

STRAIN ANALYSIS IN THE ORIJÄRVI TRIANGLE, SOUTHWESTERN FINLAND; IN PERSPECTIVE OF TECTONIC MODELS

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STEL, HARRY, VAN REES, DOUWE and SCHENKE, BART 1999. Strain analysis in the Orijärvi triangle, southwestern Finland; in perspective of tectonic models. *Bulletin of the Geological Society of Finland, Number 71, Part 2, 329–337.*

Finite strain analyses were performed in metavolcanic rocks (agglomerates and pillowed metabasalts) from the Orijärvi area, southwestern Finland. In this area, tight folding (F_1) of layered metasedimentary rocks and development of a penetrative axial plane schistosity (S_1) took place during an early stage in the Svecofennian orogeny. Within the domain, there is no evidence of older deformational structures or of a later deformation phase; except in narrow, late-stage shear zones that bound the Orijärvi triangle. During the orogenic evolution, a pervasive attenuation of the fabric in metavolcanic rocks has taken place. In order to quantify strain intensity and to investigate the relation of strain in metavolcanics and folding in metasediments, strain analyses were performed by the Rf/ϕ method on (sub)elliptical markers. Metavolcanic rocks demonstrate relatively homogeneous strain values on the outcrop scale, but strain parameters vary strongly on the scale of the study area. This variation in strain correlates with variation in rock composition; felsic metavolcanics demonstrate consistently lower strain intensities than mafic ones. Finite strain ellipsoids are prolate, indicating that the rocks underwent apparent constriction. X axes of strain are (sub)parallel to the regional fold axis. Constriction in the Orijärvi triangle is not in conflict with any of the current tectonic models. However, given the local structural setting, the most straightforward interpretation is that of progressive constriction by plutonic diapirism.

Key words: metavolcanic rocks, strain, contraction, Svecofennides, tectonics, diapirism, Proterozoic, Orijärvi, Finland

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INTRODUCTION

The Orijärvi triangle is considered to be a key area for the study of the early tectonic evolution of the Svecofennides, as the oldest generation of struc-

tures is exceptionally well preserved in this domain (Ploegsma 1989, Ploegsma & Westra 1990). The present paper is a report of a strain analysis in the Orijärvi triangle; the results are discussed with respect to current tectonic models. The pur-

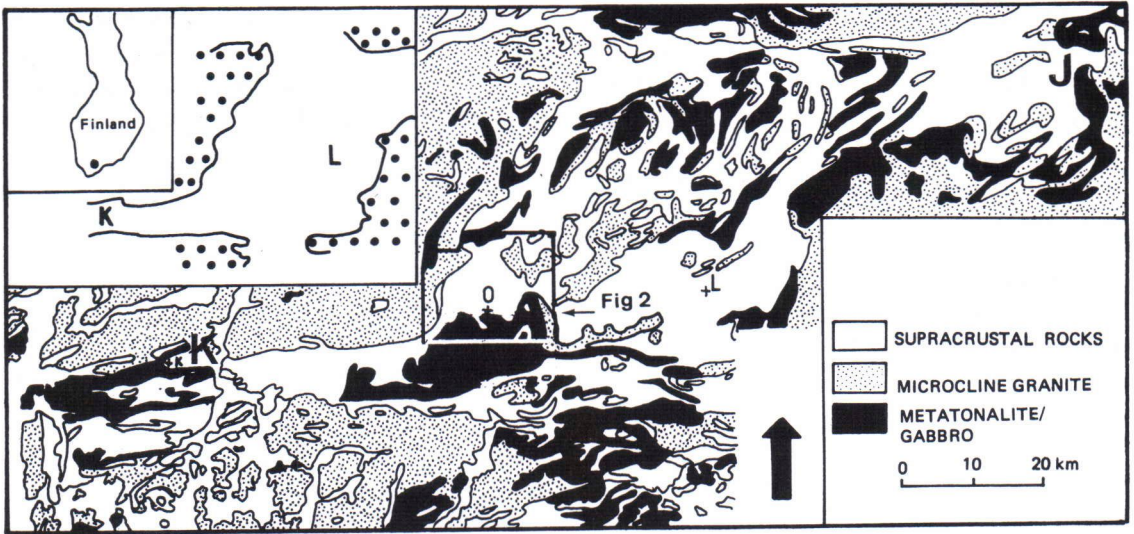


Fig. 1. Geological sketch map of the Kemiö(K)–Järvenpää(J) schist and gneiss belt. After Westra and Schreurs (1986). Study area (Fig. 2) is indicated. O = Orijärvi.

pose of our study is to determine the amount of strain and its variation on the scales of outcrop and area, to assess the shape of the strain ellipsoids, to determine the relation between strain and folding, and to evaluate the tectonic ‘facies’ at which deformation took place.

The study area is situated in the Svecofennian Kemiö–Järvenpää gneiss and schist belt of southern Finland (Fig. 1). This belt consists of metasediments, metavolcanics and syn- to post-orogenic intrusives. Early deformation in the belt is manifested by folds and by distortion of volcanic and sedimentary rock fragments.

STRUCTURAL SETTING OF THE ORIJÄRVI TRIANGLE

Three plutons enclose the Orijärvi triangle: the Orijärvi tonalite-to-gabbro batholith in the south and southeast (Eskola 1914, Stel 1991), a tonalite-to-granite batholith in the west, and a smaller microcline-granite body in the northwest (Fig. 1). The area is bounded by three shear zones (Fig. 2) that accommodated post-orogenic, vertical displacement (Ploegsma 1989, Lonka et al. 1998). There is some evidence that these are reactivated

wrench zones (Ploegsma 1989, Heeremans et al. 1996). Ploegsma (1989) suggested that the bounding shear zones “absorbed” regional post- F_1 deformation, thereby shielding the internal part of the Orijärvi triangle.

In the Orijärvi domain, primary structures in metasediments and metavolcanics are exceptionally well preserved (Latvalahti 1979). Bedding of metasediments dips steeply north and asymmetric, tight-to-isoclinal folds with an ENE striking axial plane are found. The dominant younging direction in the metasediments is towards the north. Ploegsma (1989) and Ploegsma and Westra (1990) proposed that the structures developed as recumbent, thrust-related folds. Ehlers et al. (1993) supported this interpretation.

STRAIN ANALYSIS

A nearly uniaxial symmetry of fabric can be readily observed in outcrops. Apparently non-strained objects (angular pyroclastic fragments, pillows) and sedimentary structures (cross-bedding, load casts) are observed in sections perpendicular to the local lineation. Sections parallel to the lineation show strongly aligned, distorted and attenuated

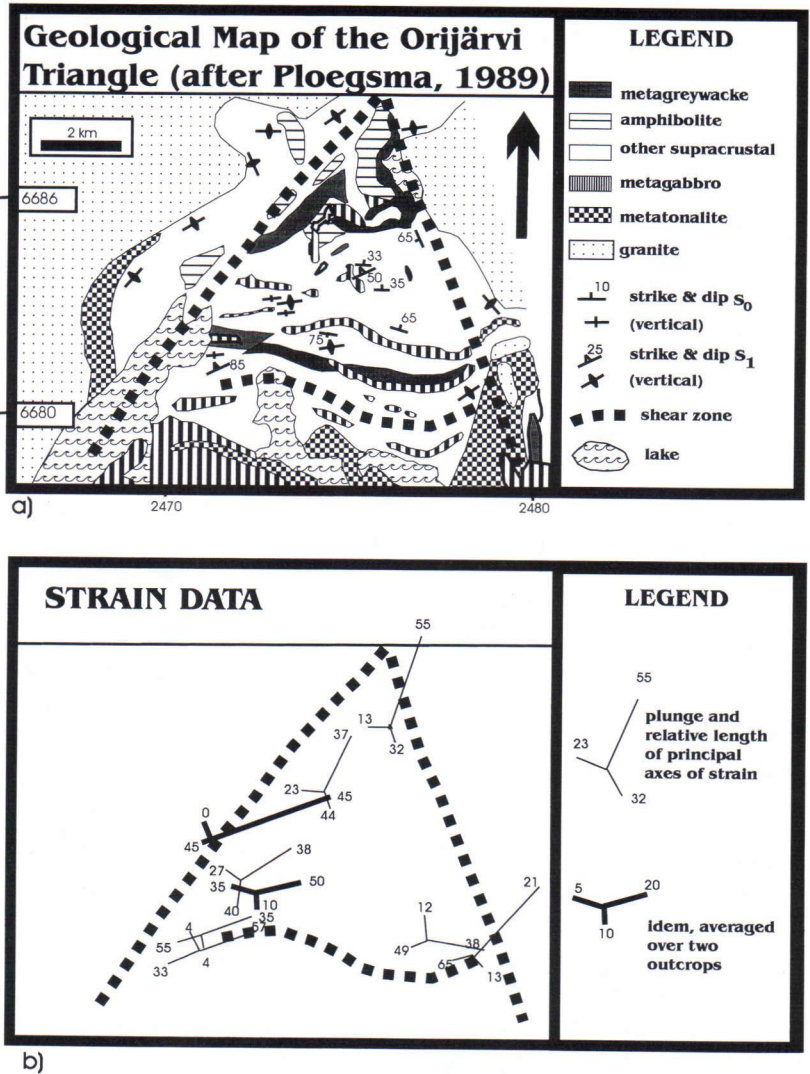


Fig. 2. a: Geological map of the Orijärvi triangle. After Ploegsma (1989). b: Localities of the outcrops on which 3-D strain measurements were performed, orientation of strain axes and their relative lengths are indicated. Geology, except shear zones, omitted.

objects (pillows, coarse pyroclasts). To quantify the strain intensity, and to determine the shape of the strain ellipsoid, Rf/ϕ analyses (Lisle 1985, Kutty & Joy 1994) have been performed. This method relates the orientation of shape axes (angle ϕ with respect to a reference line) to the aspect ratio (Rf) of (strained) objects and allows assessment of a 2-D strain ellipse from a specific outcrop section. Strain ellipses obtained from at least three sections are then combined to calculate a 3-D strain ellipsoid (Owens 1984, Hayashi 1994). Objects used for Rf/ϕ analysis in this study

include volcanic ejecta in agglomerates or tuff breccias (14 outcrops) and hyaloclastic rims of pillows. In total, a number of 16 outcrops were found suitable for strain analysis, 11 of which allowed a 3-D strain determination. The localities of these outcrops are shown in Fig. 2b.

RESULTS

Three aspects of strain are relevant for the evaluation of an area: the variation of strain intensity

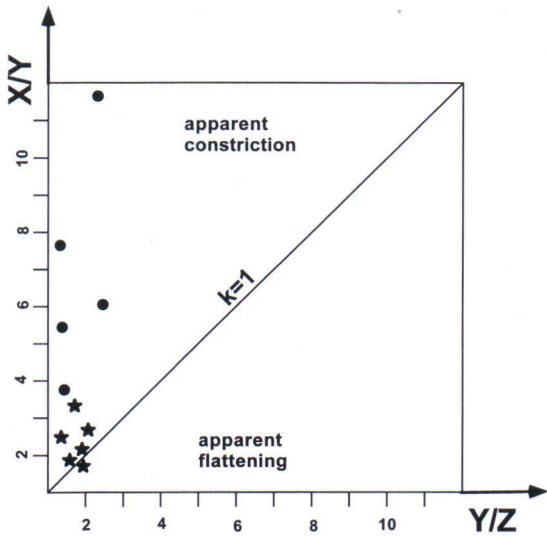


Fig. 3. Flinn diagram relating the axial ratios of finite strain ellipsoids from metavolcanic rocks in the Orijärvi area. Asterisks refer to data from felsic rocks, dots from mafic rocks. Note that the distribution is nearly linear, close to the constrictional axis.

with rock composition, the distribution of the orientation of the finite strain axes, and the relationship between the orientation of strain axes and deformation structures such as foliation, lineation and folds.

Strain parameters

The strain data are presented on a Flinn diagram which relates the ratios of the principal strain axes of X/Y and Y/Z ($X > Y > Z$) (Fig. 3). Two important strain parameters are: $k = (X/Y - 1)/(Y/Z - 1)$, which is a measure of the shape of the strain ellipsoid and, $d = \{(X/Y - 1)^2 + (Y/Z - 1)^2\}^{0.5}$ which represents the strain intensity (Ramsay & Huber 1983). Values of d range from 2.5 to 10, while k varies from 0.5 to 20. The large range of d values indicates that finite strain is heterogeneously distributed. Felsic rocks (asterisks on Fig. 3) demonstrate consistently lower strain intensities and lower k values than mafic rocks. On the Flinn diagram the data points are aligned nearly parallel to the apparent constriction axis, and 10 out of 11 points plot in the apparent constriction field. The

variations of shape (k) and intensity (d) are interrelated, i.e. low d values correlate with low k values.

Orientation of strain axes

Finite strain axes show a consistent orientation over the entire area. Orientation distributions of X and Y axes are presented in lower hemisphere equal area projections (Figs. 4a and 4b, respectively). The orientation distributions were statistically evaluated and they are represented by the eigenvectors of spherical distributions (Davis 1986). It appears that the orientations of X axes demonstrate the strongest maximum, with eigenvector $\Sigma 1$ (the orientation which is as close as possible to all direction vectors) oriented 085/47. Poles to bedding yield a point maximum located at 353/07 (Fig. 4a). The corresponding great circle of orientation, 173/83, is the "mean orientation of the bedding plane", S_0 . Poles to the schistosity in the metasediments yield a point maximum located at 323/15, corresponding to the great circle 147/75, i.e. the "mean schistosity plane", S_1 . The mean X axis of strain is close to the intersection of S_0 and S_1 , i.e. F_1 fold axis in the metasediments. The plane defined by the orientation maxima of X and Y axes of strain is subparallel to the mean schistosity in the metasediments.

INTERPRETATION

The strain data show a consistent pattern, approximating a linear distribution nearly coinciding with constriction axis on the Flinn diagram (Fig. 3). There is a fixed orientational relationship of strain axes and fold elements. This suggests that the strain recorded by the metavolcanic rocks was coeval with F_1 folding. In ten out of eleven cases, the strain ellipsoid is prolate. This indicates, at first approximation, that strain in the Orijärvi area was apparently constrictional.

There is a close correlation between rock composition, strain intensity and k value. Felsic rocks are generally less strained, and show low k values. Mafic rocks are highly strained, and show

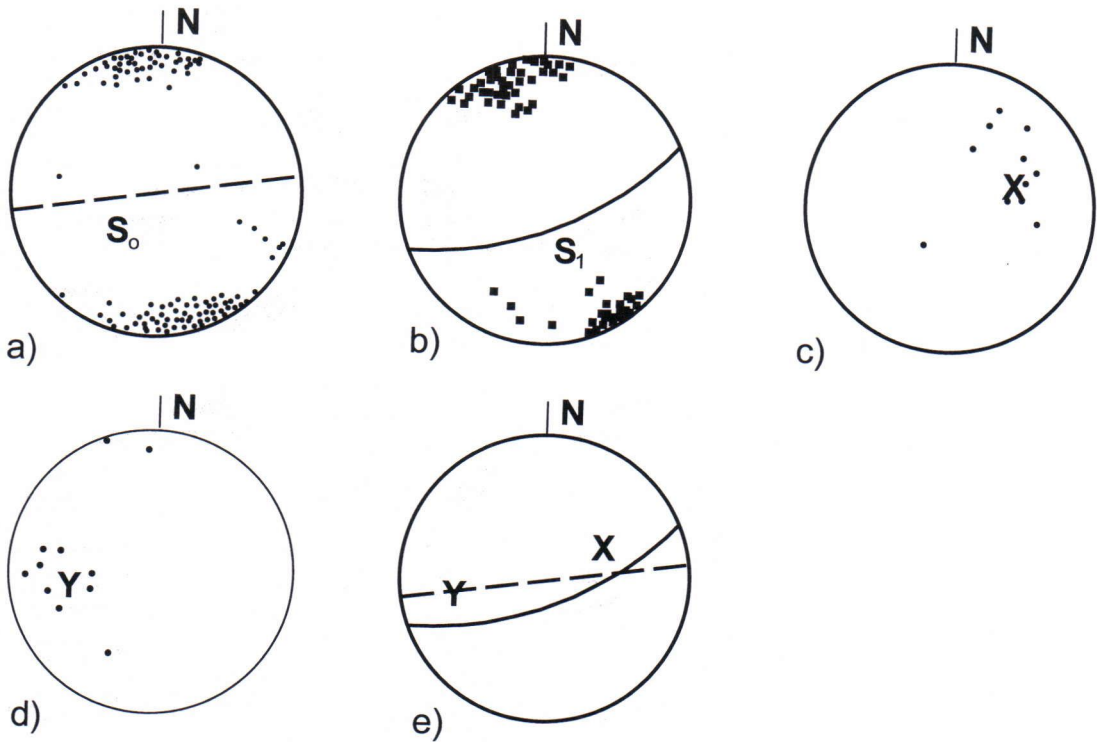


Fig. 4. *a and b*: Lower hemisphere projection of poles to bedding and poles to schistosity. Great circles refer to mean orientation of bedding S_0 and schistosity S_1 respectively. *c and d*: Lower hemisphere projection of orientation of X and Y axes of strain. "X" and "Y" refer to the centres of the populations. *e*: Synoptic diagram showing the relation between the strain axes orientation populations, schistosity and bedding. Note that X-maximum is located near the intersection of S_0 and S_1 .

higher k values. It is proposed that this difference in strain intensity reflects a competence contrast between felsic and mafic rocks.

Effects of volume loss and pre-strain fabric

The parameters presented above give a first approximation of the true strain values, and they were calculated on the basis of a number of assumptions. The most important presumptions are constant volume during deformation and the absence of a pre-strain fabric.

A technique for the detection of a pre-strain fabric by Rf/ϕ analysis was developed by Lisle (1985). He defined theta-curves in Rf/ϕ space; each curve represents a group of ellipses with similar pre-strain orientation. Preferential location of

Rf/ϕ points along a theta-curve is diagnostic for a pre-strain fabric. Statistical tests can be applied to verify uniform pre-strain distribution, or alternatively, pre-strain fabrics (Meere 1990). Results of Gi-square tests on all the Rf/ϕ data sets used in this study revealed that a uniform pre-strain distribution of objects may be accepted with a confidence level of $> 95\%$. Lisle's method does not, however, reveal a primary fabric in which the axes of symmetry are parallel to the principal axes of strain. In general, Rf/ϕ techniques cannot evaluate this situation (Ramsay & Huber 1983). So, it is concluded that either no pre-strain fabric existed in the rocks or, alternatively, that if a primary anisotropy was present it was parallel to one of the principal planes of strain. It is likely that latter was the case in the present situation. Volcanic

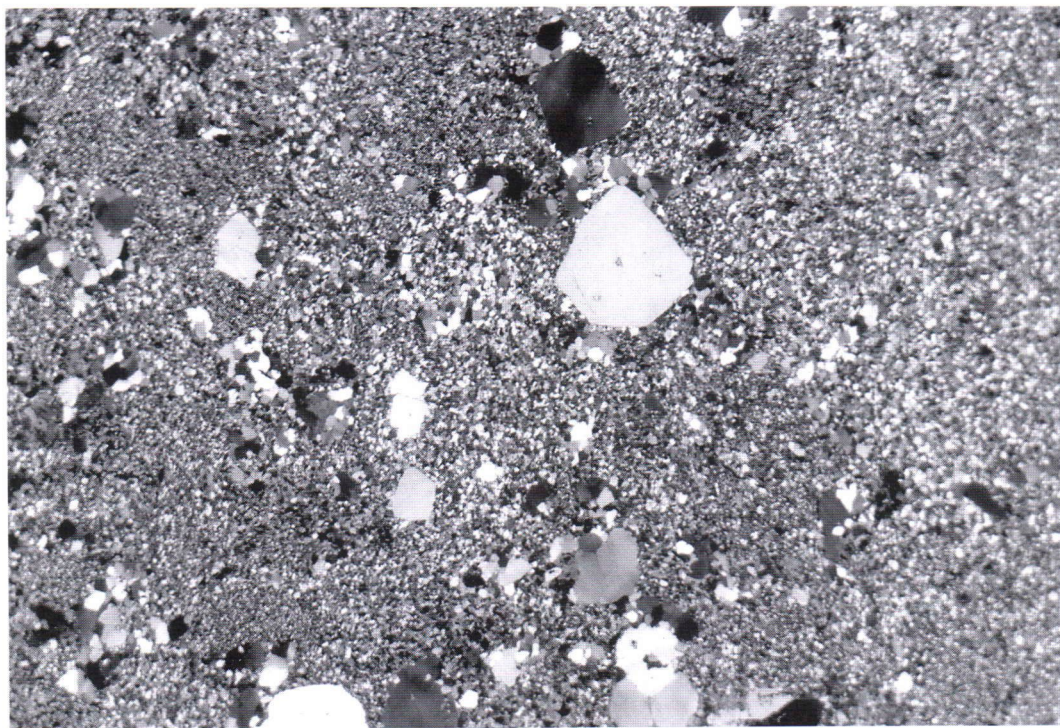


Fig. 5. Photomicrograph of a strained felsic metavolcanic rock, showing blastoporphyritic texture with strain-free pseudo-hexagonal quartz crystals floating in tuffitic matrix. Crossed polarizers, width of view 10 mm.

rocks may undergo ca. 30% volume loss during compaction (Fisher & Schmincke 1984). Because it can be expected that the compactional shortening direction is perpendicular to bedding, in the present case this would have had a similar effect as a superposed uniaxial flattening with shortening direction perpendicular to the X axis of the finite strain (Ramsay & Wood 1973). Because the XY principal plane of finite strain is subparallel to the bedding, a closer estimate of the tectonic strain may be obtained by subtraction of ca. 30% of the Z axis of the finite strain ellipsoid. This would cause a shift of all the data points towards the constrictional axis on the Flinn diagram, thereby accentuating the constrictional nature of the strain. Therefore, we conclude that the apparent constrictional finite strain that was recorded in the rocks is due to a real constrictional tectonic strain.

MICROSTRUCTURES

Microstructures of the strained metavolcanics were studied to assess the deformation conditions. Deformed felsic rocks show blastoporphyritic texture (e.g. Shelley 1993 pp. 49–50) with euhedral pseudo-hexagonal quartz, ca. 5 mm in size, that ‘floats’ in a fine-grained matrix of quartz, albite, white mica and biotite (Fig. 5). Albite and cummingtonite occur as poikiloblasts that appear to have overgrown the matrix. Biotite occurs in two microstructures: as fine-grained matrix flakes and as randomly oriented blasts. Mafic components in agglomerates and tuff breccias show a strong shape-preferred orientation of hornblende, cummingtonite and biotite in sections parallel to the X axis of strain.

In none of the samples asymmetric sense-of-shear markers were found such as described by Vernon (1987). Nor was other evidence found for a non-coaxial deformation history.

STRAIN DATA AND TECTONIC MODELS OF DEFORMATION

There are numerous models dealing with the early deformation structures of the Svecofennides: thrust-related contractional deformation (van Staal & Williams 1983, Ploegsma & Westra 1990), extension followed by orogenic shortening (Nironen 1997), gravitational gliding of non-consolidated material in rift-related half-grabens (Oen et al. 1982), and progressive diapirism (Griffin 1979). Ehlers (1978) reported on deformation of metavolcanics by comagmatic plutonic intrusion. De Groot et al. (1988) and Veenhof and Stel (1991) favoured a combination of diapirism and gravitational flow of unconsolidated sediments from topographic highs created by early diapirism of granites.

The rocks of the Orijärvi triangle recorded a constrictional finite strain, while there is no evidence of a multi-stage deformation history (Ploegsma & Westra 1990). Progressive constriction may take place in more than one tectonic settings, viz. during transpression (Dias & Ribeiro 1994), by the effects of plutonic diapirism (Bloem et al. 1997, Uken & Watkeys 1997), or by thrusting and other types of non-coaxial shearing in combination with shear-perpendicular shortening (Fossen 1993, Fletcher & Bartley 1994, Mukul & Mitra 1998). Furthermore, progressive constriction may take place as a direct result of plate movement in triple zones (Ego et al. 1996).

Was the early deformation in the Svecofennides a phase of thrusting? Thrust stacking in the Finnish Svecofennides is well demonstrated in areas close to the suture with the Archean craton (Kohonen 1988, Kärki & Laajoki 1995, Nironen 1997). However, in the Kemiö-Järvenpää belt depicted in Fig. 1, there is no hard geometric evidence of thrusting or thrust stacking, and there are no outcrops where a thrust fault can be demonstrated. In the rocks of the Orijärvi triangle there is no microstructural evidence for a non-coaxial deformation history. No asymmetric fabric elements were observed that would mark a sense-of-shear indicator (cf. Passchier & Trouw 1996). Because thrusting should have involved non-co-

axial shearing, we may expect that the microstructure of the rocks displays an imprint of such a process, i.e. we may expect to find sense-of-shear markers. As we did not observe such features, we conclude that the microstructure does not support a thrust scenario for the early deformation phase in the Orijärvi triangle.

Did the early Svecofennian deformation take place in a transpressive setting? There is *a priori* no evidence against such a model. Large-scale vertical mylonite and fault zones, like the Kisko shear zone (Ploegsma & Westra 1990), the Painio lineament (Stel et al. 1989) and the Porkkala-Mäntsälä fault zone (Heeremans et al. 1996), have evidently originated as ductile wrench zones. Therefore, it cannot be excluded that the three shear zones that bound the triangle existed already during early Svecofennian times. The Orijärvi triangle in this case might have been a triple zone (cf. Ego et al. 1996) undergoing constriction. In fact, Ehlers et al. (1993) have proposed that transpressive tectonics took place in this part of the Svecofennides, although their analysis largely concerns the late-stage orogenic development. Given that the geometry of late-stage faulting is often an inheritance of a pre-existing fault pattern, we consider the option that early Svecofennian deformation may have taken place in a comparable setting. Ehlers et al. (1993) noted that the metasedimentary belt (Fig. 1) displays a lozenge-shape, which is reminiscent of pull-apart or pop-up structures that are frequently found in regimes of strike-slip tectonics. The Orijärvi triangle is located near one of the corner-points of the lozenge structure, and the deformation in this domain may have been characterized by interfering shortening fields. All in all, it cannot be excluded that the Orijärvi triangle represents a kind of 'paleotriple zone'. Nevertheless, this solution is somewhat speculative as we have no formal information on the geometry of the belt during this specific time of its evolution.

Did the early Svecofennian deformation in the metavolcanic rocks take place in response to diapiric intrusion of batholiths? This option is certainly possible in the case of the Orijärvi triangle, as it is enclosed by three plutons, of which the

Orijärvi batholith in the south is cogenetic with the metavolcanics that recorded constriction (Colley & Westra 1987). It is likely that intrusion of this lobe-like batholith had a deformational effect on the country rock. The X axes of finite strain in the Orijärvi triangle are parallel to what has been interpreted as syn-magmatic fold axes in the neighbouring Orijärvi batholith (Stel 1991). Furthermore, a phase of constriction due to cogenetic intrusion of batholiths would explain the preservation of volcanic textures (cf. Latvalahti 1979) in deformed rocks. The latter strongly suggests that deformation took place in 'soft-sediment' stage, i.e. more or less coeval with eruption. For these reasons, we propose that intrusion-related constriction is the most straightforward interpretation of the cause of strain in the Orijärvi triangle.

CONCLUSIONS

Metavolcanic rocks from the Orijärvi area, Svecofennides, southwestern Finland, recorded a constrictional type of strain. The X axes of strain ellipsoids in metavolcanic rocks are parallel to F_1 fold axes in layered metasediments, while the XY plane of the strain ellipsoid is parallel to the axial plane of the folds. We conclude that straining of non-layered metavolcanics was coeval with folding of layered metasediments. Diapir-related constriction induced by the neighbouring co-genetic batholith intrusion explains the pattern of deformation in the Orijärvi triangle in the most straightforward manner.

ACKNOWLEDGEMENTS. We dedicate this paper to Maarten Ploegsma, who died shortly after finishing his structural analyses in the Orijärvi triangle. NSG publication No 990801.

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