Bulletin of the Geological Society of Finland, Vol. 75 (1–2) pp. 93–101

Structural evolution of the Vuotso area, Finnish Lapland

Mikko Nironen* and Irmeli Mänttäri
Geological Suvey of Finland, P.O. Box 96, FIN-02151 Espoo, Finland

Abstract
The Vuotso area is structurally interesting because the fold interference pattern in rocks of central Lapland changes into thrust-related foliation of the Lapland Granulite Belt. A felsic volcanic rock yielded a 2.45 Ga age and conformed that the volcanic rocks in the Vuotso area are (mainly) Paleoproterozoic. A structural sequence with recumbent F_2 folding and predominant S_2 foliation, and an interference pattern of F_3 and F_4 foldings could be discerned in the supracrustal rocks. A large D_3 antiform is overprinted by mafic-intermediate gneisses that form the basal part of the thrust sequence. The curving of late D_3 shear zones suggests that D_3 deformation may be associated with thrusting from east-northeast, but thrusting of the granulites and adjacent mafic-intermediate gneisses to their present position is interpreted as a post-D_3 event.

Key words: structural geology, structural analysis, granulites, gneisses, metavolcanic rocks, absolute age, U/Pb, Paleoproterozoic, Vuotso, Lapland Province, Finland

1. Introduction

The rock assemblages in the central part of Finnish Lapland are already quite well known. However, there is a need for structural studies in order to reveal the stratigraphic order of these rocks. In spring 1997 the Vuotso area (Fig. 1) was suggested for a detailed structural–metamorpic study area because of locally good outcrop density, and because the study may shed light to the relationship of the structural and metamorphic evolution in the Lapland Granulite Belt and to the south of the belt. A preliminary work was done in this area during the summer 1997; the present paper deals with the structural part of the work.

2. Field work

The study area extends from the Porttipahta dam to the margin of the Lapland Granulite Belt. A bedrock map at 1:100 000 scale was available from the southern part of the study area (map sheet 3723; Pihlaja & Manninen, 1993). The northern part is included in large-scale maps that cover the entire central Lapland (Mikkola, 1937; Lehtonen et al., 1984, Appendix map in Lehtonen et al., 1998). In addition to these, outcrop and boulder maps over the area were available.

3. Lithology

The study area in map sheet 3723 consists of mica gneisses with quartzite interlayers, and komatiitic and basaltic volcanic rocks; intermediate volcanics are also encountered (Pihlaja & Manninen, 1993). The Siltaharju area consists of komatiitic tuffs and lavas that have been altered and retrogressed to chlorite-amphibole schists. The anthophyllite and garnet-cordierite-anthophyllite rocks (retrogressed to garnet-chlorite rocks) that are found among the metalavas and metatuffs are presumably also volcanic in origin. The large area of metavolcanic rocks in the northern part of the study area is mainly comprised of amphibolites. The felsic rocks around the Porttipahta dam are medium-grained, faintly banded quartz-feldspar schists

*Corresponding author
e-mail: mikko.nironen@gsf.fi

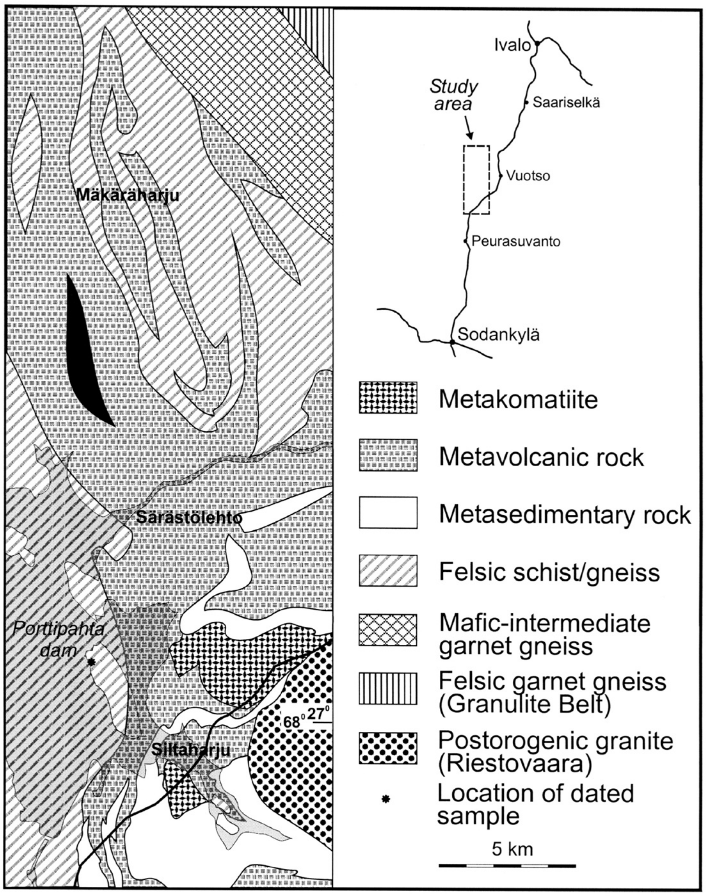

Fig. 1. Geological map of the Vuotso area (modified from Pihlaja & Manninen, 1993; Lehtonen et al., 1998).

with mafic volcanic rocks as interlayers whereas those in the northern part are migmatitic gneisses with granitic leucosome veins and amphibolitic interlayers.

A belt of migmatitic, garnet-bearing mafic-intermediate gneisses parallels the margin of the Lapland Granulite Belt. The gneisses contain interlayers of more homogeneous amphibolite. The granulites in the northeastern part of the study area are typical felsic gneisses of the Lapland Granulite Belt with abundant garnet.

The metakomatiites are considered to be part of the Paleoproterozoic (>2.05 Ga; Räsänen & Huhma, 2001) Savukoski Group whereas the other metavolcanic rocks have been thought to be part of the Archean Tankajoki Suite (Lehtonen et al., 1998). Also the felsic gneisses were previously considered to be Archean (Lehtonen et al., 1998) but recent U-Pb zircon datings suggest that the felsic rocks around the Porttipahta dam are Paleoproterozoic (~2.49 Ga; Manninen et al., 2001). The supracrustal rocks are crosscut by the Riestovaara granite which is one of the postorogenic (1.80–1.77 Ga; Huhma, 1986) *Nattanen-type* granites (Mikkola, 1941). Further northeast the postorogenic Nattanen granite crosscuts the rocks of the Lapland Granulite Belt.

4. Structures

The study area is generally poorly exposed but the outcrop density in the Siltaharju area allows a detailed structural analysis. A single outcrop in a metatuff (chlorite-amphibole rock) exhibits the whole structural succession in the Silta-

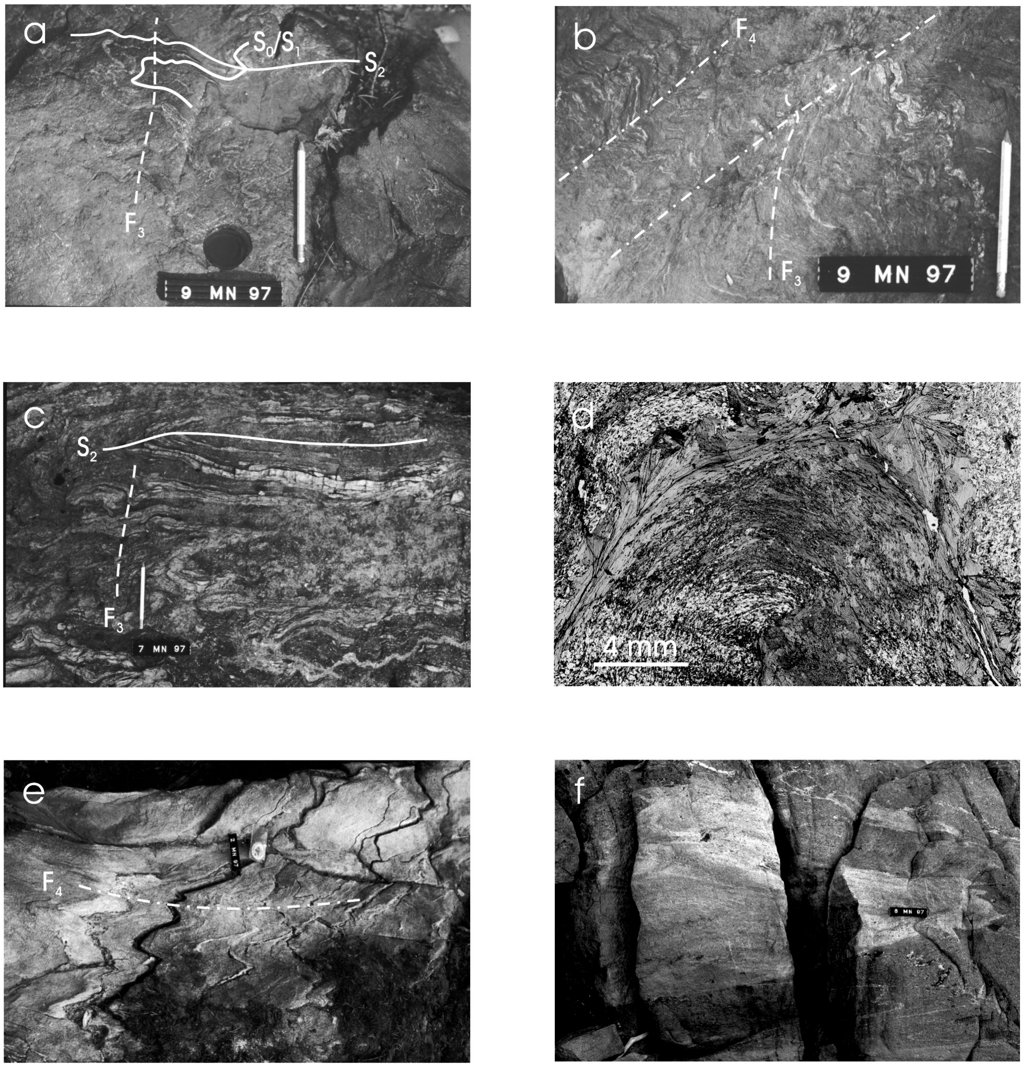

Fig. 2. Structures in rocks of the Siltaharju area. a) Komatiitic metatuff with compositional layering S_0/S_1, folded by F_2 with prominent S_2 schistosity. Open F_3 folding overprints S_2. Length of scale bar 12 cm, pencil points to north (x=7544.62, y=3493.78). b) Chevron-type F_4 folding in the same outcrop as in Fig. 2a. c) Isoclinal F_2 folding and open F3 folding in chloritized anthophyllite rock (x=7544.82, y=3494.22). d) Microphotograph of F_3 folding in chloritized anthophyllite rock. The chloritized anthophyllite rosette (upper right) overprints F_3 fold hinge (x=7544.73, Y=3494.00). e) Tight F_4 folding with E-W axial plane in komatiitic metalava (x=7543.63, y=3494.70). f) Recumbent F_2 folding in felsic and mafic metavolcanic rocks. Subvertical rock surface, length of scale bar 12 cm (x=7548.30, y=3491.14).

harju area. Fine-scale S_1 mineral foliation, parallel to compositional layering (S_0), may be discerned in small F_2 fold hinges where it is crenulated by the penetrative S_2 schistosity (Fig. 2a). The axial plane of F_3 folding trends N-S and is deformed by chevron-type F_4 folding (Fig. 2b). S_2 schistosity is the predominant foliation in the Siltaharju area. In the cordierite-anthophyllite rocks the compositional banding as well as quartz veins are tightly to isoclinally F_2 folded (Fig. 2c). An L_2 mineral lineation is associated with F_2 folding.

F_3 folding governs the structural pattern in the Siltaharju area. The wavelength of the cylindrical, open to tight F_3 folding varies fromn a few tens of centimeters to several meters. The axial plane of F_3 folding is subvertical and trends north-northeast, and the fold axis dips steeply (60–70°) to the north. F_3 folding is not associated with distinct mineral growth parallel to axial plane, hence also the L_3 intersection lineation is weak. Chlorite rosettes (alteration products of anthophyllite) overgrow F_3 structures at fold hinges (Fig. 2d). The microtextures show that the anthophyllite rosettes grew at the final stage of F_3 folding or afterwards, and chloritization occurred after D_3 deformation. Open to tight, cylindrical to chevron-type F_4 folding with an approximately east-west trending subvertical axial plane, is rather common in this area (Fig. 2e). Greenish amphibole (tremolite) laths overgrow F_4 structures in the metatuffs.

The intensity of F_3 folding decreases and becomes open from Siltaharju toward the Särästölehto area. Moreover, S_2 becomes subhorizontal; this is assumed to be the original orientation of the S_2 planes. Recumbent F_2 folding (Fig. 2f) is common in the Särästölehto area, and in a few suitable outcrops fold vergence is to the north. Recrystallization of amphibole in tuffites into polygonal arcs in F_3 crenulation hinges implies amphibolite facies conditions during D_3. Open F_4 folding with E-W trending axial plane is also visible in the Tankajoki area. Fractures filled with epidote are found parallel to the F_4 axial plane.

The outcrop density decreases toward north in the study area, and most observations are from local boulders. The mafic-intermediate gneisses bordering the granulites exhibit a foliation than dips moderately (~40°) northeast, toward the granulites. This foliation is axial planar to isoclinal folding with subhorizontal fold axis. A foliation with similar trend is found also in the granulites.

A few sharp northwest-trending lineaments, seen as negative anomalies in the aeromagnetic map, crosscut the postotogenic granites (Fig. 3). These lineaments are designated as post-1.80 Ga faults in the structural map (Fig. 4) and some of them evidently have a sinistral horizontal displacement component.

5. Structural evolution

The identified D_1 structures imply at least local mineral growth during D_1 deformation. The subhorizontal orientation of the predominant S_2 schistosity in the Särästölehto area is probably original, and the recumbent F_2 folds in the Särästölehto area suggest tectonic transport from south or southwest. The north-trending F_3 axial surfaces indicate compression in the east-west direction. The large ovoidal structure in the aeromagnetic map in the northern part of the study area (Fig. 3) is interpreted as a D_3 antiform, and the north-trending zones that deform the ovoidal structure are considered as late-D_3 shear zones with a major vertical component (Fig. 4). Subsequent north-south compression produced F_4 folding which is open in the Tankajoki area but more intense and conjugate in the Siltaharju area which is a D_4 basin area.

Based on the pattern in the aeromagnetic map (Fig. 3), the northwest trending thrust belt, including the granulites as well as in the amphibole gneisses adjacent to them, overprints the ovoidal D_3 antiform. Consequently, thrusting took place after D_3 deformation. The relationship between thrusting and D_4 deformation is obscure but the persistence and continuity of the structures in the granulites and amphibole gneisses suggests post-D_4 thrusting. The minimum age (1.77 Ga) for thrusting is set by the postorogenic Nattanen granite which crosscuts the thrust-related foliation.

The S_2 schistosity is the predominant foliation in Siltaharju, as it is generally in the entire central Lapland area (Lehtonen et al., 1998). The interpretation of the structural evolution in the Vuotso area conforms in general with the interpretation of Lehtonen et al. (1998) for the central Lapland area.

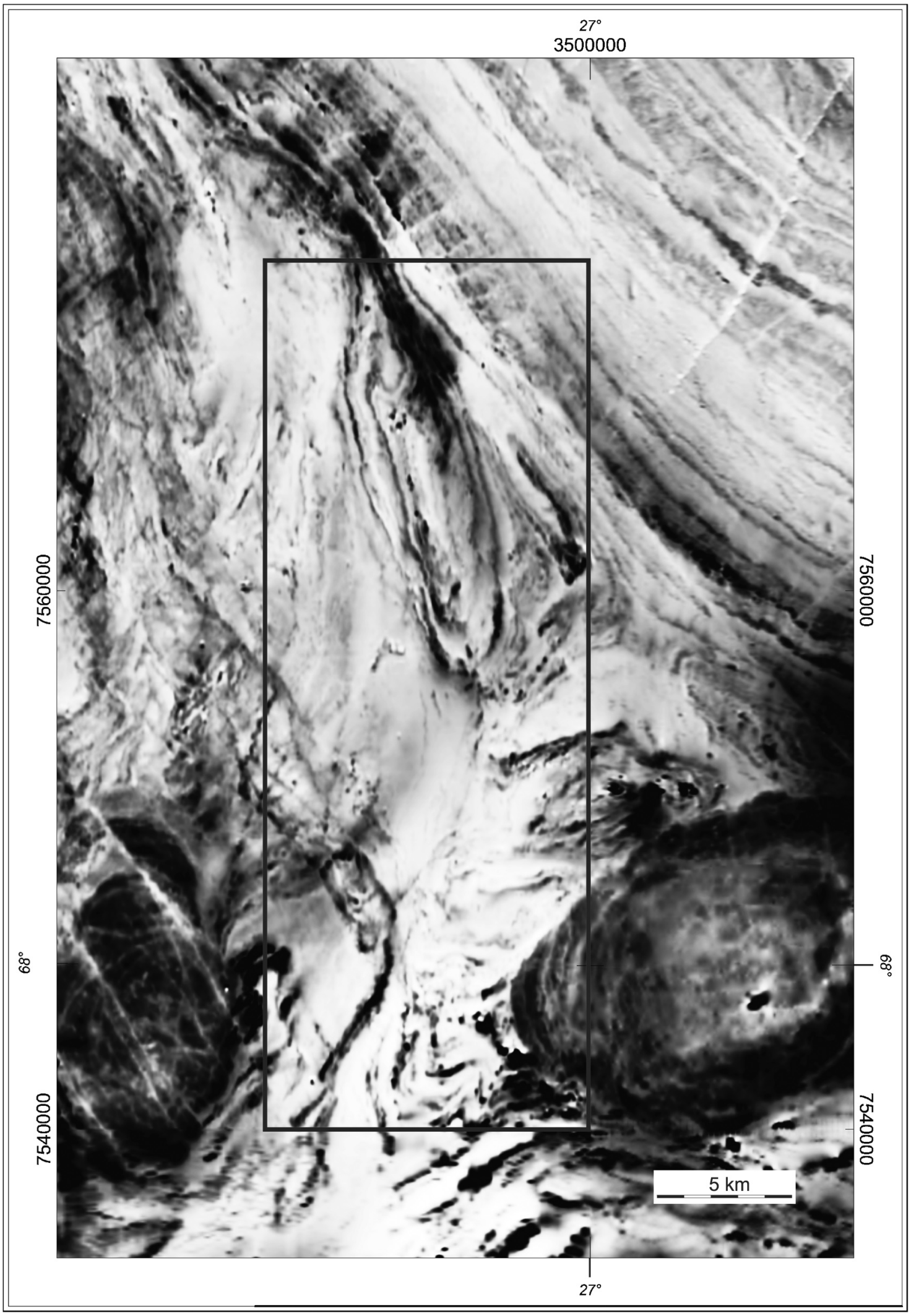

Fig. 3. Aeromagnetic map of the Vuotso area. The postorogenic granites show up as strong positive, ovoidal anomalies. The study area is shown by the rectangle.

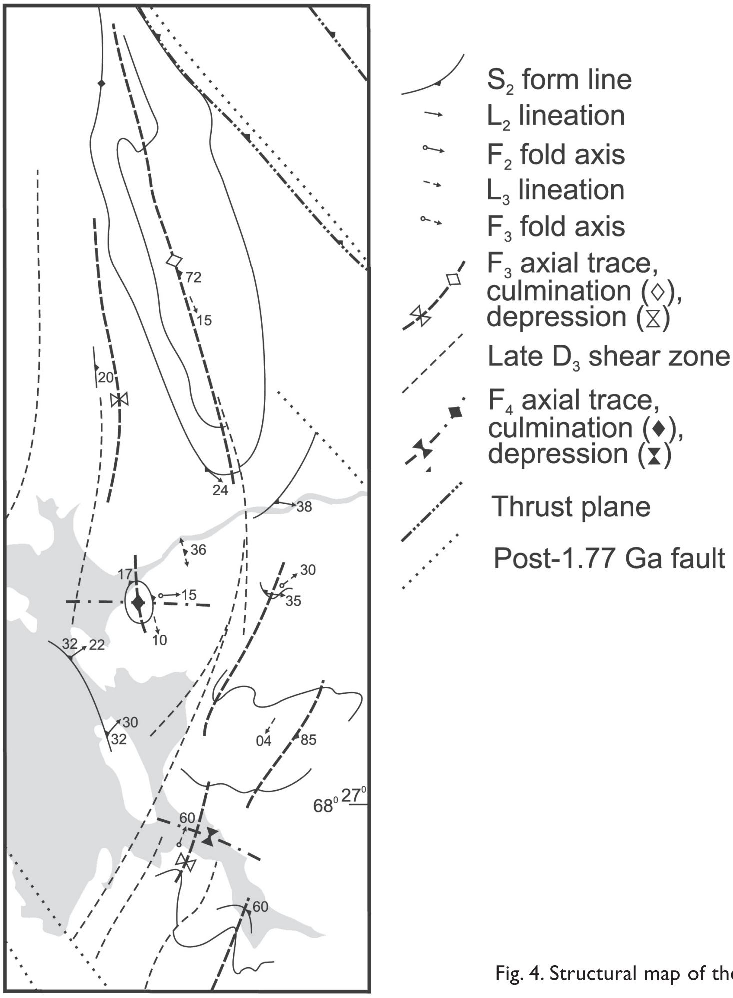

Fig. 4. Structural map of the Vuotso area.

6. U-Pb dating

6.1. Sample and methods

For U-Pb dating a felsic rock sample (A1671 Pahtavaara), named as quartz-feldspar schist, was taken from an island of the Porttipahta dam. The rock is medium-grained, schistose and shows faint banding with amphibolite. The contact between the alternating rock types is sharp (Fig. 2f). Presumably both rock types are volcanic in origin.

The zircon population of the quartz-feldspar schist A1671 Pahtavaara is rather heterogeneous. In the density fraction d>4.2 gcm^{-3}, the transparent, almost colorless or reddish by Fe-pigment, elongated zircons with short prisms are the most common ones in fine-grained (< 75 μm) mineral fraction. In addition, the smallest zircons in coarse-grained fraction (>0.75 μm) are similar, although they show normally longer prisms. All the dated zircons are of the previously described type (Table 1). Most of the coarse-grained zircons (>75 μm) in the density fraction d>4.2 gcm^{-3} and the majority of the zircons in the density fraction 4.2–4.0 g cm^{-3} are large, dark brown to dark red pigmented, turbid, and prismatic to anhedral type although other, usually more pale types also exist. Although no age evidence is available, it is considered that at least the large, dark brown zircons are inherited. The sphene in sample A1671 is quite turbid.

The decomposition of zircons and extraction of U and Pb for conventional isotopic age determinations follows mainly the procedure described by Krogh (1973). ^{235}U-^{208}Pb-spiked and unspiked isotopic ratios were measured using a VG Sector 54 thermal ionisation multicollector mass spectrometer. The measured lead and uranium isotopic ratios were normalized to the accepted ratios of SRM 981 and U500 standards. The U-Pb age calculations were done using the PbDat-program (Ludwig, 1991) and the fitting of the discordia lines and calculation of intercept ages using the Isoplot/Ex program (Ludwig, 1998).

6.2 Results

The five analyzed zircon fractions (Table 1) from the sample A1671 Pahtavaara construct a discordia line which intercepts the concordia curve at 2451±12 Ma and 445±130 Ma (MSWD=4.2; n=5) (Fig. 5). However, the somewhat high MSWD value, expressing a scatter larger than expected by the given errors and error correlation, is caused by the most discordant zircon fraction B. When the analyse point B is rejected, the four zircon fractions fall on a line with a MSWD value of 0.75. This line intercepts the concordia curve at 2454±5 Ma and 497±52 Ma. It is considered that this age is a good approximation for the timing of volcanism in the area. The question if the resulting age is a metamorphic age is contradicted by the facts that 1) the zircons are prismatic and therefore magmatic in origin, 2) the U contents of the zircons are moderate, not low as is normally the case in metamorphic zircons, and 3) such a fairly good regression line is not expected from the metamorphic zircons, as they usually contain some older U-Pb memory and are quite resistant to further lead loss.

The turbid sphene gives a discordant age result with a $^{207}Pb/^{206}Pb$ age of ca. 2.26 Ga (Table 1 and Fig. 5). This age must be considered

Table 1. Conventional U-Pb age data on zircons, A1671 Pahtavaara quartz-feldspar gneiss.

Sample information	Sample	U	Pb	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	ISOTOPIC RATIOS[1]						Rho[2]	APPARENT AGES/Ma±2 sigma		
Analysed mineral and fraction	weight/mg	ppm	ppm	measured	radiogenic	$^{206}Pb/^{238}U$	2σ%	$^{207}Pb/^{235}U$	2σ%	$^{207}Pb/^{206}Pb$	2σ%		$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A) zircon: d>4.2 gcm^{-3}, >75 μm, transparent, l:w=1.5-4.0, abraded 5h	0.42	376	173	9525	0.11	0.4195	0.65	9.118	0.65	0.1576	0.15	0.97	2258	2350	2431±2
B) zircon: d>4.2 gcm^{-3},>75 μm, transparent, l:w=1.5-4.0	0.40	547	229	1319	0.11	0.3720	0.65	7.966	0.65	0.1553	0.15	0.97	2039	2227	2405±2
C) zircon: d>4.2 gcm^{-3}, <75 μm, transparent, l:w=1.5-3,abraded 5h	0.53	537	241	2981	0.10	0.4069	0.65	8.792	0.65	0.1567	0.15	0.97	2201	2317	2420±2
D) zircon: d>4.2 gcm^{-3}, <75 μm, transparent, l:w=1.5-3	0.54	549	234	1191	0.10	0.3769	0.65	8.054	0.65	0.1550	0.15	0.97	2062	2237	2402±2
E) zircon: d>4.2 gcm^{-3}, >75 μm, transparent, l:w=1.5-4, abraded 18h	0.48	414	202	2606	0.13	0.4329	0.65	9.454	0.65	0.1584	0.15	0.97	2319	2383	2438±2
F) sphene: turbid, abraded 1/4 h	2.85	60	31	312	0.32	0.3655	0.65	7.1846	0.65	0.1426	0.34	0.86	2008	2135	2258±6

1) Isotopic ratios corrected for fractionation, blank (50 pg), and age related common lead (Stacey and Kramers 1975; $^{206}Pb/^{204}Pb$±0.2, $^{207}Pb/^{204}Pb$±0.1, $^{208}Pb/^{204}Pb$±0.2).
2) Rho: Error correlation between $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios.

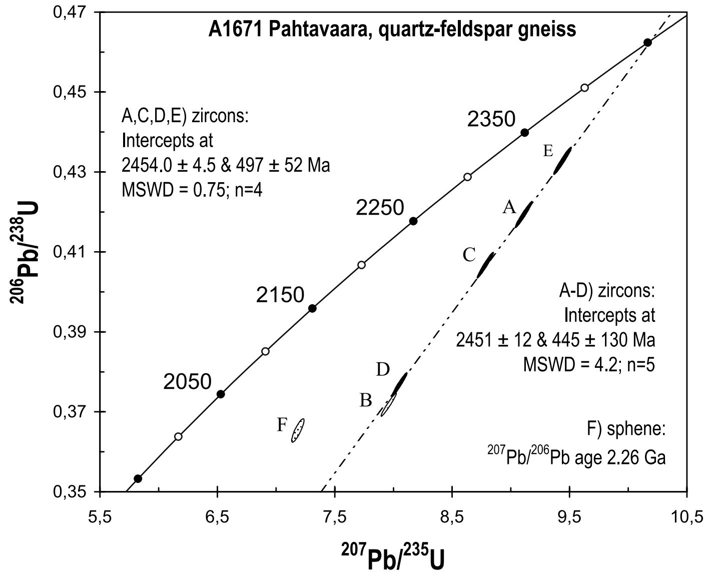

Fig. 5. Concordia diagram for analyzed zircon fractions, A1671 Pahtavaara quartz-feldspar gneiss.

as a minimum age for the closure of the U-Pb system in sphene. On the other hand, the age cannot be much older than 2.30 Ga, if the lower intercept age is considered as normal. More or less correspondingly, Manninen et al. (2001) reported a strongly discordant age for sphene ($^{207}Pb/^{206}Pb$ age ca. 2.17 Ga) from faintly banded quartz-feldspar schist (A416 Kunnasenvaara) from the SW shore of the Porttipahta lake.

7. Discussion

Belyaev and Kozlov (1997) made a geochemical and metamorphic study from the northern part of the Vuotso area. They considered the migmatitic felsic gneisses and the amphibolitic interlayers in the Mäkäräharju area as Archean in age and concluded that these rock types exhibit two tectonometamorphic cycles: the early cycle is characterized by static granulite metamorphism and the later one by ambhibolite facies metamorphism and associated deformation. In contrast, the mafic volcanic rocks in the Särästölehto area are Proterozoic and characterized by only one metamorphic cycle and "simple" deformation. The interpretation of Belyaev and Kozlov (1997) is based mainly on metamorphic assemblages, and such a distinction cannot be verified with structural methods. Their 'late tectonometamorphic cycle' consists of D_3 and D_4 deformations of the present study; hence the earlier deformations may have counterparts in the structures found in the Siltaharju area.

Recent Paleoproterozoic ages on the felsic rocks around the Porttipahta dam (Manninen et al., 2001) contradict with the assumed Archean age of the metavolcanic rocks of the Tankajoki Suite (Lehtonen et al., 1998). The new age from the felsic schist fof the Porttipahta island further suggests that the whole mafic-intermediate volcanic sequence that extends to the northern part of the study area and further northeast is Paleoproterozoic in age. The felsic gneisses in the northern part of the study area appear to be higher grade analogues of the felsic schists in the Porttipahta area but as there is no isotope data on them, their origin and age still remains unclear.

The structures in the low grade rocks can be correlated from Siltaharju to Mäkäräharju. In the belt of higher grade mafic-intermediate gneisses the older structures have been largely obliterated during metamorphism, hence structural correlation to lower grade rocks is difficult. The gneisses were probably thrusted from the northeast as a basal package of the Lapland Granulite Belt. According to Tuisku and Huhma (1998) radiometric ionprobe datings confirm that granulite facies metamorphism, deformation, and igneous activity in the Lapland Granulite Belt took place at 1905–1880 Ma in the middle and lower crust, and that thrusting occurred at the late stage of metamorphism. On the other hand, Lehtonen et al. (1998) concluded that the maximum age of regional D_2 deformation is 1885 Ma. Since thrusting in the Vuotso area took place after D_3 deformation, it is possible that there were more than one thrusting episode; the structures we see in the Vuotso area are due to the latest one.

Acknowledgements

We are grateful to Tuomo Manninen for field introduction to the study area and for providing outcrop data. Peter Sorjonen-Ward made valuable comments on the manuscript. Maija Kurimo is thanked for the aeromagnetic map and Marita Niemelä for assisting in U-Pb laboratory.

Editorial handling: Petri Peltonen

Rererences

Belyaev, O.A. & Kozlov, N.E., 1997. Geology, geochemistry and metamorphism of the Lapland Granulite Belt and adjacent areas in the Vuotso area, northern Finland. Geological Survey of Finland, Report of Investigation 138, 21 p.

Huhma, H., 1986. Sm-Nd, U-Pb and Pb-Pb isotopic evidence for the origin of the Early Proterozoic Svecokarelian crust in Finland. Geological Survey of Finland, Bulletin 337, 48 p.

Krogh, T.E., 1973. A low-contamination method for hydrothermal decomposition of U and Pb for isotopic age determinations. Geochimica et Cosmochimica Acta 37, 485–494.

Lehtonen, M.I., Manninen, T., Rastas, P., Väänänen, J., Roos, S.I. & Pelkonen, R., 1984. Geological map of Central Lapland, northern Finland 1:200 000. Geological Survey of Finland.

Lehtonen, M., Airo, M.-L., Eilu, P., Hanski, E., Kortelainen, V., Lanne, E., Manninen, T., Rastas, P., Räsänen, J. & Virransalo, P., 1998. Kittilän vihreäkivialueen geologia. Lapin vulkaniittiprojektin raportti. Geological Survey of Finland, Report of Investigation 140, 144 p.

Ludwig, K.R., 1991. PbDat 1.21 for MS-dos: A computer program for IBM-PC Compatibles for processing raw Pb-U-Th isotope data. Version 1.07. U.S. Geological Survey Open-File Report 88-542, 35 p.

Ludwig, K.R., 1998. Using Isoplot/Ex Version 1.00. Berkeley Geochronological Center, Special Publication 1, 43 p.

Manninen, T., Pihlaja, P. & Huhma, H., 2001. U-Pb geochronology of the Peurasuvanto area, northern Finland. Geological Survey of Finland, Special Paper 33, 189–200.

Mikkola, E., 1937. General geological map of Finland 1: 400 000, Pre-Quaternary rocks. Sheet C7 Sodankylä. Geological Survey of Finland.

Mikkola, E., 1941. Kivilajikartan selitys, Muonio-Sodankylä-Tuntsajoki. English summary: Explanation to the map of rocks.

Tuisku, P. & Huhma, H., 1998. Eclogite from the SW-marginal zone of the Lapland Granulite Belt: evidence from the 1.90–1.88 Ga subduction zone. Geological Survey of Finland, Special Paper 26, 61.

Pihlaja, P., 1987. The diabase of Laanila. Geological Survey of Finland, Report of Investigation 76, 189–197.

Pihlaja, P. & Manninen, T., 1993. Peurasuvanto, Geological map of Finland 1:100 000, Pre-Quaternary rocks. Sheet 3723. Geological Survey of Finland.

Räsänen, J. & Huhma, H., 2001.U-Pb datings in the Sodankylä schist area, central Finnish Lapland. Geological Survey of Finland, Special Paper 33, 153–188.

Stacey, J.S. & Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters 26, 207–221.