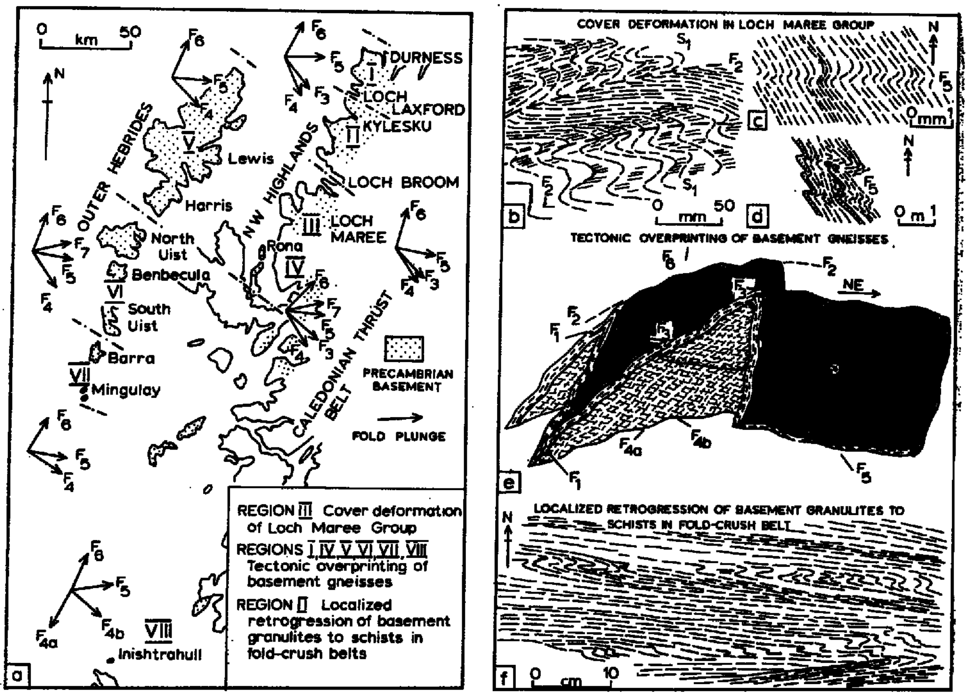


Fig. 6

a — Axial trends of successively formed folds in the Lewisian complex of north-western Britain; partly *after* Hopgood & Bowes (1972a, b) whose numbering of fold phases is used

b—d — Structural elements formed during the Laxfordian episode in metasedimentary schists, southwest of Loch Maree (*cf*. Bhattacharjee 1963, 1968)

e — Structural framework resulting from tectonic overprinting of much older quartzofeldspathic gneiss during the Laxfordian episode; Inishtrahull (*after* Bowes & Hopgood 1975b)

f — Tectonic overprinting of pyroxene granulites in fold-crush belt formed during the Laxfordian episode; south of Scourie corresponding to the c 2700 m.y. old granulites south of Scourie (Pidgeon & Bowes 1972) below quartzofeldspathic gneisses dated at c 2850 m.y. (Lyon & Bowes *in press*).

COVER DEFORMATION IN NORTHWESTERN BRITAIN

While the proportion of cover rocks affected by the Laxfordian episode that remain is small (Bowes 1976b), they show evidence of at least six phases of deformation. The first two are associated with amphibolite facies metamorphic mineral growth with S_1 being strongly developed and S_2 being axial planar to F_2 folds that vary from being open to isoclinal (Pl. 3*a*; Text-fig. 6*b*). Isotopic data indicates that metamorphism in the Loch Maree region took place c 1970 m.y. ago but that c 200 m.y. elapsed before the emplacement of pegmatites into F_3 folds. During this time interval thrusting brought the metasediments and paragneisses of the cover into juxtaposition with gneisses of the basement (Bikerman & al. 1975).

The F_3 folds, which are the most prominent folds of the region, are commonly asymmetrical (Pl. 3*c*). They were formed under conditions of

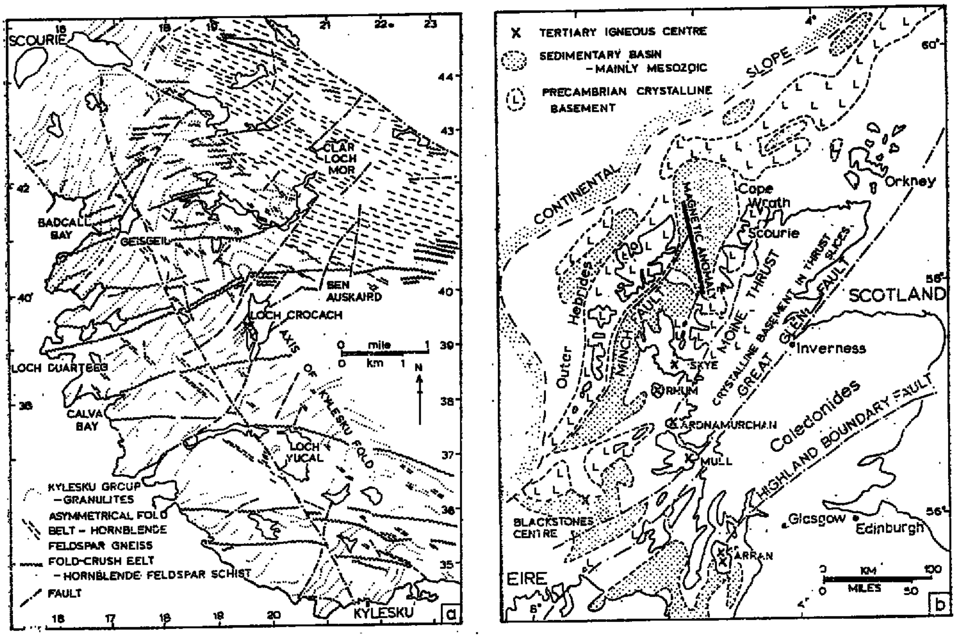


Fig. 7

a — Geological map of part of the Lewisian complex, south of Scourie (*after* Bowes 1969)

b — Outline geological map of northern Britain (mainly based on 1 : 2,500,000 map — The sub-Pleistocene Geology of the British Isles and Adjacent Continental Shelf; Institute of Geological Sciences, 1972) little elevation of temperature, as low as c 150°—200°C in parts (Keppie 1969) but where somewhat deeper crustal levels are now exposed, a weak axial planar cleavage is seen, particularly in fold hinge zones (Pl. 3c; Bhattacharjee 1968). Their axial trend as well as their range of styles corresponds with those of F_8 folds occurring due to tectonic overprinting of basement gneisses elsewhere in Britain (*cf*. Pl. 3*c*, *d*; Text-fig. 6*e*). Correspondence in axial trends of F_4, F_5 and F_6 folds (Fig. 6*a*; Bhattacharjee 1963) is also shown. This and comparability of expression from place to place (Fig. 6*c*, *d*) of these structures formed in the latter part of the Laxfordian episode suggests generally similar competence contrasts in cover and part of the basement at this stage. This is in marked contrast to the differences in deformation shown in cover and basement rocks resulting from the effects of the Svecokarelian episode in Finland and could be related to extensive horizontal movements following the metamorphic phases. The production, by tectonic means, of a part of the basement composed of thin layers below a lithologically layered cover of metasedimentary schists would account not only for general correspondence of the latter part of the structural sequence in basement in northwestern Britain with that in cover in Fennoscandia as well as northwestern Britain, but also for comparability in expression of structural elements.

CONCLUSIONS

The crystalline rocks over large areas of the Presvecokarelian basement show few obvious effects of deformation during the 2000—1500 m.y. period apart from the development of localized ductile shear zones and faults, and some disturbance of isotopic systems.

An extensive polyphase deformational sequence is shown in supracrustal metasedimentary and meta-igneous rocks of both the Karelian and Svecofennian parts of the Svecokarelian belt. Despite differences in expression of some structural elements from place to place, correlation can be made on the basis of structural sequence and there is an overall unity of the complex structural framework from eastern Finland to Sweden.

Correspondence in structural sequences in gneisses and amphibolites affected by the Sveconorwegian event in western Sweden and in basement gneisses and cover metasediments involved in the Laxfordian episode in northwestern Britain, with that in the Svecokarelian belt, suggest the existence of a very large region (Fig. 8) subject to cognate deformation during early to middle Proterozoic times. The size of this region may be indicative of the operation of some form of internal deformation processes, during the c 200—250 m.y. long orogenic stage of the cycle.

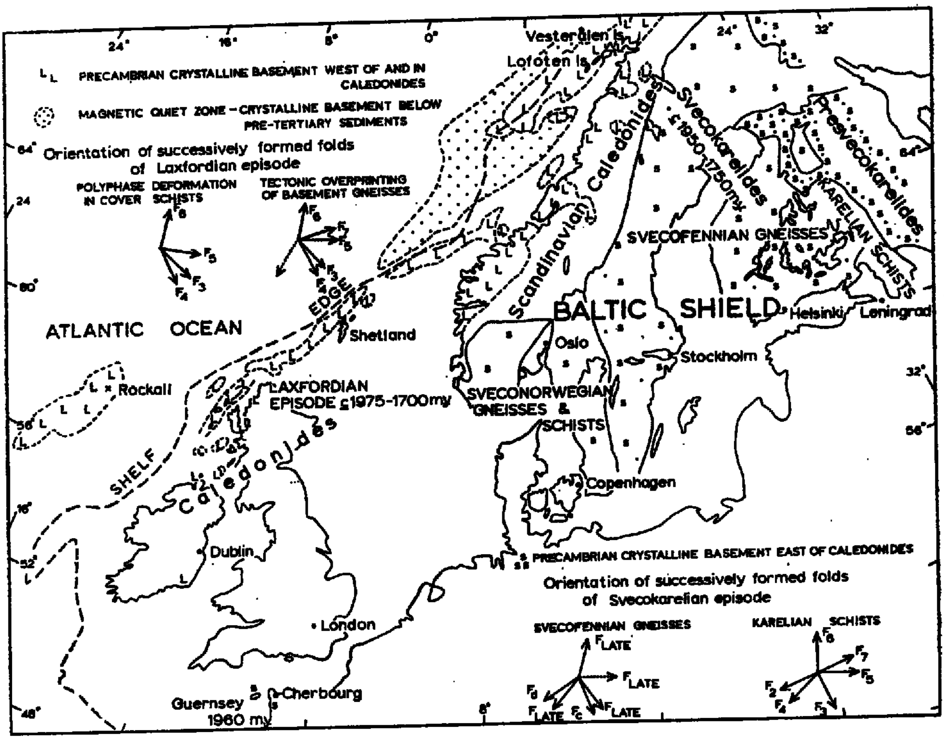


Fig. 8. Outline geological map of the Baltic Shield and correlation of successively formed folds during the period 2000—1500 m.y. ago

Most of the structures formed as the result of deformation of basement rocks during the Laxfordian episode developed in the final c 50 m.y. of the orogenic stage with the response to deformation of quartzofeldspathic gneisses and related rocks being markedly different from that of pyroxene granulites.

The first major faults developed in at least part of the region developed during the post-orogenic cratonic stage of the orogenic cycle c 1700—1500 m.y. ago. The fault pattern now seen in granulites, that were at a low crustal level, appears to be expressed in the pattern of development of geological features formed during late Proterozoic and Phanerozoic times.

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