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Geometry of sheath folds and related fabrics at the Luikonlahti mine, Svecokarelides, eastern Finland

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Abstract—The Luikonlahti Cu–Co–Zn sulphide ore deposit is hosted by metasediments associated with serpentinites in the 1.97 Ga old Outokumpu assemblage in the Svecokarelides of eastern Finland. Polyphase deformation of the host rocks, a history shared by the ore body, includes a phase of sheath fold propagation. A modified vergence rule, utilizing only the intersection geometry of planar fabric elements, permits recognition of these extremely curvilinear folds in poorly exposed terrain. The detailed geometry of these rocks is independently resolved from borehole and underground stope records. Sheath fold propagation occurred during D_2, the second phase of regional deformation. In the Kaavi district D_2 major structures are either thrusts or thrust-related. The Luikonlahti sheaths are located in a steeply dipping shear zone formed during this deformation episode.

INTRODUCTION

THE Luikonlahti mine is located in the parish of Kaavi, eastern Finland, and exploited a low-grade, strata-bound Cu–Co–Zn sulphide deposit between 1968 and 1983 (Eskelinen *et al.* 1983). The ore body was of the strata-bound Outokumpu type (pyrrhotite–pyrite–chalcopyrite–sphalerite) hosted by a metamorphosed chemogenic quartz rock within the 1.97 Ga old Outokumpu assemblage, a distinctive group of serpentinites, black metapelites, carbonates, skarns and amphibolites forming part of the early Proterozoic Karelian Supergroup (Huhma & Huhma 1970, Huhma 1975, 1976, Gaál *et al.* 1975, Koistinen 1981, Park in press). Though Huhma (1971, 1975) produced a revision of the 1:100,000 geological map, based on a 1:20,000 survey, and Park (1983) and Park & Bowes (1983) presented the results of structural mapping of part of the Kaavi area, including an interpretation of the structure of the Luikonlahti mine site, detailed information had not been available since the original survey (Frosterus & Wilkman 1920, Väyrynen 1939). These recent overviews depended on access to Huhma's (1971) survey, carried out in 1960–1962 before substantial drilling and mining operations began.

The immediate area around the mine is poorly exposed, and the closure of the mine,with subsequent release of data by the operating company, Myllykoski Oy, presented the opportunity to investigate this structure with good three-dimensional control from borehole and stope records. These permit construction of serial section through the mine area revealing a sheath structure; the first such structure reported from the Svecokarelides. Despite limited surface outcrop this structure was predictable from fabric relationships seen at the surface. A modified vergence rule, similar to that using minor fold and cleavage–bedding geometry, but avoiding any preconceptions of cylindrical fold geometry has been developed, which should be applicable in mapping similar poorly exposed high-grade terrain elsewhere.

Flooding of both surface and underground workings has precluded detailed kinematic analysis in this initial study; what follows is a geometrical analysis of the form of the Luikonlahti structure and associated fabrics.

GEOLOGICAL BACKGROUND

The bedrock of the Luikonlahti area (Figs. 1 and 2) consists of three major units, the Archaean Presvecokarelian basement gneiss complex (Presvecokarelides), the early Proterozoic supracrustal cover of the Karelian Supergroup, and the early–middle Proterozoic Maarianvaara granite. For the purposes of this account the basement complex may be regarded as homogeneous granodioritic orthogneiss. The supracrustal cover consists of two tectono-lithostratigraphic sub-divisions, an autochthon–para-autochthon containing mica schists and meta-psammites (Kalevian) overlying meta-arenites, phyllites and amphibolite (Jatulian), that in turn rest unconformably on the basement gneiss complex, and an allochthonous Outokumpu Nappe containing mica schists and meta-psammites (Kalevian), with the Outokumpu assemblage at its structural and stratigraphic base (Huhma 1975, Park & Bowes 1983).

The Outokumpu assemblage (Park 1984) consists of altered meta-igneous rocks (largely serpentinized dunite and saxonite), metavolcanic amphibolites and greenschists, carbonates, Cr-rich calc-silicate skarns, metachert and black carbonaceous metapelites (black schist) with lamellae of fuchsite schist and talc schist. The outcrop of this unit across the Savo-Pohjois Karjalan region defines the Outokumpu mining district (Vähätalo 1953, Gaál *et al.* 1975, Koistinen 1981) and the metacherts are host to a number of stratabound, origi-

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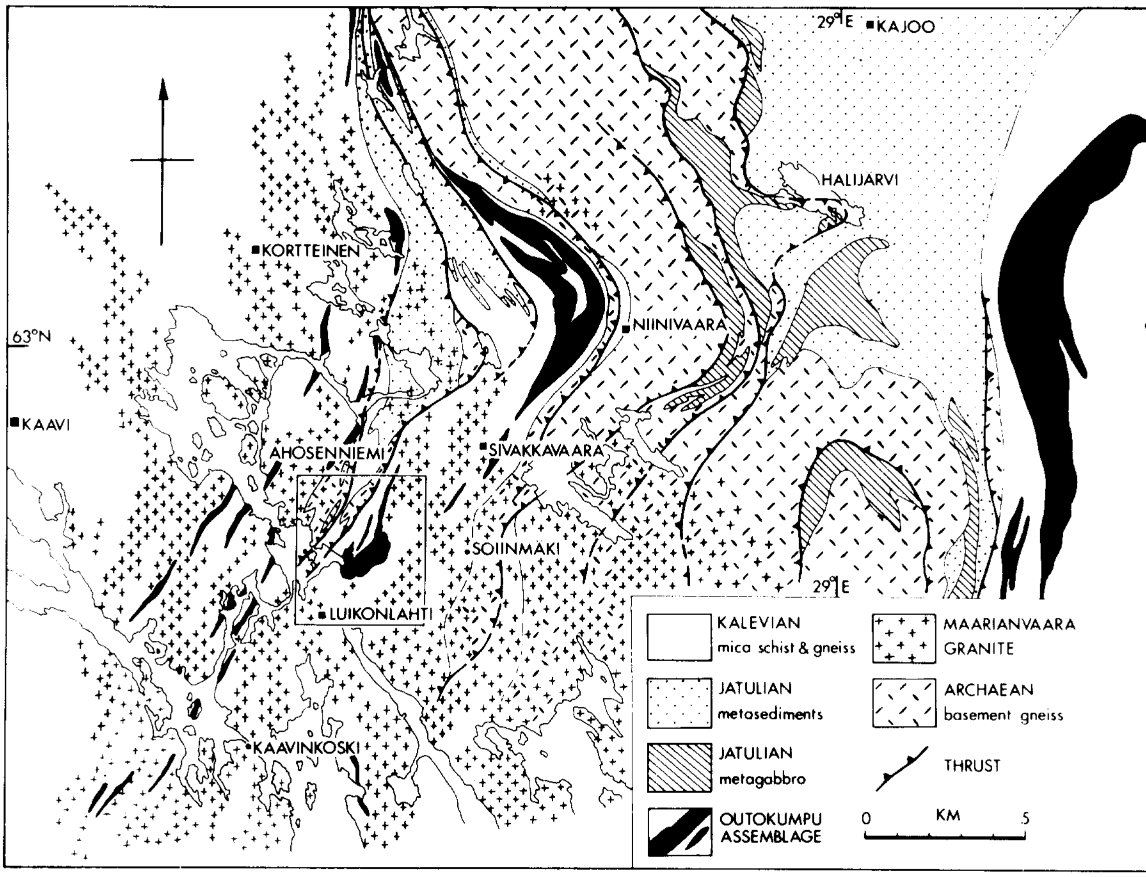


Fig. 1. Outline geological map of the Kaavi district, after Huhma (1971) and Park & Bowes (1983). Localities cited in the text are either here or on Fig. 2. The box delineates the area covered by Figs. 2 and 3.

nally stratiform, metamorphosed and deformed Cu–Co–Zn sulphide ore bodies (viz Outokumpu and Luikonlahti).

Both cover and basement rocks in the area display the effects of deformation and metamorphism imposed during the Svecokarelian orogeny. Park & Bowes (1983) recognized four penetrative and pervasive generations of structural elements in the cover rocks, plus several more locally developed features; a summary is included here as Table 1.

Table 1. Deformation sequence in the cover rocks of the Kaavi district; after Park & Bowes (1983); includes the modified position of the Maarianvaara granite (see text). Dates are from Huhma (1981, 1986)

	Emplacement of the Outokumpu Nappe (post-1.97 Ga) Development of pressure solution fabric—segregation
D_1	Rare isoclinal folds (F_1), recrystallization of segregation (S_1) with biotite growth in mica schists and gneisses, transposition of S_0 producing composite fabric S_{0-1}
D_2	Open to tight folds (F_2) overturned to the E; axial planar schistosity (S_2); thrusts in overturned limbs. Peak of local metamorphism (600–700°C, 2–4 kbars), partial melting produces neosomes in mica schists and gneisses. Earliest Maarianvaara granitoids (quartz-diorite, granodiorite, granite) intruded.
D_3	Open, upright folds (F_3); axial planar cleavage (S_3), local crenulation. Onset of metamorphic retrogression. Probable maximum intrusion of Maarianvaara granitoids.
D_4	Open folds plunging SW (F_4); axial planar cleavage (S_4), local crenulation. Continued metamorphic retrogression. Last Maarianvaara granitoids intruded (*ca* 1.87 Ga).
D_{late}	Several sets of late fractures. Post-tectonic microtonalite and lamprophyre dykes intruded (1.86–1.83 Ga).

The Maarianvaara granitoid suite was emplaced as a complex of discordant sheets largely cutting the folds and fabrics related to D_3 (F_3, S_3) and showing a pre-, syn- and post-tectonic relationship to those of D_4 (F_4, S_4).

In the rocks of the Kaavi district metamorphic grade is difficult to determine exactly, but Park (1983) presented evidence for a syn-D_2 peak of *ca* 600–650°C at 2–4 kbars, overprinted by a pervasive syn-D_4 greenschist-facies retrogression. Evidence for *in situ* development of neosome by partial melting in the mica schists and gneisses SW of the mine is consistent with this temperature, but Väyrynen's (1939) report of kyanite around the mine site suggests pressures in excess of 5 or 6 kbars.

Local structural sequence (Kaavi district)

Deformation of the rocks at Luikonlahti is polyphase; therefore before any realistic interpretation of geometry or kinematics can be attempted this must be understood. Two fabrics and sets of related structures dominate the Karelian supracrustal rocks in the Kaavi district (Fig. 1), referred to as D_1 and D_2. D_1 structures include rarely seen F_1 isoclinal folds with an axial planar fabric (S_1) in all lithologies except the purest Jatulian metaquartzites.

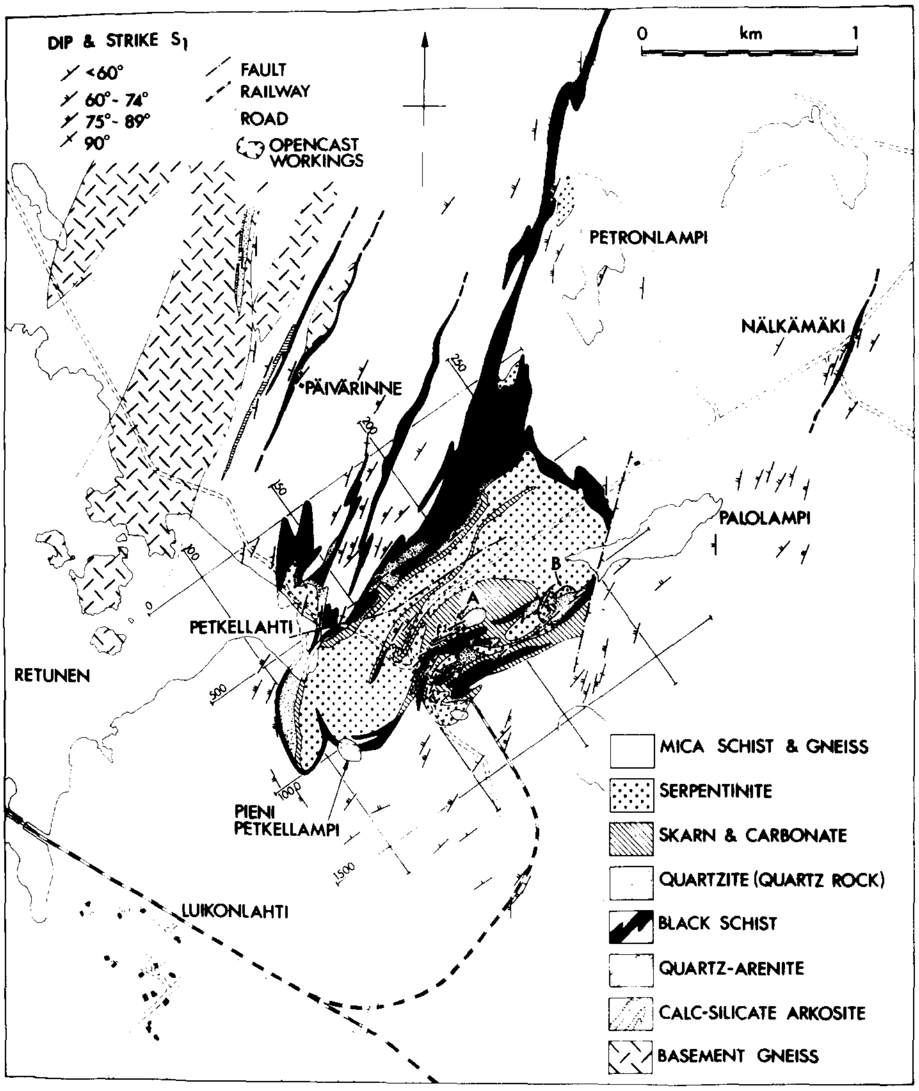


Fig. 2. Geological map of the vicinity of the Luikonlahti mine site. The numbered grid over the mine site gives the co-ordinates for the sections in Figs. 4 and 8. Dip and strike symbols refer to the S_{0-1} composite fabric and S_1 schistosity. Lithological base map compiled by Malminetsintä (Exploration Dept, Myllykoski Oy). Maarianvaara granite veins and sheets are omitted for clarity. A and B are, respectively, the Pajamalmi ('small') and Asuntotalon ('large') open pits.

It is a recrystallized metamorphic segregation banding in the pelitic Jatulian and Kalevian metasediments, picked out by biotite accumulations and is usually parallel to and transposes lithological layering (S_0), except in the hinges of F_1 folds. It has not proved possible in the Kaavi district to map out large-scale D_1 structures, and the overall spatial disposition of S_1 follows lithological layering (Park & Bowes 1983). The Outokumpu Nappe, as a structure in this area, has an ambiguous relationship to D_1. Analogy with the Outokumpu area, where it is folded about F_1 structures, suggests that it is a pre-D_1 structure (Koistinen 1981).

D_2 structures are seen on all scales, and exercise the most important effect on outcrop pattern. They form the essential framework of the Savo thrust belt that can be traced for some 300 km through eastern Finland (Park & Doody in press). F_2 folds are usually open to tight structures overturned to the E. As these folds tighten, axial planes become parallel, or sub-parallel, to the overturned limbs, which are often the sites of slides or thrusts. S_2 forms an axial planar fabric, with mica (biotite) growth in pelites and psammites. This fabric is occasionally a transposing schistosity in the overturned limbs of F_2 antiforms and, like the axial planes, varies from dipping steeply W near Kaavi, to sub-horizontal NE of Niinivaara. At its least transposing, S_2 is a biotite-preferred orientation that leaves the S_1 segregation banding intact. D_2 thrust planes are the first Svecokarelian structure to affect the basement gneisses to any depth beneath the basement–cover interface.

D_3 and D_4 are the only other structural elements to strongly affect the rocks of this area, in terms of imposing fabrics and influencing outcrop pattern. D_3 structures include open, upright folds (F_3) disturbing the S_2 and S_{0-1} surfaces. They have axes running N–S, either horizontal or gently plunging to N or S. An axial planar crenulation cleavage (S_3) is developed in the most schistose rocks (e.g. pelites, phyllite and talc-chlorite schist).

D_4 structures are open, upright folds (F_4) that plunge consistently to the SW at 30–40°. A weak, but pervasive, axial planar spaced cleavage (S_4) develops as a crenulation in suitable lithologies, and a hinge parallel lineation (L_4), often an amphibole growth, is conspicuous in the schistose mafic metavolcanites of the Outokumpu assemblage.

FABRIC AND STRUCTURE DEVELOPMENT AT LUIKONLAHTI

All fabric elements are best developed in the psammites and pelites that dominate in outcrop; more detailed descriptions may be found in Väyrynen (1939) and Park & Bowes (1983).

Mica schist and gneiss

These psammites and pelites constitute the country rock to the mineralized Outokumpu assemblage at Luikonlahti. They are all Kalevian and consist of one or two feldspar (oligoclase, microcline)–biotite–quartz rocks with variable modal composition, from quartz–feldspar–poor pelitic schists to massive, quartzofeldspathic gneiss. In all but the most massive quartzofeldspathic material S_1 is a segregation banding of biotite-rich lamellae. Very few F_1 minor folds have been reported, and S_1 and S_0 are almost always parallel in the area covered by Figs. 2 and 3. The composite fabric is referred to as S_{0-1}, S_0 being occasionally picked out by calc-silicate layers in the massive psammites.

S_2 takes on a variety of forms. In most layers it is defined by a biotite-preferred orientation that leaves S_1 intact. In one psammitic lithology S_1 is disrupted producing a shape fabric with mica orientations defining S_2 and biotite aggregate elongation parallel to F_2 axes (L_2). This lithology is not widespread enough to determine whether this form of L_2 is hinge parallel with respect to F_2 or not. The fissility of the rocks is usually controlled

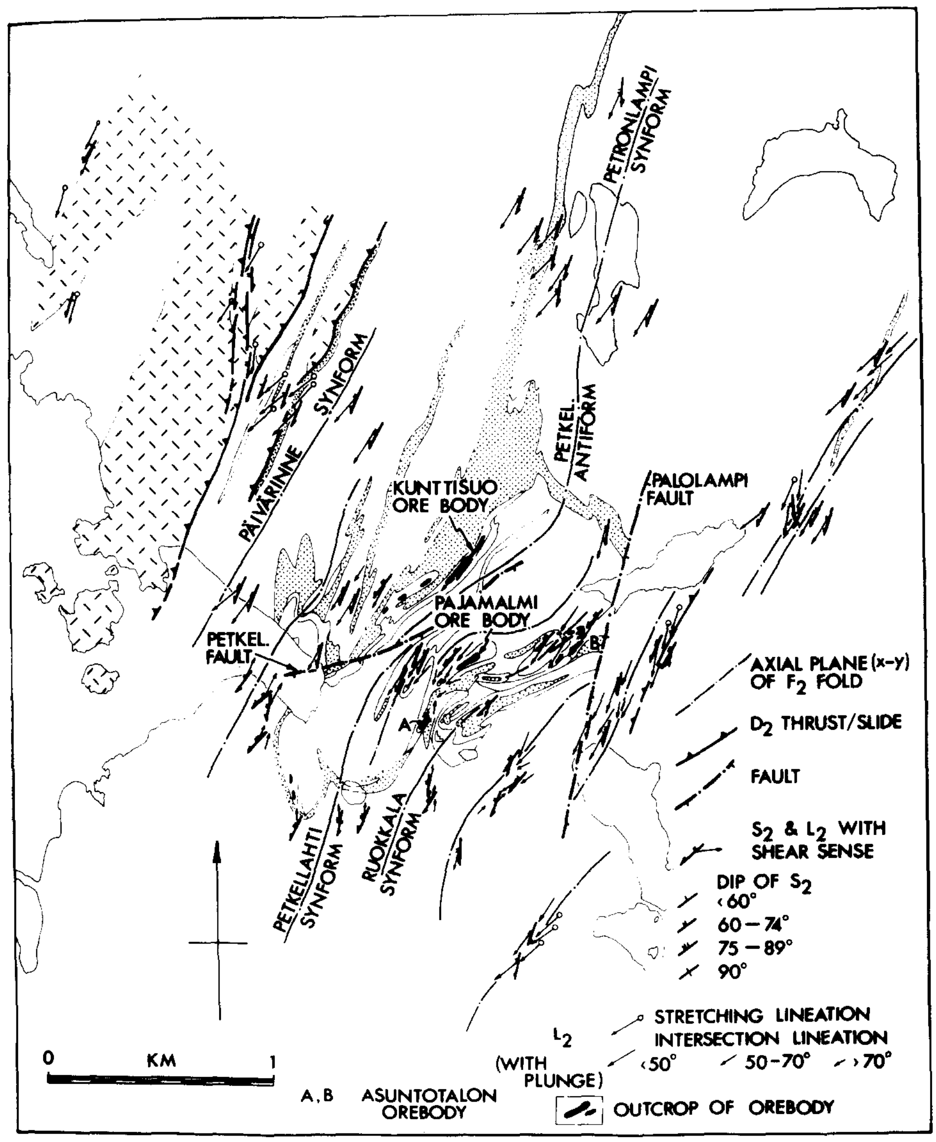


Fig. 3. Outline geology of the vicinity of the Luikonlahti mine site with dip and strike of S_2, plunge and trend of the L_2 intersection (S_{0-1}–S_2) lineation and the axial planar traces of the F_2 folds. Vergence symbols are based on shear sense derived from S_2–S_{0-1} and L_2 relationships (see Fig. 5 and text for explanation). Lithological boundaries are the same as on Fig. 2; the stipple shading is black schist.

by S_1, and the F_2 hinge-parallel lineation (L_2) is the intersection of S_2 on S_{0-1}. From the point of view of determining overall structure this lineation is the more valuable.

Within mappable zones S_2 is a strongly transposing fabric, parallel to S_{0-1}. Ubiquitous quartz vein arrays are streaked out and parallel to S_2 in these instances, with abundant quartz boudins. As a consequence of this limited and well-defined transposition in S_2, the vergence of D_2 structures can usually be determined, whether they be F_2 minor folds and S_2, or the intersection of S_{0-1} and S_2 fabrics. F_2 minor folds are rare around the mine and most vergence determinations are based on S_2–S_{0-1} relationships and the L_2 intersection lineation.

Around the mine rare F_3 and F_4 folds, and S_3 and S_4 crenulations are seen only in the more micaceous layers. The regional orientation of D_3 structures to the general orientation of S_2 around the mine (Fig. 3) would account for this. D_4 structures are orientated very close to D_2 features and are swamped by the latter. They are only clear where the crenulation is particularly strong, or where refolding relationships are clear; a feature also seen in other schistose lithologies.

Other lithologies

D_1 fabrics in the quartz rock and black schists are picked out by sulphide segregations and lithological layering (transposed S_0) defining S_{0-1}. S_2 is picked out by a biotite growth in the black schists, but is weak or absent in more quartzose lithologies. L_2 is either the intersection of the S_2 biotite with S_{0-1}, or a sulphide segregation akin to the biotite aggregate lineation seen in the psammites and is demonstrably parallel to the F_2 hinges.

Chromium-silicate carbonate skarns are usually structurally isotropic, though local talc development may pick out S_2 as a spaced schistosity. Barren skarn (including the 'carbonated diopside syenite' of Väyrynen 1939) is locally micaceous, with segregations picking out S_1 and a mica growth defining S_2. Calc-silicate (diopside–plagioclase–scapolite) lithons are often disrupted into linear augen rods which define L_2.

In serpentinite, an S_2 phyllonitic, spaced schistosity dominates, with talc, chlorite and anthophyllite growths. Lithons contain relics of an S_1 chlorite growth, but none of the fine, pervasive fabrics seen in bodies to the NW (Park 1983) are recorded here.

Granite

Huhma (1975) used the term Maarianvaara granite to denote a diffuse pluton whose centre lies S of Luikonlahti. It consists of a plexus of discordant and mutually cross-cutting veins and sheets varying from a few cms to tens of metres thick. Compositionally these range from quartz-diorite through granodiorite to granite and alkali granite.

Though the granite itself is well exposed, clean exposure of its contacts with country rock are quite rare. Park & Bowes (1983) recorded late, discordant veins and syntectonic migmatite, termed the Maarianvaara granitoid suite (post-D_3) and Kaavinkoski migmatite (syn-D_2). A road improvement programme between Luikonlahti and Sivakkavaara provided extensive new exposure, permitting a reappraisal of the tectonic position of much of this granite. All stages are now recognized from foliated neosome with selvages, coarse neosome with anisotropic biotite fabrics (both of these are usually folded or boudinaged), through non-foliated granite veins showing no selvages, highly marginal foliation but extensive boudinage, to entirely non-foliated granite only weakly boudinaged, as well as abundant, undeformed and completely discordant, post-tectonic sheets. Around the Luikonlahti mine vertical veins orientated NE–SW are usually not folded but show extensive boudinage, whereas NW–SE vertical veins show intense, even ptygmatic folding, depending on thickness. On cross-cutting criteria, early veins are more intensely deformed than later ones. Thus both orientation in the strain field and timing of emplacement during deformation are important factors in determining present morphology. Initial emplacement of the Maarianvaara granite appears to have begun with early D_2 *in situ* neosome development, followed by successive injection during D_2 and D_3, locally post-D_4.

The deformation of the vein arrays to the SW of the mine are consistent with a dextral sense of shear across the Luikonlahti shear zone; this is also consistent with the displacement of the main basement–cover contact in this area (Fig. 1). Where boudinage and folds are developed in granite veins they are always geometrically related to D_2. Boudin long-axes lie in the plane of S_2, even when the veins themselves are discordant.

GEOMETRIC ANALYSIS

Definition of the F$_2$ *folds: use of modified vergence rule*

The above descriptions show that fabric elements related to the F_2 folds are diverse. Minor folds are rare, but as S_2 is only occasionally completely transposing, the S_2–S_{0-1} intersection geometry and L_2 intersection lineation can usually be determined. Stretching lineations are more problematic; a rodding developed by boudinage of pre-D_2 quartz veins is seen around the slides at Päivärinne and to the SE of the mine, but is not developed generally. A stretching direction can be determined, based on an interpretation of the syn- and late-D_2 granite veins where they display unambiguous D_2 boudinage. The scarcity of kinematic indicators precludes any detailed kinematic analysis of the Luikonlahti shear zone based on study of these folds. Given the availability of detailed three-dimensional control from borehole records and stope section records, the viability of a modified vergence rule for recognizing the existence of non-cylindrical folds in poorly exposed high-grade terrain can be tested. In all that follows x, y and z denote geometrical co-ordinates, and X, Y and Z are used for strain axes.

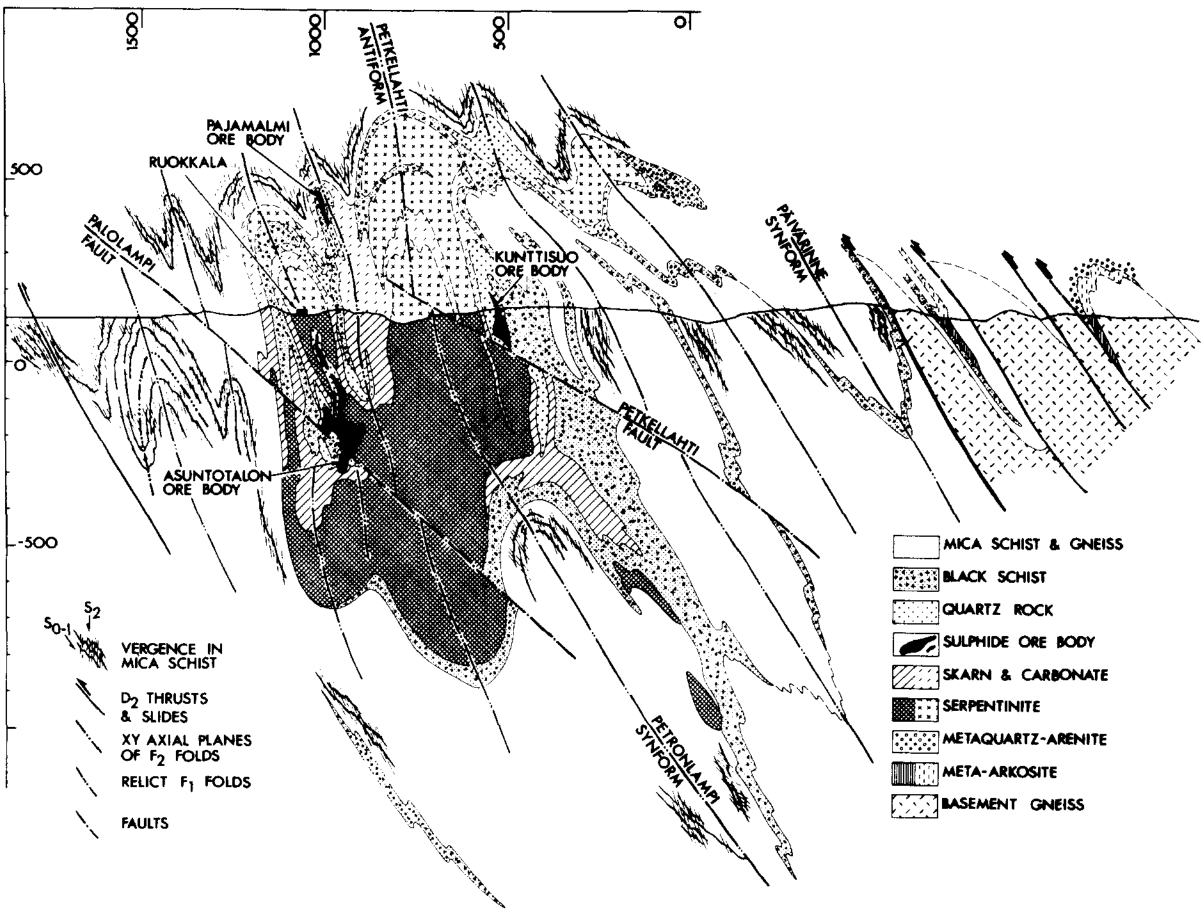


Fig. 4. Cross-section NW–SE along line 202 (see Fig. 2) looking SW (down plunge). Across the mine site the section is constrained by borehole and stope records to a depth of 500 m below the surface. The rest of the section is constructed by projection of information from the surface and other serial sections along paraboloid trajectories reflecting the x–y profile of the F_2 folds, controlled by the L_2 intersection lineations.

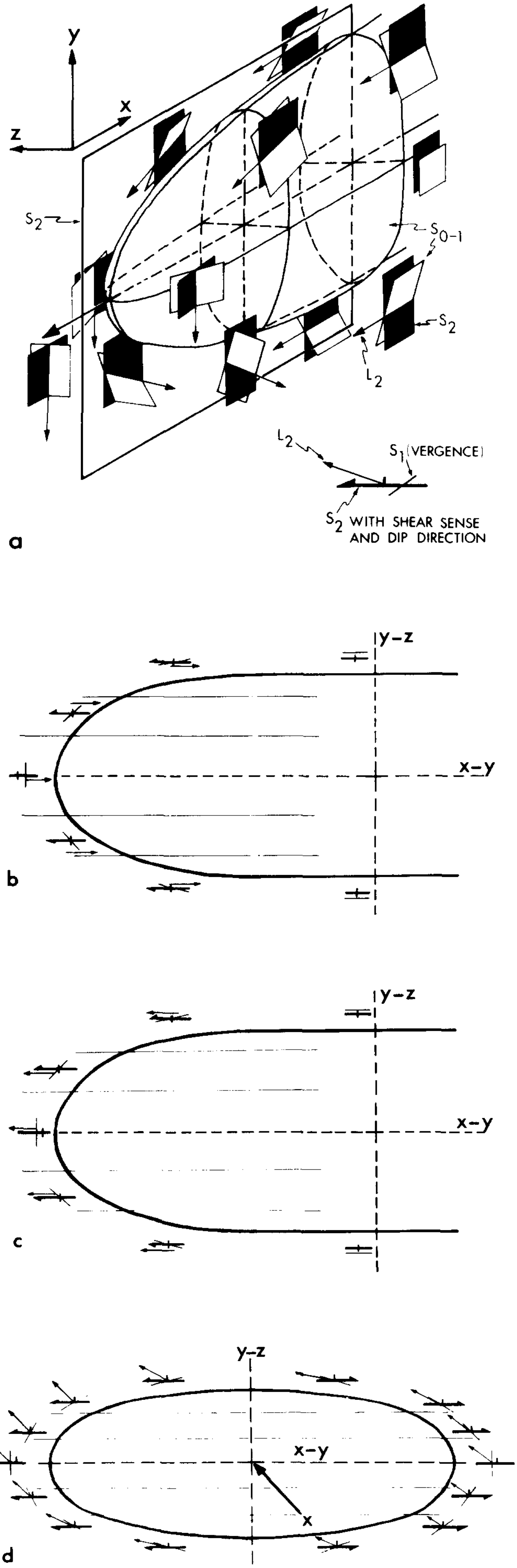
Study of present exposure around the mine, supplemented by maps showing exploration trenches and borehole records reveals a more complex geometry than earlier workers suspected (Väyrynen 1939, Park & Bowes 1983). The NE-plunging synform to the SW of Petkellahti is an F_2 fold, as is the SW-plunging synform at Petronlampi (Figs. 2 and 3). Between these, NE from Petkellahti, the main serpentinite mass lies in the core of a SW-plunging F_2 antiform. The trend of S_2 from Petronlampi to the area SW of Petkellahti indicates that these three structures share the same axial plane (Figs. 3 and 4). This large fold has an extremely curvilinear hinge. The L_2 intersection lineation follows the F_2 hinge and defines an arcuate, curvilinear form, especially within the mine site between the two open pits and around Petkellahti and Pieni Petkellampi (Fig. 3).

The extreme curvilinearity of the F_2 hinge seen across Petkellahti and SW of the small open pit is amplified by the stope and borehole information. The Outokumpu assemblage lithologies define a sheath structure (cf. Cobbold & Quinquis 1980) closing upward in the Petkellahti antiform, downward in the projected continuation of the Petronlampi synform, and to the SW in the steeply plunging Petkellahti synform. The geometric x-axis of the sheath (Fig. 5a) plunges SW at between 20 and 30°.

This is not a single sheath, as is evident in Figs. 3 and 4. It is the largest of three proven structures affecting the Luikonlahti outcrop of the Outokumpu assemblage. Another two are suspected to the NW where outcrop is poor and underground data sparse. To the N of the Petkellahti–Petronlampi sheath another is picked out by black schist outcrop and the Päivärinne structure may be a third. To the SE lies the Ruokkala ore zone, involving at least one sheath and a number of smaller parasitic structures. It is this complex structure that carries the Asuntotalon ore body, analysed below.

The modified vergence rule used to map these structures at the surface uses two fabric components: the intersection geometry of S_2 and S_{0-1}, and the orientation of the L_2 intersection lineation. Shear sense may also be incorporated into this in much the same way as in the vergence rule used for cylindrical folds. Minor folds are not used, partly because of their rarity, but largely because reliance on an inappropriate cylindrical fold model is thereby avoided. This modified vergence rule is illustrated in Fig. 5(a).

Figure 5 illustrates three situations, two involving a sheath fold with a horizontal x-axis (cf. Henderson 1981), where the ground surface, respectively, lies below and above the x–z plane (Fig. 5b & c), and the case applicable to the Luikonlahti folds, where none of the geometric axes are parallel to the ground surface (Fig.



5d). In Fig. 5(b) & (c) note that shear sense does not change as the plunge and trend of L_2 reverses above and below the x–z plane, and that only exactly on the sheath tip and where S_2 is exactly parallel to S_{0-1} is it impossible to determine shear sense from this convention.

Shear sense is defined in the plane of S_2 (x–y plane), which also contains the shear direction, as defined by stretching lineations (see below). As the x-axis plunges more steeply, however, while still in the same plane, it deviates progressively from the shear direction when the two are determined on the ground surface. This deviation is greatest where the x-axis is vertical, when shear sense and shear direction bear least relationship to one another.

Stretching direction

No single, unambiguous stretching lineation is developed uniformly across the mine site or its vicinity (Fig. 3). The biotite shape fabric is only seen in the railway cuttings S of the mine, where it lies sub-parallel to the F_2 hinge and the x-axis of the large sheaths, but it is not possible to determine if it defines a hinge-parallel lineation. Likewise the rodding defined by extreme boudinage of pre-D_2 quartz veins is only found in the vicinity of D_2 slides at Päivärinne and SE of the mine (Fig. 3), where it is sub-parallel to the x-axis of the Luikonlahti folds.

A stretching direction can be derived by interpretation of the boudinage of the syn- and late-D_2 granite veins, which are distributed (albeit sparsely) all across the area. These boudin long-axes that invariably lie in the plane of S_2, are parallel to the x–y plane of the F_2 sheath folds, though the veins themselves are usually discordant to varying degrees. The boudins are linear on outcrop scale, with no chocolate-tablet types, suggesting that the strain axes X and Y lie close to S_2, and the x–y plane of the F_2 sheaths. Boudin morphology implies that $X > Y$. If these assumptions hold, then the stretching direction also lies in the plane of S_2 ($X - Y$), and should lie crudely perpendicular to the boudin long-axes. This is the stretching direction used in what follows.

Fabric geometry

The geometry of F_2 folds at Luikonlahti is defined by surface mapping and underground stope and borehole records. In this context a stereographic analysis of fabric data merely permits a more exact resolution of certain geometric parameters: it does not provide independent criteria for the resolution of fold geometry. Neverthe-

Fig. 5. (a) Stylized vergence of S_1 and S_2, and the attitude of L_2 intersection lineation around a sheath fold with steeply dipping x–y axial plane, parabolic hinge profile and elliptical y–z profile. Inset shows stylized map symbol incorporating S_2, S_{0-1}, L_2 and shear sense. This is used on Fig. 3, where the symbol for the strike of S_{0-1} is omitted as redundant. (b) Cartoon representing vergence of fabrics at outcrop where ground surface lies below the x-axis, and the x-axis is horizontal. (c) Same as (b), but where ground surface is above the x-axis. (d) Vergence on outcrop where all three geometric axes are oblique to the ground surface. Plunge of the x-axis is indicated.

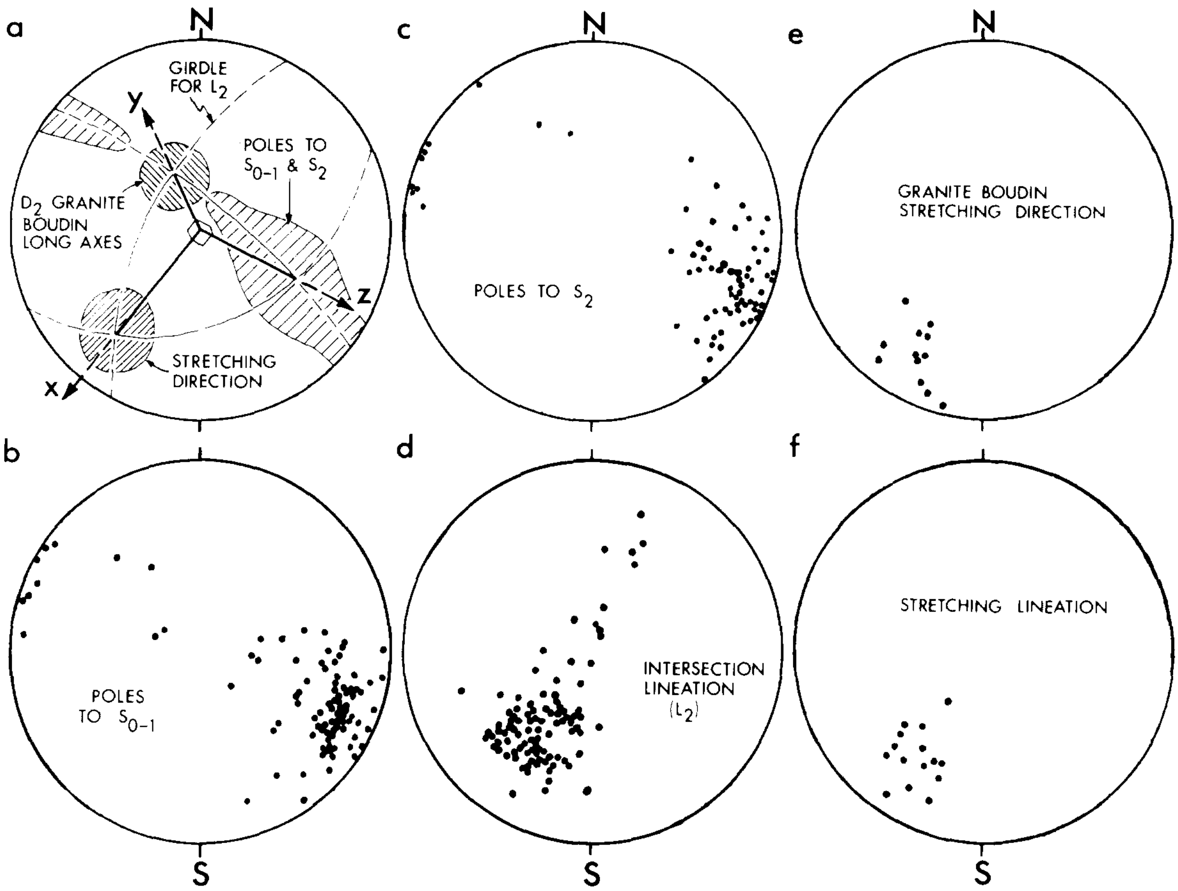


Fig. 6. Lower-hemisphere, equal-area stereograms showing (a) stylized and idealized distribution of fabric elements around a sheath fold such as those at Luikonlahti. See text for explanation and discussion. Distribution of (b) poles to S_{0-1}, (c) poles to S_2, (d) L_2 lineation—this is the hinge-parallel S_2–S_{0-1} intersection. (e) D_2 stretching directions determined from boudin of the syn-D_2 granite veins by taking a line on S_2 perpendicular to the boudin long-axis. (f) L_2 stretching lineations from quartz vein boudins and biotite-aggregate fabrics, from the D_2 slides at Päivärinne and SE of the mine site (Fig. 3).

less, a sheath fold with the form of those seen at Luikonlahti, namely with a parabolic hinge-line in the x–y plane, an elliptical profile in the y–z plane, and a distinct axial planar fabric parallel to the x–y plane, will possess a predictable fabric geometry. Figure 5(a) illustrates the form of fabric vergence and fabric relationships around such a sheath fold.

Fabric analysis can be compared with the predictable form of the intersection lineations as hinge-parallel elements, and the poles to S_{0-1} and S_2 surfaces (Fig. 6a). The elliptical y–z profile, parabolic hinge and relatively small area of the sheath tip produce a bias in distribution, such that the bulk of the S_{0-1} and S_2 poles will fall on a girdle in the stereogram, whose pole is the x axis. S_2 poles should cluster around z. Reflecting the non-cylindrical nature of the fold, there should be a scatter of poles to S_{0-1} and S_2 away from this girdle towards the x axis. This distribution is a consequence of the parabolic hinge; in the more general case of a hyperbolic hinge the girdle effect would not be seen and scatter towards the x axis would be greater.

A similar bias should be evident in the data for the L_2 intersection lineations, for though these parallel the hinge, data will be scarce from the relatively small tip region around the x axis. This should produce a clustering towards the x axis with least points around z.

The data presented on Fig. 6(b)–(d) largely conform to this prediction. S_{0-1} and S_2 poles cluster some 90° from the hinge line (x–y plane), which is defined by the swathe of points for the L_2 lineations. The girdle defined by L_2 lineations is not continuous; a relative scarcity of points occurs 90° from the x axis. Figure 6(e) shows the sparse data for the stretching direction derived from boudin long axes, which cluster around the x axis, indicating extension parallel to this axis. This direction is similar to that of the stretching lineations seen in the vicinity of the slides at Päivärinne and to the SE of the mine (Fig. 6f).

GEOMETRICAL CONSTRUCTIONS FROM THE MINE STOPE AND BOREHOLE RECORDS FOR THE RUOKKALA ORE ZONE

Figures 7 and 8 present serial sections of the Ruokkala ore zone, including the Pajamalmi and Asuntotalon ore bodies, produced from detailed lithological cross-sections made in the ore stopes, augmented by drill core obtained from boreholes sunk from the surface and the now abandoned and flooded underground workings. Additional information came from the open pits and limited surface outcrop in this zone.

Three lithologies in this three-dimensional recon-

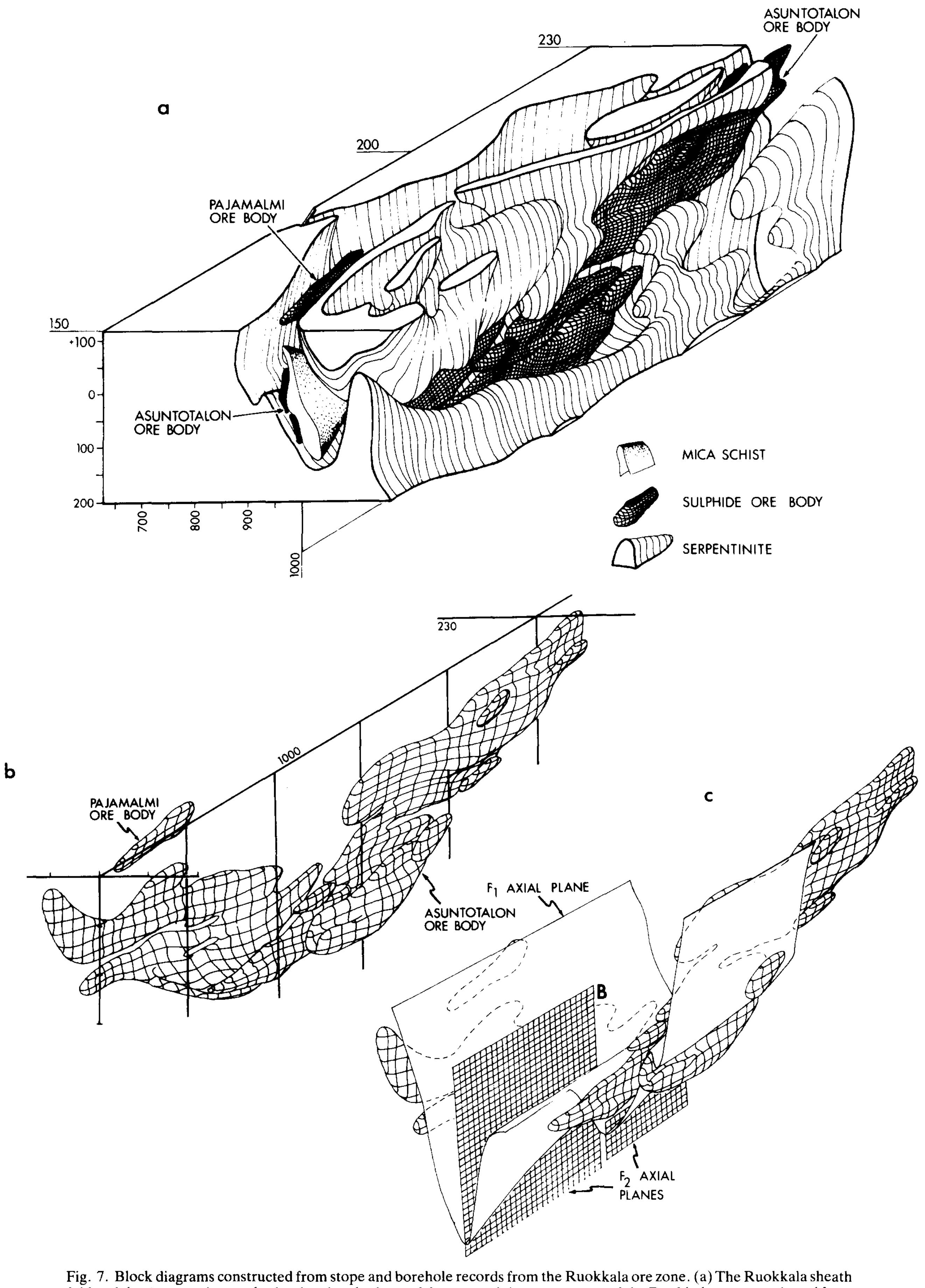


Fig. 7. Block diagrams constructed from stope and borehole records from the Ruokkala ore zone. (a) The Ruokkala sheath fold and the Asuntotalon ore body, showing the form of the serpentinite masses around the Ruokkala ore zone viewed from the S. Scale is indicated in metres, and the co-ordinate lines refer to those on Figs. 2 and 8. (b) The shape of the Asuntotalon ore body extracted from the Ruokkala ore zone. Co-ordinates are the same as in (a); viewed from the S. (c) Semi-idealized form of the F_2 axial planes and the relict F_1 structure effecting the deformation of the Asuntotalon ore body.

struction pick out the structure most clearly; the serpentinite, the ore bodies and the mica schist. A number of F_2 axes are clear and the smaller serpentinite bodies and mica schist pick out the tips of the two larger sheaths (Fig. 7). The serpentinite body SW of Ruokkala defines a SW-plunging, SW-closing sheath tip, 'capped' by the serpentinite, while the mica schist body adjacent to the SW extension of the Asuntotalon ore defines an upward-to-the-NE closing, SW-plunging sheath tip. Likewise, in profile, the F_2 and S_1–S_2 vergence across the large open pit at the surface reveals a SW-plunging F_2 synform cored by serpentinite. Below ground this structure becomes an F_2 antiform cored by serpentinite (section 218, Fig. 8).

The Asuntotalon ore body reveals a more complex structure. The large F_2 axial planes through the large open pit and across the small serpentinite SW of Ruokala both affect the ore body. However, an earlier fold is also apparent, with its axial plane refolded by the sheaths. This is one of the best defined candidates for an F_1 fold on the mine site. Figures 7 and 8 also illustrate that the now modified shape of the ore body is a crudely elongate, tabular plate. The Pajamalmi ore body, exposed in the small open pit and the various ore bodies NE of the main serpentinite (the Kunttisuo ore, and the small bodies around Petkellahti) lie at the same horizon, but are probably small independent bodies, rather than detached fragments of the Asuntotalon mass.

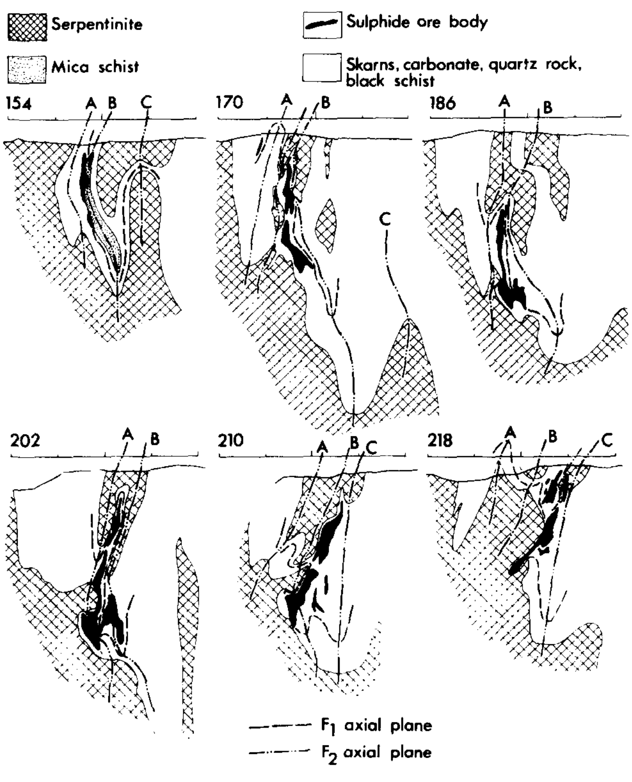


Fig. 8. Selected serial sections through the Ruokkala ore zone from mine stope records and borehole information, showing the position of F_2 axial planes (x–y planes of F_2 sheaths) and the relict F_1 axial plane. Co-ordinate numbers refer to Figs. 2 and 7. Details of the quartz rock, black schist and skarns, and the veins and sheets of the Maarianvaara granite are omitted for clarity. All sections are seen looking NE. The position of axial plane B is represented on Fig. 7(c).

Partial fragmentation of the Asuntotalon ore body appears to be by boudinage, producing the elongate lobes evident in Fig. 7 and the general elongation of the Kunttisuo and Pajamalmi bodies. This cannot, however, be verified by direct observation. Such boudins have long-axes parallel to the x-axis of the F_2 sheaths, in contrast to the boudins formed from syn- and late-D_2 granite sheets.

FOLD INTERFERENCE

Several candidates for F_1 fold structures can be identified. The best defined is in the Ruokkala ore zone, the only other identified with any confidence encloses the serpentinite body NE of Petkellahti. This NE-closing structure (the orientation of its axis is not defined) appears to be one of a pair, whose complementary SW-closing companion is wrapped around the tip of the F_2 Petkellahti antiform (Figs. 2, 3 and 9). Both axial planes, though indistinct, lie in the plane shared by the S_{0-1} fabric, and it is within this composite fabric that the few recorded F_1 minor folds occur as relict structures. All the identified F_1 structures are essentially isoclinal folds, consistent with the observed general parallelism of S_1 and S_0. Effectively, the F_2 sheath folds are superimposed on what was originally a sub-parallel layered assemblage, with S_{0-1} and the included F_1 axial planes defining a single, coherent surface. Though an F_1–F_2 interference pattern is evident at outcrop and in the stope sections, the F_2 folds alone are responsible for the gross geometrical features, of which the most important is the sheath geometry of F_2 folds (Fig. 9). Post-F_2 folds have an effect, most conspicuous in outcrop in the evident bending of the trace of the axial planes of the F_2 folds (Fig. 3).

CONCLUSIONS AND DISCUSSION

The sheath folds at the Luikonlahti mine are the first such structures reported in the Svecokarelides. The combination of poor but adequate exposure and good underground records permits a geometric, but not kinematic, definition of extremely non-cylindrical folds.

In determining the form of this structure a modified vergence rule has proved useful. By referring to planar fabric relationships and intersection lineation geometry this modified rule avoids vergence indicators based on cylindrical folds models, and permits a ready assessment of shear sense. At the Luikonlahti mine it is possible to test the geometric implications of surface mapping using this modified vergence rule against the three-dimensional form of the structure defined independently from stope records and borehole data. This modified vergence rule should prove useful in defining the geometry of structures in similarly exposed high-grade terrains elsewhere. Where circumstances permit, such geometries provide the necessary framework for kinematic studies and analysis.

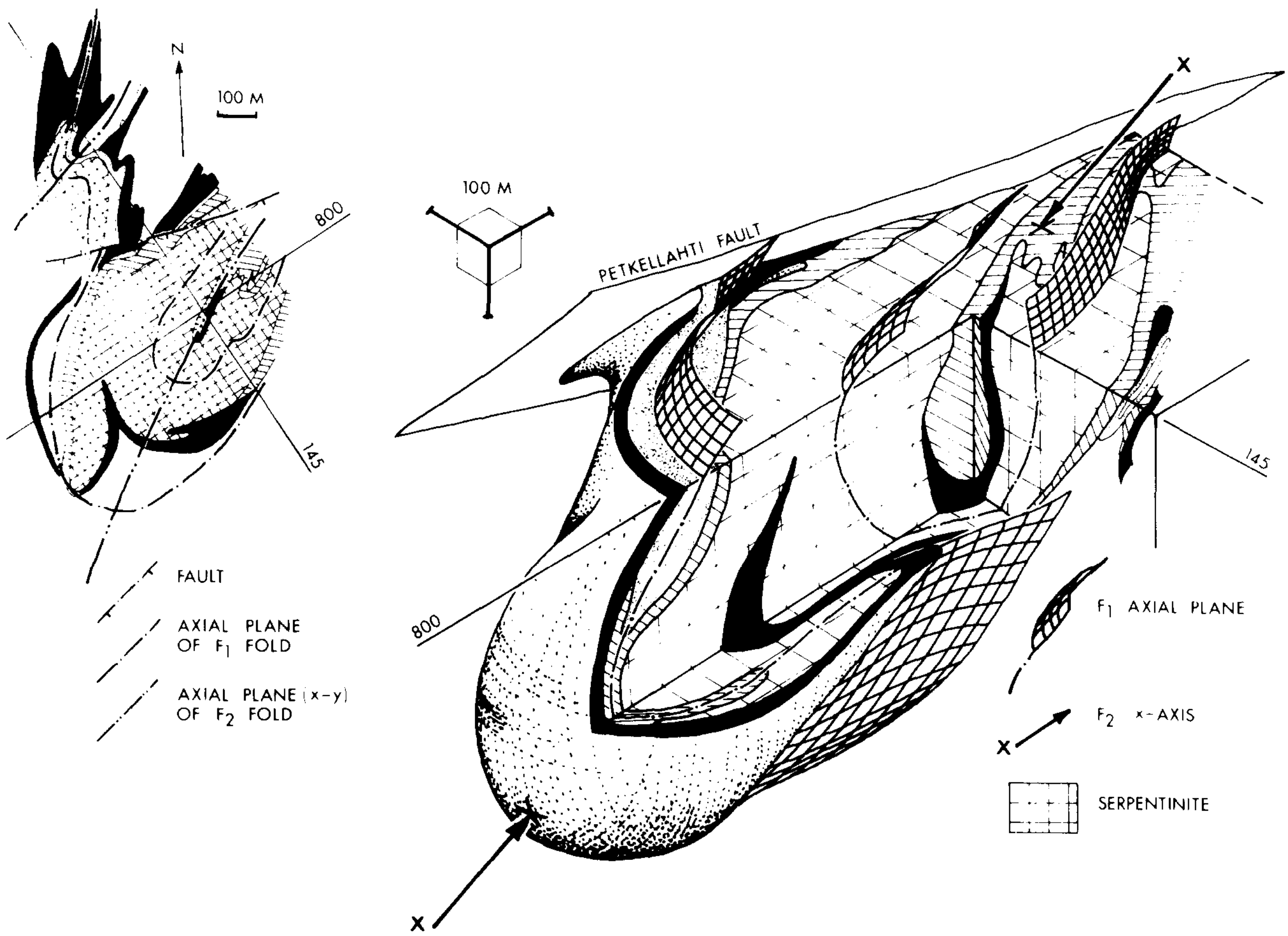


Fig. 9. Isometric construction of the Petkellahti area S of the Petkellahti Fault, from borehole and stope records, illustrating the superimposition of the F_2 sheath folds on an earlier, isoclinal F_1 structure. Co-ordinates are from Fig. 2. Apart from serpentinite lithological legend is the same as Fig. 2.

Boudinage was used to define a stretching direction in the absence of anything better. The deformation of the syn- and late-D_2 granite veins proved useful but also begs an important kinematic question. In a sheath fold the long axes of passive strain markers should tend to rotate parallel to the extension direction, crudely to become parallel to the x axis of the fold (Sanderson 1974). Markers like the locally rodded quartz veins appear to behave in this fashion, as do the boudin-like shapes defined by pinches and swells in the Asuntotalon ore body and the serpentinite bodies in the Ruokkala zone. This parallelism to the x axis is emphatically not observed in the granite veins. This appears to reflect their mode of origin, emplaced during D_2, or even late in D_2, and therefore not taking up the whole of the D_2 strain increment.

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