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Structural sequence in the gneissose complex of eastern Finland as a basis for correlation in the Presvecokarelides

ABSTRACT: Structures and mineral growths formed in seven successive deformational phases in gneisses in late Archaean times form a basis for the determination of chronological sequences from place to place in the Presvecokarelides of eastern and eastern central Finland. Refolded folds and refolded metamorphic rock fabrics, formed under particular P-T conditions and deformed under other P-T conditions, together with a variety of igneous masses whose positions in structural sequences can be determined, provide such a complex framework that the likelihood of random matching is remote while the lack of expression of one parameter does not appreciably reduce the strength of the correlation. Isotopic data demonstrating corresponding events in the gneisses from different parts of the region is an additional factor for correlation. With this being associated with matching complex structural frameworks that show evidence of having been formed under the same successive stress systems, together with matching metamorphic and igneous histories, the gneisses of the Presvecokarelides of eastern and eastern central Finland are interpreted as having formed in one orogenic regime. Corresponding sets of features in the granitoid association of northern Finland indicate that the successively formed stress systems were operative over a large crustal segment, while the expression of the various structural, metamorphic and igneous features and their interrelations correspond, in many respects, to those of orogens whose evolution has been related to the movement of large lithospheric plates.

INTRODUCTION

For large tracts of the Presvecokarelian orogenic belt of eastern, eastern central and northern Finland and adjacent parts of the USSR, the dominant rock types are quartzofeldspathic gneisses and related migmatites. Together with associated amphibolites and metasediments, and a number of sets of acidic, intermediate and basic intrusions, this granitoid association represents the products of a late Archaean cycle of earth history (Text-fig. 1). The U-Pb zircon and Rb-Sr whole-rock isotopic data have shown not only a c. 3.0—2.5 b.y. range of ages, with most in the 2.8—2.6 b.y. interval, but also that these rocks did not have a lengthy crustal history before the Presvecokarelian orogenic episode with no clear evidence indicative of the presence of products of early Archaean times (Kouvo & Tilton 1966; Kouvo & Sakko 1974; Merilläinen 1976; Bowes 1976a; Blais & *al.* 1977a; Gaál & *al.* 1978). Both U-Pb zircon (Kouvo & Tilton 1966) and K-Ar mineral studies (Lobach-Zhuchenko & *al.* 1972) have provided evidence of disturbance and overprinting of the products of late Archaean times. Some K-Ar mineral data have been interpreted as indicative of crustal history going back to 3.3 b.y. ago. However this conclusion is inconsistent with the mutually consistent evidence from Pb-Pb studies (J.-M. Bertrand, *pers. comm.*) as well as from U-Pb and Rb-Sr studies. In addition the confidence with which corresponding Pb-Pb, U-Pb and Rb-Sr isotopic data have been interpreted in comparable crustal environments (*e.g.* Moorbath & *al.* 1975; Moorbath 1976, 1977; Bowes 1978a,b) is in marked contrast to the widely varying interpretations of K-Ar data in complex gneissose terrane (*e.g.* Moorbath & Park 1972; Bikerman & *al.* 1975), while the role of excess argon in mineral lattices is not fully understood. Accordingly the rocks involved in the Presvecokarelian orogenic episode are interpreted as having been derived from the mantle only shortly before the orogenic stage of the Presvecokarelian cycle in late Archaean times.

In addition to the gneissose association, which Gaál & *al.* (1978) consider comprise about two thirds of the exposed Archaean rocks of the crustal segment, there is a greenstone belt association in the Presvecokarelides (Blais & *al.* 1977a; Bowes 1976a; Lobach-Zhuchenko & *al.* 1976; Gaál & *al.* 1978) containing the products of komatiitic as well as tholeiitic and andesitic volcanism (Blais & *al.* 1977b, 1978). These rocks commonly show the effects of intense deformation and generally have middle to upper greenschist facies mineral assemblages. The gneissose association generally shows evidence that it was affected by amphibolite facies conditions, indicative of development in the middle levels of the continental crust.

BASES OF CORRELATION

Stratigraphical methods applied to the study of rock assemblages formed at or near the surface of the earth, and the bases of correlations amongst such assemblages, are not directly applicable to the study of, or correlations amongst, assemblages within the deeper levels of an orogenic zone of mantle-derived material, much of which appears to represent igneous products that cooled, crystallized, recrystallized and were deformed under amphibolite facies conditions. Yet within such rocks, chronological sequences can be established as igneous masses cross-cut pre-existing structures, folds are refolded and metamorphic rock fabrics, formed under particular P-T conditions, are deformed under other P-T conditions. On the basic principles that an intrusion is younger than what is intruded, a fold is younger than what is folded (Hopgood & Bowes 1972, p. 109), the geometry of a cognate set of folds, foliations and lineations is an expression of the stress field operative at the time of formation and that mineral assemblages are expressions of P-T conditions, it is possible to establish complex patterns of crustal evolution from place to place that form the basis for correlation. The greater the complexity of the igneous, metamorphic and structural histories of the gneissose crustal segment, the larger are the number of independent and related factors that can be considered and, accordingly, the stronger is the basis for a reliable correlation. Hence the complexity shown in gneissose terrane, the very feature that is commonly considered to inhibit correlation in gneisses, does, in fact, provide a basis for correlation. With so many parameters of igneous, metamorphic and tectonic derivation available, the likelihood of random matching is remote while the lack of expression of one parameter does not appreciably reduce the strength of the correlation as the many other features are sufficient to establish its lack of expression. If, added to this, there is isotopic data that demonstrates the corresponding age of a specific event in the sequence in different parts of the crustal segment, then this is an important additional factor for correlation. However comparability of age alone does not necessarily imply that the dated rocks originated in the same orogen, just as comparability in lithology alone does not form a sound basis for correlation. But where matching geochronological information is associated with matching complex structural frameworks that show evidence of having been formed under the same successive stress systems, and there is additional matching of metamorphic and igneous histories, the conclusion must be that the rocks originated within one orogenic regime.

With particular reference to the gneissose terrane of the Presvecokarelian orogen of eastern and eastern central Finland (Text-fig. 1), folded folds and folded foliations are common (Text-fig. 2 *e,g* and Pl. 1b), a changing pattern of stress fields and of associated P-T conditions can be established and the emplacement of igneous masses can be demonstrated to separate certain deformational phases (Text-fig. 2 *f,g* and Pl. 3b,c). However successively emplaced igneous masses may show different relationships to the same structural feature from place to place and their value in elucidation of crustal history is dependent upon demonstration of their particular positions in the overall structural sequence, *e.g.* having demonstrated a succession of quartzofeldspathic intrusive masses, their progressive changes in composition (Gaál & *al.* 1978, p. 203) can be used as an indicator of changing environments of derivation. In addition, the sequence of events established in the gneissose terrane of the Presvecokarelides has a pattern that is not only similar from place to place, but also similar to that shown in many other intensely polyphase deformed mobile zones *viz.* early deformational phases are characterized by the development of intense penetrative foliation associated with the formation of tight to isoclinal folds (Text-fig. 2 *b,c* and Pl. 1a), middle deformational phases are characterized by the development of asymmetrical folds with mobile quartzofeldspathic material in hinge zones and localized new axial planar schistosity (Text-fig. 2 *c,d,e* and Pl. 2a,b), and later deformational phases are characterized by open, upright folds, cleavage formation that passes into brittle fracture and a variety of granitic intrusions (Text-fig. 2 *h,k,l* and Pl. 4a,b,d). With such a pattern of development expressed over large tracts of schistose and gneissic terrane in orogens whose evolution has been related to the movement of large lithospheric plates, for example the Caledonides (*cf.* Bennison & Wright 1969, pp. 142—143; Bowes & Wright 1967, 1973; Wright 1976) and the Svecokarelides (*cf.* Bowes 1976b, 1980), the structural pattern expressed in the Presvecokarelian orogen is also likely to be present over a large crustal segment. This, together with the demonstration of the nature of the stress patterns that controlled the sequence of structures present in these products of late Archaean times, means that the criteria for correlation exist in this gneissose terrane. It also means that the criteria exist for discrimination of the products of the Presvecokarelian orogen form other orogens (*e.g.* Svecokarelides), whose products resulted from a different sequence of stress patterns (*cf.* Hopgood 1973).

STRUCTURAL SEQUENCE IN THE KUOPIO DISTRICT

The *c.* 2800 m.y. old basement gneisses of the Kuopio district of eastern central Finland (Text-fig. 1) occur in the cores of fold interference domes formed during the *c.* 1900—1800 m.y. old Svecokarelian episode (Preston 1954). Road-cuttings combined with natural exposures, particularly in the south-western part of Kuopio and at Petosenmäki on the E5 road 7 km to the south of Kuopio, permit study of complex fold patterns in three-dimensions and elucidation of an extensive sequence of tectonic, metamorphic and igneous events (Text-fig. 2 and Pls 1—4). The sequence of structures in the overlying schists, and their attitudes, indicate that the superimposed deformation during the Svecokarelian orogeny has no obvious structural imprint on the exposed basement rocks in the Kuopio district although the isotopic systems of minerals, including zircon, were disturbed (Kuovo & Tilton 1966). While it is possible that ductile shear zones affecting basement rocks are present below unexposed areas, particularly between domes, the formation of the domes can be explained as part of the retrocharriage stage of a plate tectonic evolutionary model of the Svecokaralides, following the formation of nappes in the cover rocks and before the development of regionally expressed asymmetrical folds (Bowes 1976b). Accordingly the structural patterns in the basement and the rock fabrics are taken to represent those of the Presvecokarelian orogen that have undergone subsequent vertical movements, but not rotation.

For convenience and ease of reference, the successive deformational phases are referred to as D_1, D_2, D_3 etc. with folds (F), foliations-schistosities-cleavages (*S*) and lineations (*L*) correspondingly numbered sequentially. The earliest recognised foliation (S_1) pre-dates the first recognized set of folds to which the second foliation (S_2) is axial planar. These folds are labelled F_2 (not F_1) so that cognate sets of structures have corresponding numerical subscripts (F_2, S_2 and L_2 formed during D_2; F_3, S_3 and L_3 formed during D_3 etc.). This follows the usage of Bowes (1976a) for the Presvecokarelides rather than that of Bowes (1975; *cf.* also Bowes 1978a) in which the earliest recognised foliation is not numbered and the first fold set labelled F_1 with its genetically associated features S_1 and L_1.

The earliest recognised structures, the S_1 foliation of the *first deformational phase*, is deformed by folds (F_2) to which the most prominent and widespread foliation (S_2) in the gneisses is axial planar (Text-fig. 2*a*,*b*,*c* and Pl. 1a). The S_1 foliation is best shown in amphibolitic units where there is evidence of mineral banding resulting from metamorphic segregation, presumably at amphibolite facies conditions (*cf.* Bowes & Park 1966). It is also shown in the quartzofeldspathic gneiss where dimensionally aligned hornblende crystals and, to a lesser extent, biotite flakes are deformed around the hinges of F_2 folds (Bowes 1976a, Text-fig. 4*a*,*b*,*c*). However in many F_2 hinge zones new hornblende and biotite crystals define the S_2 axial planar cleavage with only remnants of S_1 remaining (Text-fig. 2*c*). No folds of the first deformational phase have been recognised, nor have lineations of this phase been seen. With so much of the rock of the district being of igneous derivation, it is possible that S_1 represents, at least in considerable part, flow banding in largely concordant, deep level, plutonic intrusions with subsequent mimetic recrystallization and enhancement by metamorphic differentiation under amphibolite facies conditions operative at the level of emplacement.

The foliation of the quartzofeldspathic augen gneiss, which is the dominant rock type at some localities, such as Petosenmäki, is axial planar to F_2 folds (Pl. 1a) and is a product of the *second deformational phase.* There is much variation in the amount of flattening shown by the large feldspar crystals which, at least in part, could represent modified original phenocrysts of oligoclase. However, in many instances, S_2 is penetrative although its parallelism with S_1 on the limbs of isoclinal F_2 folds (Text-fig. 2*b*) means that much of the strong regional foliation is transposed S_1 (S_{1-2}). How far some of the S_2 represents an enhancement of flow banding in igneous masses later than, but concordant with S_1, is not known. Nor is it known whether weak expression of S_2 represents superimposition on a post-S_1, non-foliated, porphyritic rock.

The F_2 folds are shown in amphibolites, interbanded amphibolites and gneisses and in gneisses, many being intrafolial (Pl. 1a, b, c; Fig. 2*a*, *b*, *c*, *d*, *e*, *j*). Most are recumbent and tight, a few are close to open and some are isoclinal. Limb thickness is commonly much less than hinge thickness, indicating operation of a flow mechanism during formation, while development under amphibolite facies conditions is indicated by the associated mineral growths. Where observed, fold hinges trend WNW-ESE to NW-SE or this direction can be determined by removing the effects of superposed deformation. This direction is interpreted as corresponding to the minimum stress direction during the second deformational phase, at which time the direction of maximum stress was near to vertical.

Structures of the second deformational phase are themselves deformed with the S_2 foliation, as well as the S_1 foliation, defining the shapes of later formed folds (Text-fig. 2*d*). Refolded F_2 folds occur (Text-fig. 2c and Pl. 1b) with folds (F_3) of the *third deformational phase* generally being asymmetrical, upright and open (Pl. 2a) although axial planar dips as low as 60° have been recorded. The F_3 folds change shape along their axial traces (Text-fig. 2*d*), a feature characteristic of flexural folds, some show axial planar cleavage that is commonly, but not completely, localized in hinge zones (Text-fig. 2c, *e*, *g*) and both rodding and intersection lineation (L_3) occur. Quartzofeldspathic vein material is often present in F_3 hinge zones with the thin, elongate "veins" generally having more diffuse margins than the patchy masses (Text-fig. 2*d*). In places the mobile neosome penetrates and disrupts amphibolitic units giving rise to localized patches of agmatite (Pl. 2b). The F_3 fold hinges show more than one trend, a feature not related to superimposed deformation. NNW, N, NNE and NE trends are shown (Text-fig. 2*d*), with the NNE to NE trend predominating. The upright attitude of the folds indicates that the maximum stress at the time of the third deformational phase was subhorizontal.

Basic to intermediate, composite minor intrusions cross-cut both F_3 folds and S_3 cleavage (Text-fig. 2*g* and Pl. 3b, c). Locally they define arcuate forms resembling tight to close folds, but both the F_3 fold hinges and S_3 which they intrude are not disposed in corresponding structures (Text-fig. 2*j* and Pl. 3a). However in some places both the minor intrusions and the structures they cross-cut define very open, upright folds with NW-SE axial trends (Text-fig. 2*f*). Corresponding folds (F_4) of the *fourth deformational phase* are also defined by curved F_3 axial planes and S_3 (Text-fig. 2*g*) but most occur on the long limbs of F_3 folds. There their position in the structural sequence is determined by the cross-cutting relationship of a NW-SE cleavage to F_3 fold limbs, a cleavage which is parallel to the axial planar cleavage (S_4) to F_4 folds (Text-fig. 2*h*). Its cross-cutting relationship to the margins of the minor intrusions that were emplaced after F_3 fold development also established its position in the overall sequence of events. In some amphibolites a healed cleavage containing epidote is expressed as ribs on the weathered surface (Pl. 4c). This and related mineralogical evidence indicate lower greenschist facies conditions while the attitudes of the structures

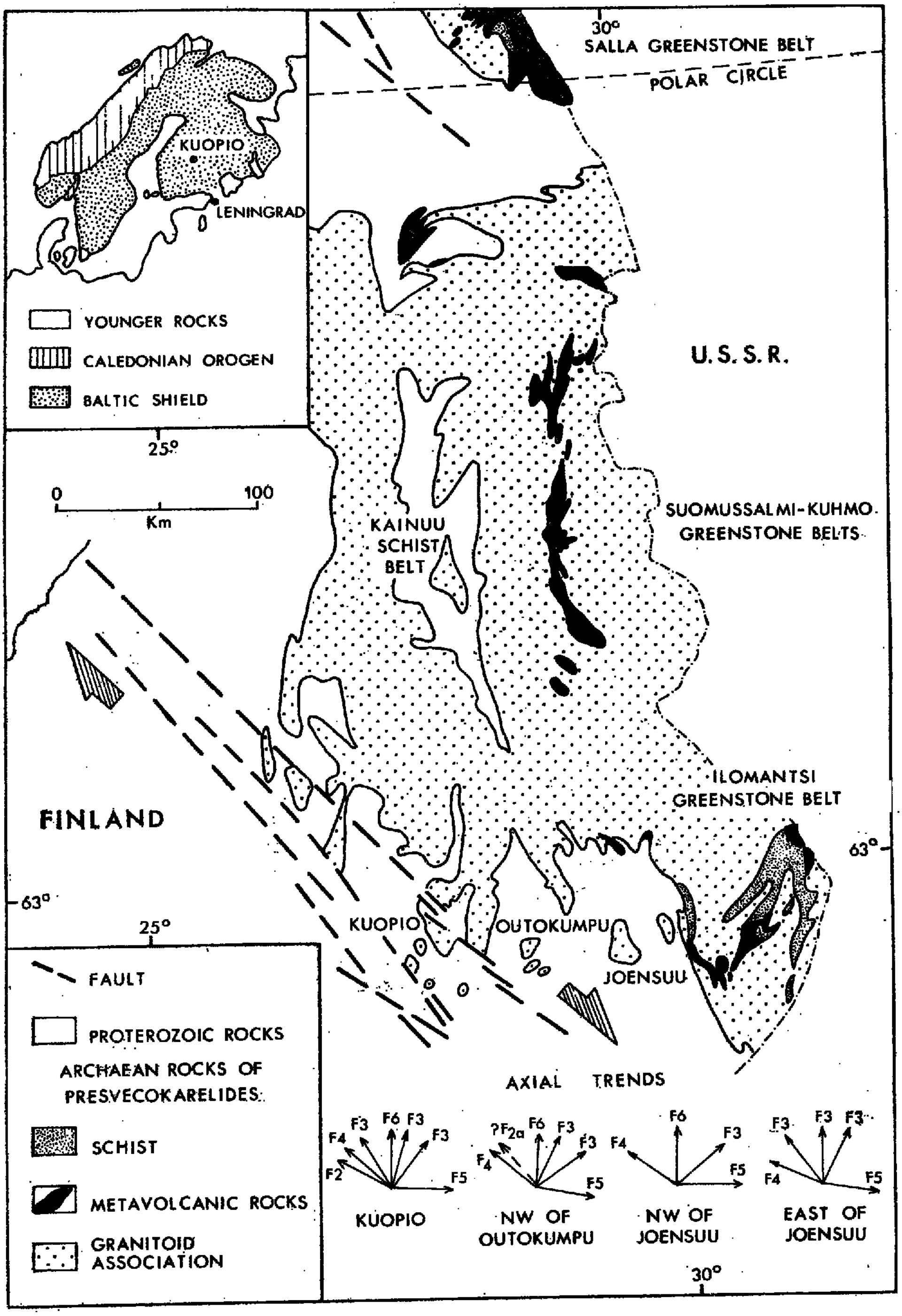


Fig. 1. Outline geological map of Archaean terrane to show the investigated part of Finland (*after* Gaál & *al.* 1978) and axial trends of folds

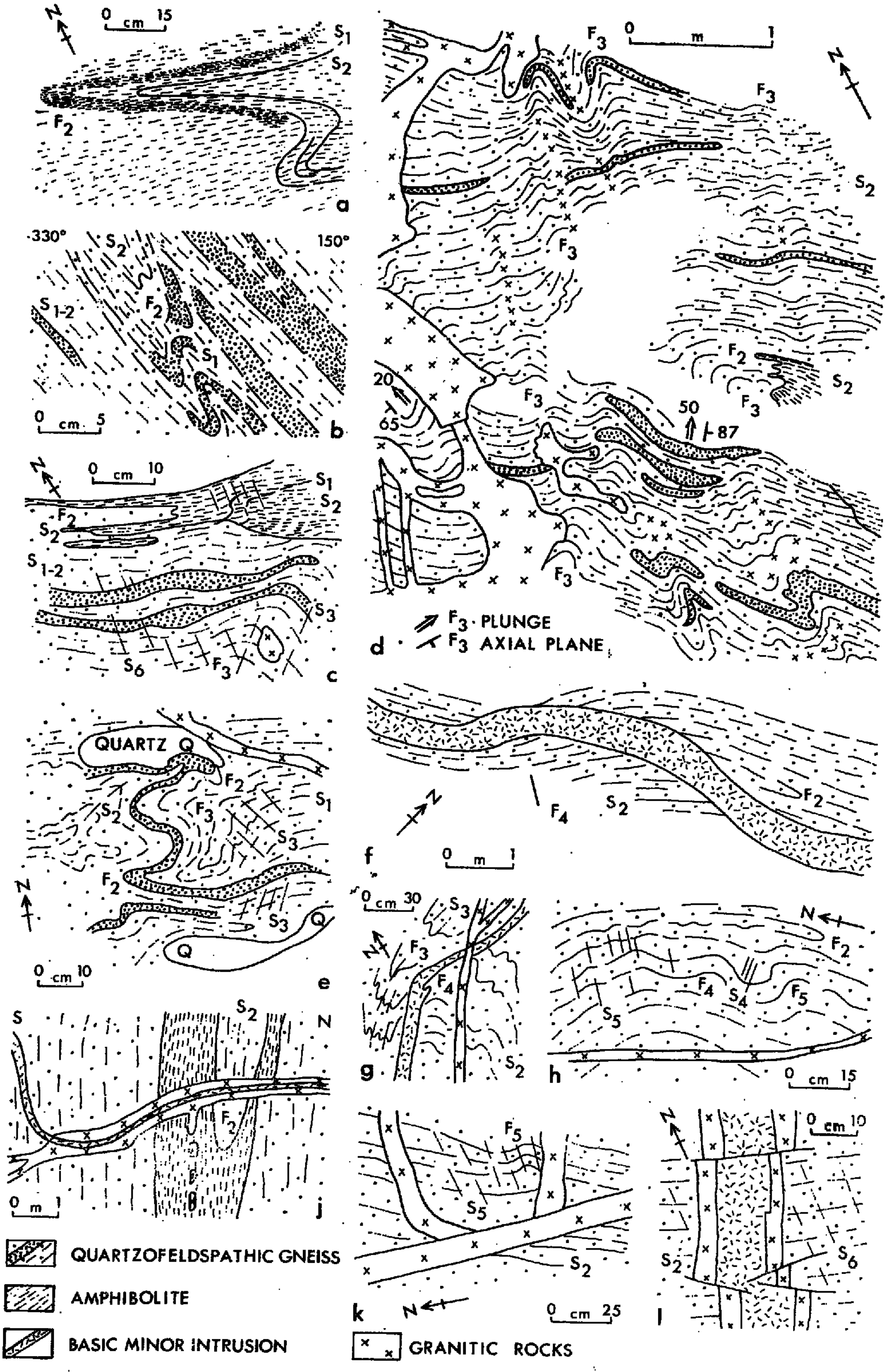


Fig. 2. Structures in gneisses: *a, c, d, e, j, k* from Petosenmäki, Kuopio district; *b, f, g, h, l* from area SW of Kuopio

mean that a subhorizontal NE-SW maximum stress and a subhorizontal NW-SE minimum stress can be deduced.

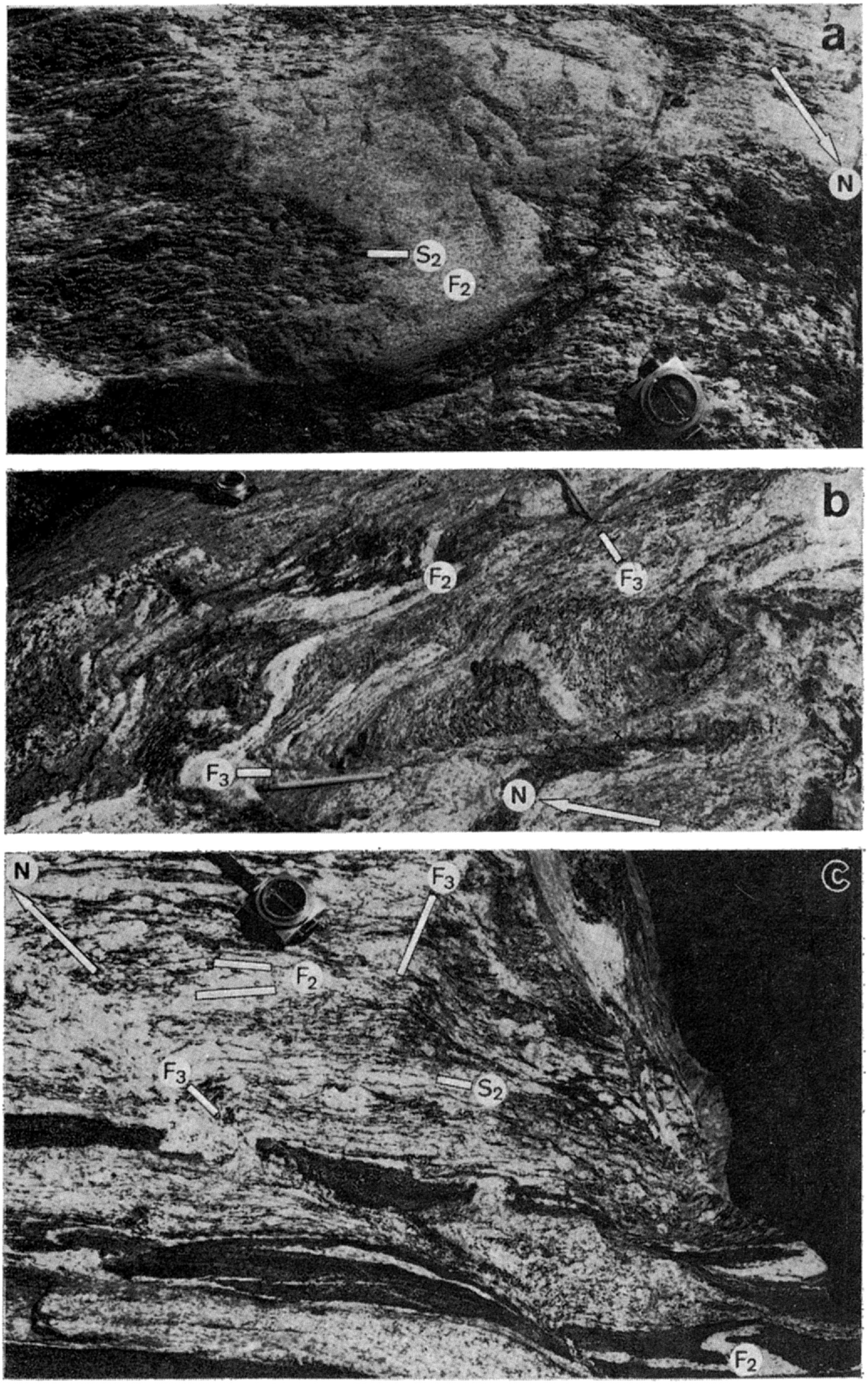
Like the F_4 folds, folds (F_5) of the *fifth deformational phase* are most commonly seen on the long limbs of F_3 folds. They are upright, generally open, commonly monoclinal (Pl. 2c) and have approximately E-W axial trends. Juxtaposition with F_4 folds with the opposite sense of movement (*e.g.* sinistral F_5 with dextral F_4 — Text-fig. 2*h*) gives fold forms resembling box-folds but whose development was not conjugate. Some S_5 cleavage is developed, particularly in fold hinge zones where its axial planar attitude is clear. The F_5 hinge zones also form the locus of emplacement of discrete granitic veins (Text-fig. 2*k*) although individual veins often swing away from this position and, together with granitic veins that were emplaced after folds (F_6) and cleavage (S_6) of the *sixth deformational phase,* locally contribute to areas of intense injection (Pl. 4a). Like F_5 folds, F_6 folds are upright, generally open, commonly monoclinal and have granitic vein material in hinge zones (Pl. 4b). However, their axial trend is approximately N-S indicating that while the maximum stress at that time was still disposed in a subhorizontal plane, as it had been since D_3, its direction had changed yet again as it had between D_3 and D_4 and D_4 and D_5. The S_6 cleavage, which is clearly axial planar to F_6 in some exposures, is seen in many outcrops (Text-fig. 2*l*) including in some amphibolites where, like S_3, S_4 and S_5, it is expressed as ribs due to some reconstitution along the S_6 planes (Pl. 4c).

The *seventh deformational phase,* and the last recognised in the c. 2800 m.y. old gneisses of the Kuopio district, is expressed as very localized zones of folds which pass into brittle fractures trending ESE and SE (Text-fig. 2*l*). Such structures do not appear to be common in the exposed rock faces, but could be more common in areas covered by glacial debris. Their late development is indicated by offsets in granitic veins, including those assigned to the D_6 phase.

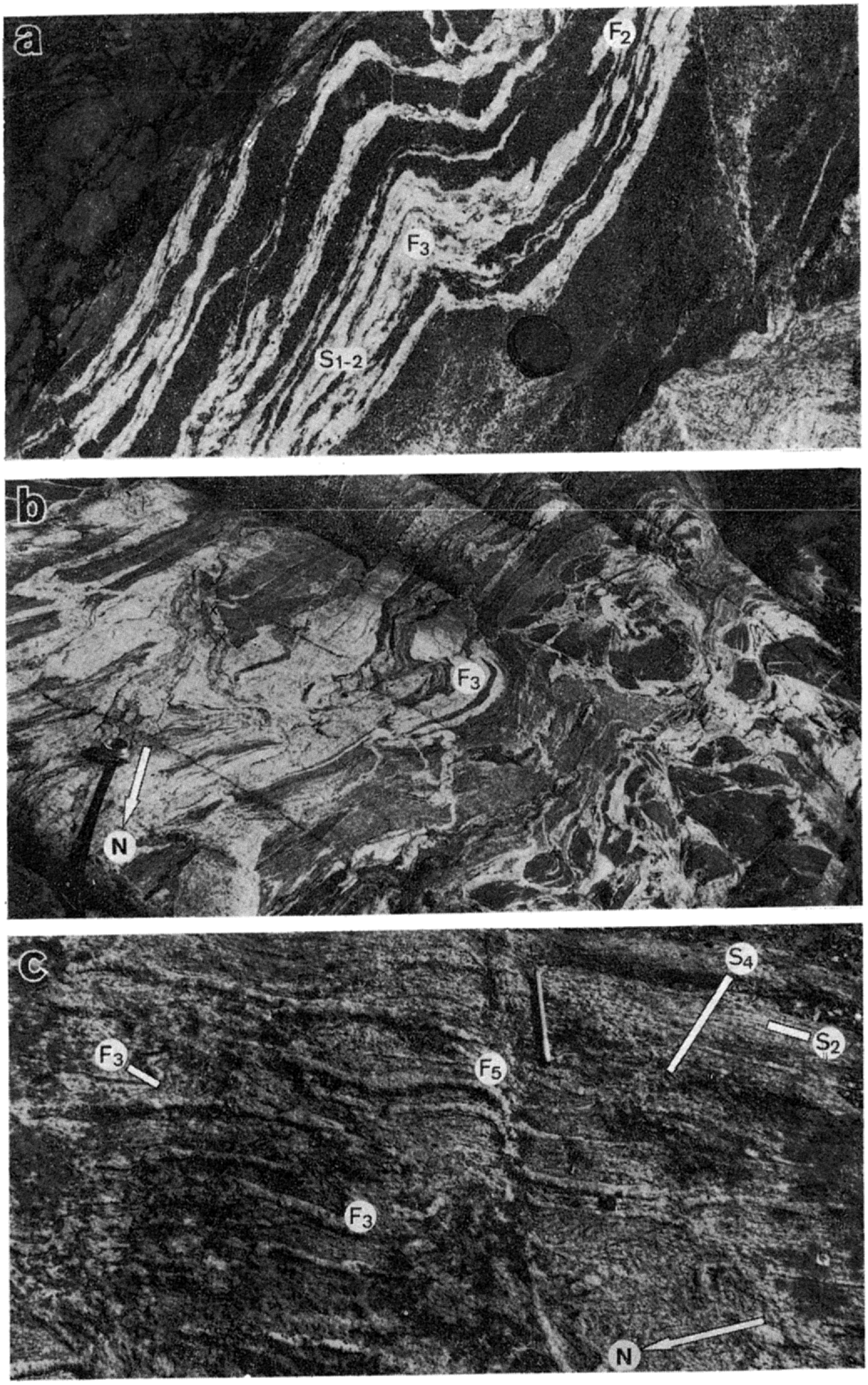
STRUCTURAL SEQUENCE IN OTHER PLACES

The structural sequence that is so clearly represented in the gneisses of the basement of the Kuopio district, and whose development there during Archaean times can be established, is seen in the gneisses of the Presvecokarelides in many other parts of eastern Finland. Variations in expression do exist, but the existence of so many features of structural and metamorphic derivation, each with its respective trend, permit the absence of an individual feature, or the presence of an additional one, to be determined. For example, the composite basic to intermediate minor intrusions emplaced between D_3 and D_4 in the Kuopio sequence have not been recognised in the gneissose terrane of the Sotkuma dome, 20 km NW of Joensuu, where expression of six of the seven sets of structures recognized at Kuopio have been observed (Text-fig. 1; cf. *also* Bowes 1976a, Fig. 4*e*—*b*). The set not recognized is that of D_7, which is only locally expressed at Kuopio, while an additional set of basic minor intrusions emplaced between D_2 and D_3 can be shown to occur.

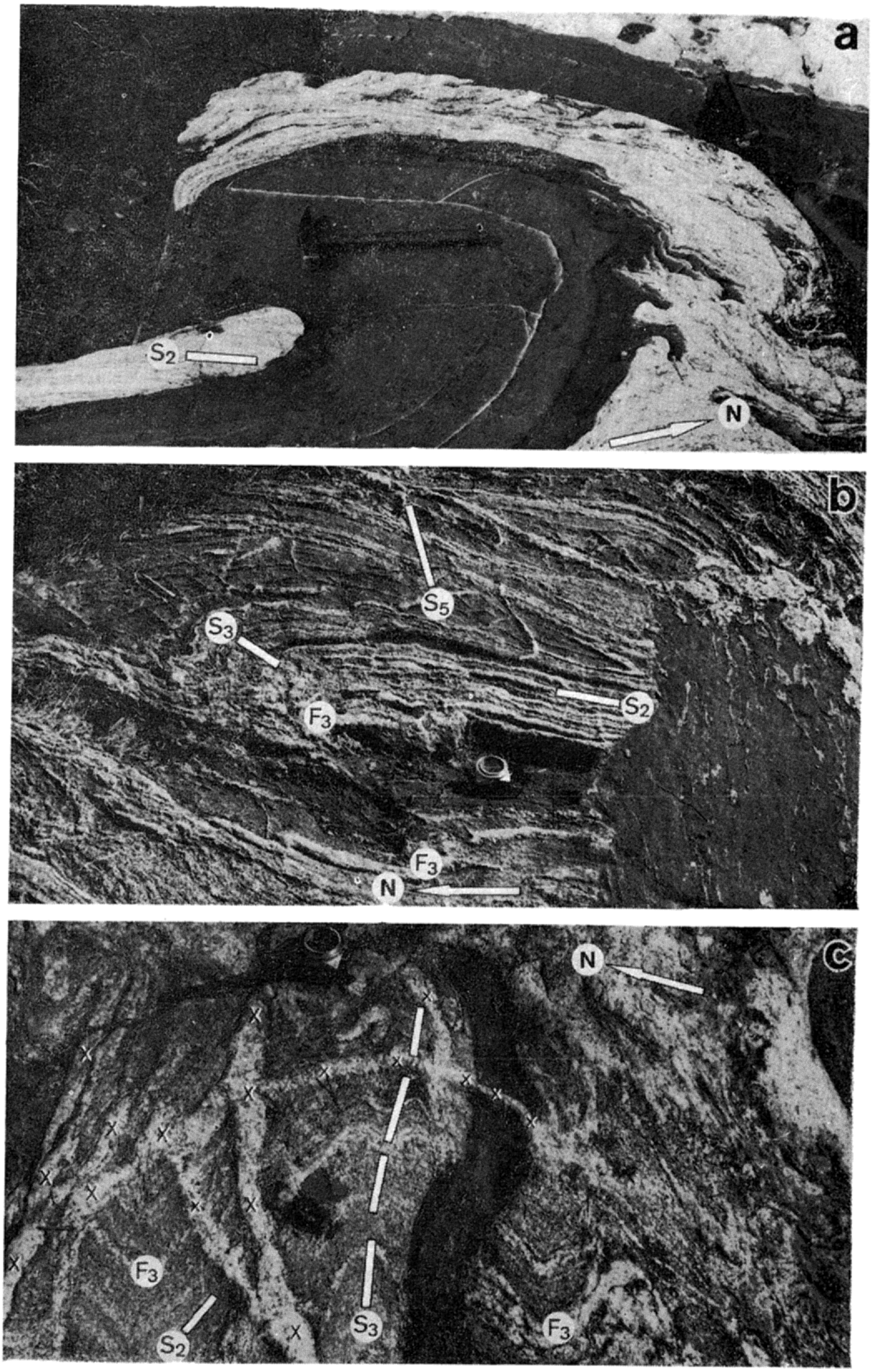
Folds that appear to have been developed between D_2 and D_3 have been observed in the gneisses of the basement 40 km NNW of Outokumpu (?F_{2a} in Text-fig. 1) where structural and metamorphic elements corresponding to whose of D_1 to D_6 of the Kuopio sequence are expressed, although F_3 axial trends are only in the NE quadrant and locally L_3 is prominent (Bowes 1976a, Fig. 4*f*). Likewise in the vicinity of Kotalahti, 30 km south of Kuopio, evidence of seven deformational phases has been observed, corresponding to D_1 to D_6 of the Kuopio



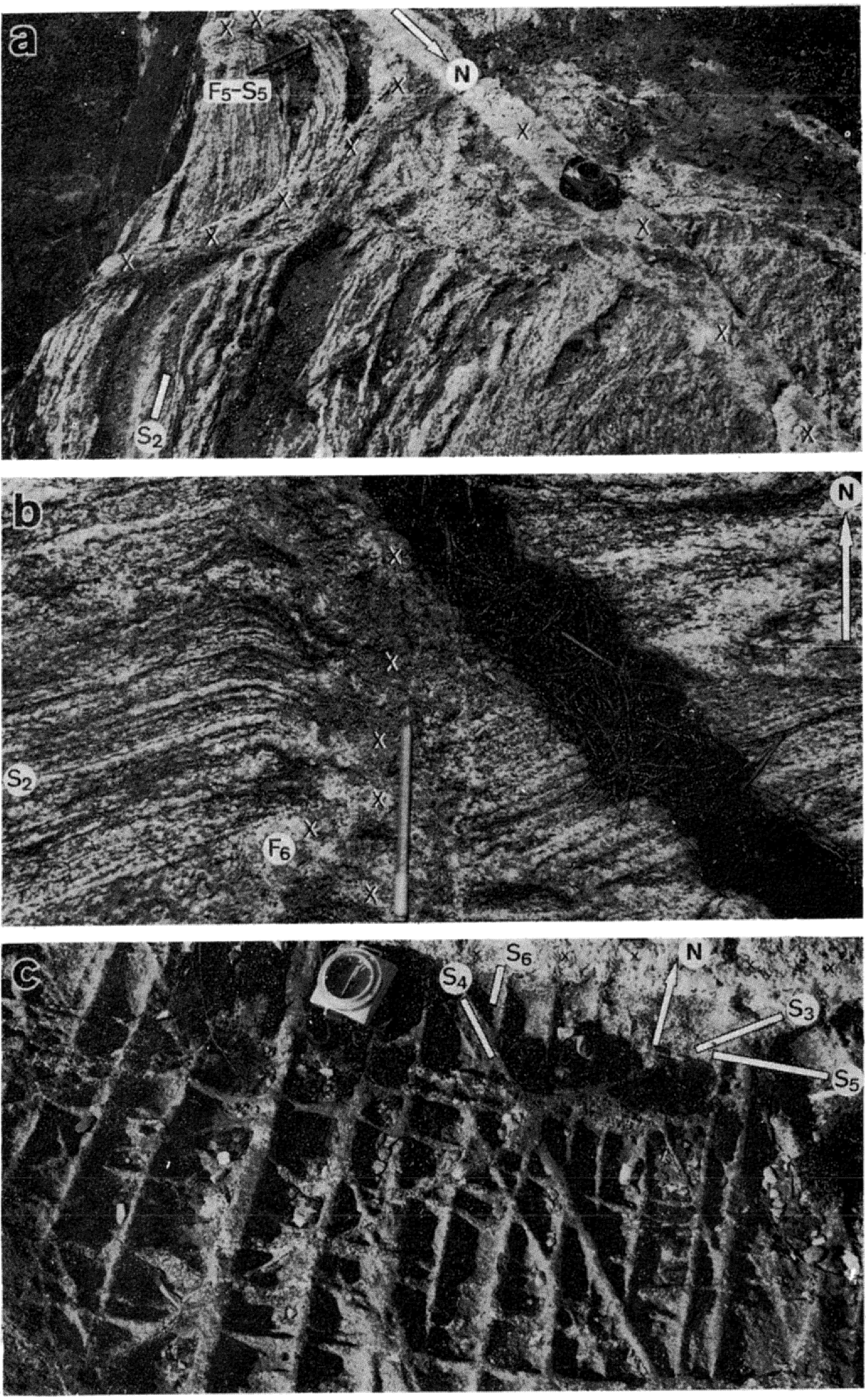
Structures in quartzofeldspathic gneisses with siliceous and amphibolitic bands; Petosenmäki, Kuopio district



Structures in gneisses: **a**, **b** Haminalahti, Kuopio district; **c** SW of Kuopio



Structures in gneisses, basic minor intrusions and granitic veins; SW of Kuopio



Structures in gneisses and amphibolite; SW of Kuopio sequence but with an additional set of tight folds between D_2 and D_3. These tight folds deform both a strong amphibolite facies foliation (S_1) and tight to isoclinal folds (F_2), many of which are rootless and with which is associated an axial planar mineral growth. (Some of these F_2 folds are clearly displayed in three--dimensional road-cutting exposures at the major road junction on the E4, 19 km south of Kuopio). At Kotalahti, like at Kuopio, F_3 axial trends are NW, N-S and NNE to NE (*cf.* Text-fig. 2*d*), while F_4, F_5 and F_6 not only have expressions similar to those in the gneisses at Kuopio, but also have corresponding axial trends *viz.* NW, E-W and N-S, respectively.

Evidence that the extensive sequences of polyphase deformational and polymetamorphic features determined in the gneisses of the Presvecokarelides of eastern Finland are expressions of late Archaean activity, and not due to Proterozoic earth movements associated with the formation of the Svecokarelides, is given by the cross-cutting relations of an early Proterozoic suite of basic minor intrusions to at least D_3 features in the polyphase deformed gneisses between Joensuu and Ilomantsi (Text-fig. 1; *cf. also* Sakko 1971; Bowes 1976b, Fig. 1). Effects of the earth movements associated with the Svecokarelian orogeny on the gneisses of the basement appear to be largely confined to disturbance of isotopic systems of minerals (Kouvo & Tilton 1966; Lobach-Zhuchenko & *al.* 1972), at least over large areas, with structural and metamorphic features remaining largely extant.

The deformational features and sequence recorded by Gaál & *al.* (1978) in Archaean rocks of Finland, north of the Polar Circle, show general correspondence with those described here from further south (Text-fig. 1). An S_1—S_2 composite foliation was formed at greenschist facies conditions with approximately E-W trends being expressed by the products of D_2. Folds (F_3) deforming S_1 and S_2 and related to strong development of L_3 have an NNE to NE axial trend while F_4 folds are upright and with a NW axial trend. Folds of the fifth and sixth deformational phases have E-W and N-S axial trends, respectively, and, like the products of D_5 and D_6 at Kuopio and other places in eastern central Finland, are not prominent. Gaál & *al.* (1978) interpret the latter part of the sequence as representing activity during early Proterozoic times. The validity of this interpretation awaits regional structural studies related to geochronological investigations. However, the correspondence of at least part of the sequence of events in late Archaean times in the granitoid association of Lapland with that in the granitic gneisses further south, indicate the large crustal region over which successively developed stress systems were operative at that time.

DISCUSSION

Correspondence in both structural sequence and the orientations of successively formed structures in the polyphase deformed gneisses of the Presvecokarelides in part of eastern and eastern central Finland forms a basis for correlation. Evidence for the extension of the same tectonic regime to northern Finland suggests the operation of a number of successively formed stress systems over a considerable crustal segment during late Archaean times. Add to this the evidence that (1) the early formed deformational phases are characterized by the development of intense penetrative foliation associated with the formation of often rootless tight to isoclinal folds, (2) middle deformational phases are characterized by the development of asymmetrical folds with mobile quartzofeldspathic material in hinge zones and localized new axial planar schistosity and (3) later deformational phases are characterized by open, upright folds, cleavage formation that passes into brittle fracture and a variety of granitic intrusions, and the Presvecokarelian orogen must be interpreted as having a history of development that corresponds, at least in certain respects, to orogens whose evolution has been related to the movement of large lithospheric plates.

Consideration of aspects such as heat flow and the nature of the mantle suggest that tectonic regimes in Archaean times should show marked differences compared with tectonic regimes in Proterozoic and Phanerozoic times (Sun & Hanson 1975; Drury 1978), with any down-going lithospheric plates being at a much shallower angle than in present day analogues and any zones of magmatism and tectonic mobility much wider. Such conditions would result in the successive development of stress systems with configurations like those that can be inferred from the characters of the gneisses of the Presvecokarelides of part of eastern Finland. And these stress systems would have been operative over very large regions. This is consistent with the marked similarities shown not only by the rock assemblages of eastern and eastern central Finland formed in late Archaean times, but also by the products of the Presvecokarelian episode in northern Finland and those of comparable age, of the Scourian episode of northwestern Scotland (Bowes 1975, 1976b). If associated with such a major, wide zone of plutonism there were back-arc marginal basins containing volcanic, sedimentary and plutonic types, then the evolution of the crustal segment could result in the development of greenstone belts in and on a dominantly tonalitic-grandioritic gneiss complex (Tarney & *al.* 1976; Bowes 1978a, p. 69). This is the association that dominates the Presvecokarelides of the Baltic Shield. Hence correlation within at least the widespread granitoid association on the basis of the polyphase structural and metamorphic sequence not only provides means of delineating the extent of this crustal regime, but also provides an avenue of elucidation of the nature of processes operative in late Archaean times.

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