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Postglacial Deformation of the Fennoscandian Crust

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Abstract

Generally speaking, crustal deformation has three components, one vertical and two horizontal. This must hold true also for the Fennoscandian Shield. One of them, the vertical component, has been under intensive study for many centuries in Fennoscandia and is, therefore, relatively well-known. On the contrary, only little is known of horizontal components, until now.

Very recently, horizontal components of the deformation of the Fennoscandian crust have been taken under investigation, and the first results of analyses of geotechnical rock measurement, seismic, and geodetic data indicate that the maximum horizontal compression prevails in Scandinavia in the NW-SE direction.

Key words: crustal deformation, geodynamics, glacial isostasy, land uplift, postglacial rebound, stress phenomenon

1. Introduction

The Fennoscandian Shield is the northwest part of the old protocontinent Baltica. This protocontinent, formed in the Archaean and Proterozoic eons, differs essentially from the central and southern parts of today´s Europe, mostly formed in the Phanerozoic eon. It is characterized by a thick lithosphere (110 - 170 km) and low thermal heatflow (< 50 mW/m^2), while the Phanerozoic Europe has a thin lithosphere (50-90 km) and relatively high heatflow (50 - 80 mW/m^2). It is presently undergoing crustal uplift with a maximum rate of about 10 mm/yr. A large geoidal depression, related with the uplift, is visible in the centre of the Shield (*Kakkuri*, 1993).

The uplift of land from the sea has been the subject of observations in Finland and Sweden for over 300 years. During this very long time people have been able to follow, how regression of the shore line has produced rapidly new land on the shallow shores of the Gulf of Bothnia, in Finland even 7 km^2/yr! The recent uplift is rather well-known, due to repeated geodetic observations over a long time.

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The study of the state of stress in Europe, recently described by *Müller et al.* (1992), shows that the NW-SE orientation of the maximum compressive horizontal principal stress, which generally prevails in Europe, is not so consistent in Northern Europe. This conclusion may be due to the sparsity of Scandinavian data used in the study, which mostly comprises results from geotechnical rock stress measurements in mines and construction sites as well as from shallow, low magnitude earthquake observations. On the contrary, geodetic triangulation data (*Chen*, 1991), which were not included in the study of *Müller et al.* (1992), indicate the consistency, i.e. the maximum horizontal compression prevails also in Scandinavia in the NW-SE direction, see Fig. 3.

In the following, the uplift and horizontal stress phenomena of the Fennoscandian crust are treated in a detailed way.

2. *Fennoscandian uplift, latest results*

2.1 *Geodetic observations*

Three kinds of geodetic observations are available for determination of the uplift rates, namely: 1) *sea level records,* 2) *lake level records,* and 3) *repeated levellings*. Sea level records show the rate of continuous rise of land from the sea along the coasts of the adjacent seas, whereas lake level records and repeated levellings indicate the uplift differences (i.e. tilts) inside the land.

Sea level time series of many decades long are needed to determine the land uplift rates accurately. This is due to the periodicity which is evident in the records of all the tide gauges of the Baltic Sea. Namely, the amplitude power spectra of the monthly mean data show the distinct peaks for the annual, semiannual, and Chandler periods (*Sjöberg & Fan,* 1986, *Vermeer et al.,* 1988, and *Dietrich et al.,* 1991). In addition, some long periods are visible in the spectra, e.g. the 2.7 and 6.4 (or 6.3) year cycles, but the 18.6 years long lunar nodal and the 11 years long solar cycle are missing.

The idea to use the lake level records for computing the land uplift differences (or tilts) in the inner parts of Fennoscandia was suggested by *Sieger* (1893). Later *Bergsten* (1930) used the old water level series of Lake Vänern for the purpose, and *Sirén* (1951) did the same in Finland, where the lake level observations span over a hundred years in some cases. Lake level records can be used where at least two water gauges are situated in the same lake fairly remote from each other. The greatest difficulties in determination are caused by winds, air pressure variations, and the influence of the erosion in the outlet beds.

Repeated levellings span, in many a Fennoscandian country, already over a hundred years, and comprehensive data coming from the Baltic States (*Randjärv,* 1993), Denmark (*Andersen et al.,* 1974), Finland (*Kakkuri and Vermeer,* 1985, *Kääriäinen,* 1966, *Suutarinen,* 1983, *Takalo and Mäkinen,* 1983), East-Germany and Russia (*Boulanger,* Ed., 1975, *Rehov,* 1990), Norway (*private comm.*), and Sweden (*Ussisoo,* 1977), have been applied to drawing the land uplift map below, Fig. 1.

2.2 Land uplift map

The uplift map shown in Fig. 1 is a combination of the sea level, lake level, and repeated levelling data. The accuracy of the isobases shown is not easy to estimate, although the standard deviations for Finnish and Swedish land uplift determinations are known to be 0.2-0.5 mm/yr, and in the Baltic States, Denmark and Norway it is not worse than 0.5 mm/yr. The accuracy of the newest Russian data (*Rehov*, 1990) is not known, but because it fits well with the Finnish data on the border, it gives the impression of reliability. It is interesting to find the strong uplift anomaly that prevails on the northernmost area of Lake Ladoga as well as in Southern Norway.

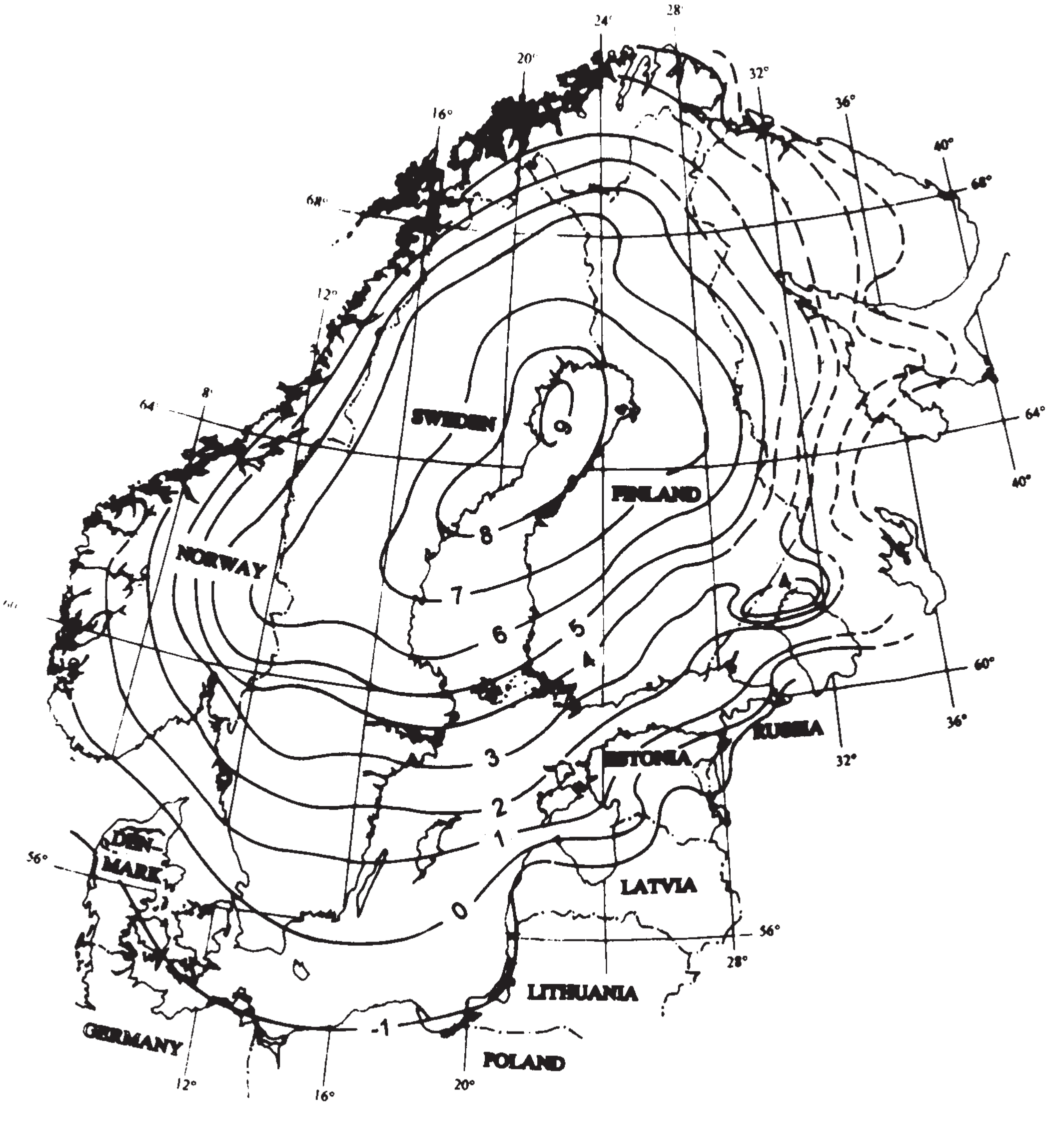

Fig. 1. Observed land uplift in mm/yr in the area of the Fennoscandian Shield. Notice the land uplift anomaly that prevails on the northernmost area of Lake Ladoga. In its center the maximum uplift value is as high as 6.4 mm/yr (according to *Rehov*, 1990).

2.3 Corrections to be made to the observed land uplift

The land uplift isobases in Fig. 1 show the uplift of the crust relative to the mean sea level, known as observed (or apparent) land uplift, v_o. It comprises the major portion of the "absolute" land uplift, v_a. The minor portions are the eustatic rise (v_e), the effect of varying salinity (v_s), and the rise of the geoid (v_g). When putting them together, we have

$$v_a = v_o + v_e + v_s + v_g \tag{1}$$

As soon as the numerical values of v_e, v_s, and v_g are known, absolute land uplift values can be calculated with eq. (1) for Fennoscandia.

2.3.1 The eustatic rise

The eustatic rise of the mean sea level is due to various factors, such as folding of the sea bed, accumulation of sediments on the sea floor, increase in mean ocean temperature (expansion), and melting or formation of continental ice masses.

In the 20th Century, the average value of the eustatic rise has been 1.0 - 1.1 mm/yr in the world oceans, and this rising trend has been consistent in the Baltic Sea up to 1975. Since then a change probably has taken place, as the 15-year moving average of the tide gauge at Hanko then no longer followed the trend, and this change was statistically significant at the 90% rejection level (*Kahma*, 1993).

2.3.2 Changing salinity

Salinity rates are rather low in the Baltic Sea, 0.7 % in the South and 0.1% in the North of the Sea. Due to infiltration of the Atlantic Ocean through the Danish Straits, the salinity varies in the Baltic Sea in time.

All measurements performed in this century show that the salinity has somewhat increased in the Baltic Sea, probably by 1 - 2 ‰ (*Vermeer et al.*, 1988). Because an increase in salinity by 1 ‰ causes a lowering of the sea surface by 10 mm, the lowering rate has been 0.1 - 0.2 mm/yr in this century.

2.3.3 The rise of the geoid

The rise of the geoid is related to postglacial rebound through subcrustal mass flow. The rise can be estimated by taking the time derivative of the Stokes formula (*Sjöberg*, 1982) as follows:

$$v_g = \frac{R}{4\pi\gamma_0} \iint_{\sigma} \left(\frac{\dot{g}}{v_o + v_e} + \frac{2\gamma_0}{R} \right) (v_o + v_e) S(\psi) \, d\sigma \tag{2}$$

where R is the radius of the Earth, γ_0 is normal gravity on the Earth´s surface, $\dot{g}$ is the time derivative of observed gravity, and $S(\psi)$ is the Stokes function. As, according to repeated high precision gravity measurements along the Fennoscandian land uplift gravity line at the approximate latitude 63° (*Ekman and Mäkinen,* 1994), $\dot{g}/(v_o + v_e) \cong -0.216$ μGal/mm and $2\gamma_0/R \cong 0.309$ μGal/mm, we have:

$$v_g = \frac{R}{4\pi\gamma_0}\iint_{\sigma} 0.093(v_0 + v_e)S(\psi)d\sigma \tag{3}$$

When using the observed values from the map of Fig. 1 for v_o and 1.0 mm/yr for v_e, the map shown in Fig. 2 was computed. The maximum value for the rise of geoid, around 0.6 mm/yr, is thus found to be in the centre of the Fennoscandian Shield.

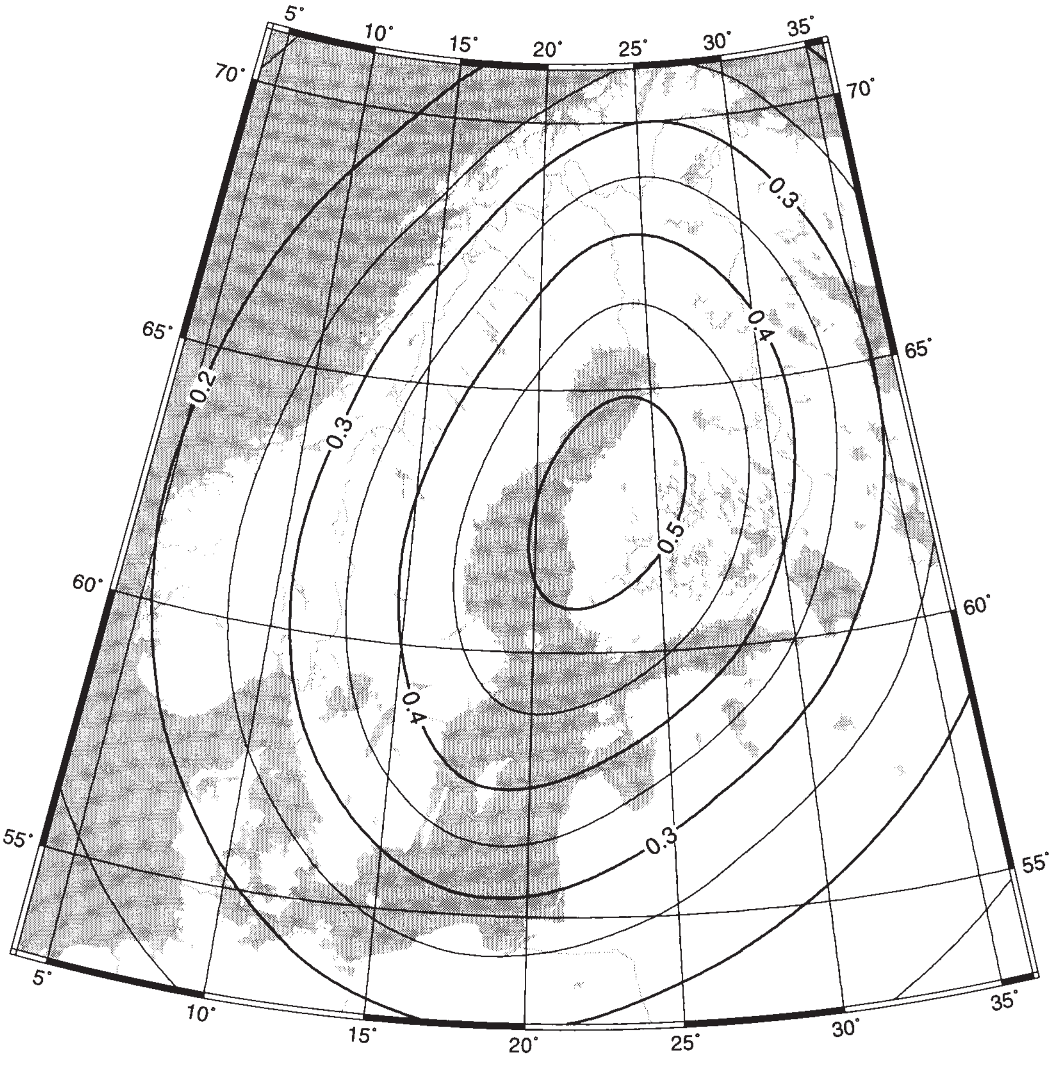

Fig. 2. The rise of the geoid in mm/yr in the area of the Fennoscandian Shield.

3. *Horizontal deformation*

Three sources of horizontal stress are possible in Fennoscandia: 1) remaining stresses from the last glaciation, 2) topography, and 3) ridge push from the Mid-Atlantic Ridge. The last-named source is the most important, and it can set so-called “forced” subduction in motion, as the oceanic lithosphere, still relatively young and warmer than the asthenosphere, is not able to subduct spontaneously but resists sinking along the subduction zone (see *Nicolas,* 1995), giving cause for the uplift and horizontal compression in Scandinavia.

3.1 *Analyses of repeated triangulations*

The I-order terrestrial triangulation of Finland, performed during the years from 1922 to 1987, was a combination of terrestrial triangulation chains that formed closed loops, and these trilateration nets that fullfilled the interiors of these loops. A span of 12 to 46 years (on the average 30 years) existed between the terrestrial and trilateration measurements.

The relative accuracy of the terrestrial triangulation was 2.5 ppm. When performing trilateration measurements, tellurometers MRA2, MRA3, and MRA 101 with relative accuracies 2.5 to 3.5 ppm or geodimeters M8 with a relative accuracy 0.5 ppm were used. The scales of both types of measurements, terrestrial triangulations and trilaterations, were derived from the same standard baseline.

3.1.1 Mathematical method used

When analysing the triangulations, horizontal strain can be treated with a 2-dimensional strain tensor (*Kakkuri,* 1993)

$$\mathbf{e} = \begin{vmatrix} e_{xx} & e_{xy} \\ e_{xy} & e_{yy} \end{vmatrix} = \begin{vmatrix} \dfrac{\partial u_x}{\partial x} & \dfrac{1}{2}\left(\dfrac{\partial u_x}{\partial y} + \dfrac{\partial u_y}{\partial x}\right) \\ \dfrac{1}{2}\left(\dfrac{\partial u_x}{\partial y} + \dfrac{\partial u_y}{\partial x}\right) & \dfrac{\partial u_y}{\partial y} \end{vmatrix} \tag{4}$$

where u_x and u_y are the elements of the 2-dimensional displacement vector $\mathbf{u} = (u_x u_y)^{\mathrm{T}}$ of a triangulation point.

The strain rate ε_i for a line from a triangulation point to another point is given as follows:

$$\varepsilon_{\mathrm{i}} = \frac{\Delta s_i}{s_i} = e_{xx}\cos^2\theta_i + e_{xy}\sin 2\theta_i + e_{yy}\sin^2\theta_i \tag{5}$$

where s_i is the unstrained length of the line, Δs_i the change in s_i during a time interval Δt_i and θ_i the azimuth of the line. Eq. (5) has three unkowns, e_{xx}, e_{xy}, and e_{yy}, which are solved from a sufficient number of repeated observations performed at least for three directions. They are further used for computing the strain parameters as follows:

Dilatation	$\Delta = e_{xx} + e_{yy}$
Pure shear	$\gamma_1 = e_{xx} - e_{yy}$
Engineering shear	$\gamma_2 = 2e_{xy}$
Total shear	$\gamma = \sqrt{\gamma_1^{\ 2} + \gamma_2^{\ 2}}$
Principal strains	$\varepsilon_1 = \frac{1}{2}(\Delta + \gamma)$
	$\varepsilon_2 = \frac{1}{2}(\Delta - \gamma)$
Direction of ε_1	$\beta = \arctan(e_{xy} / \varepsilon_1 - e_{xy})$

3.1.2 Results of the analyses

Chen (1991) determined values for ε_i at each triangulation point from the above mentioned repeated triangulation measurements and further used them to calculate the strain parameters. The resultant map of the horizontal strain is shown in Fig. 3. The magnitude of the strain rate seems to range from 0.0 to 0.5 μstrain/yr, with predominant values of 0.1 to 0.2 μstrain/yr. In general, maximum compressions in the NW-SE direction can be identified. Some features of the geological structures can also be identified, e.g. the Ladoga-Bothnian Bay Tectonic zone, as well as the Granulite Arch far in the North. Because the territory of Finland is seldom affected by anything but microearthquakes in our time, it is not possible to see any clear correlation between the strain and seismicity patterns

3.2 Monitoring systems

The GPS technique offers an effective way to study relative crustal motions, especially along the active plate boundaries. This is because the achievable accuracy is as high as ±1 centimetre for distances ranging from dozens of kilometres up to a few hundreds of kilometres.

When keeping the GPS stations permanently occupied, day-to-day data can be collected. This is further used for monitoring relative crustal motions that take place inside the network of the permanent stations. A regional deformation pattern may be obtained in less than 10 years.

Three categories of permanent GPS networks exist: global, regional, and national. Among the few global networks there is the IGS or *the International Geodynamics GPS Service Network*, established by the International Association of Geodesy for, e.g., monitoring deformations of the solid Earth.

Numerous regional networks are tied to the IGS Network. Among them there is *the Fennoscandian Regional Permanent GPS Network*, established by the Nordic

Geodetic Commission in response to an initiative from the directors of the Nordic mapping institutes. The main object of this network is to contribute to geodetic control surveys, but it will play an important role also in geodynamic investigations. It is a combination of the national permanent GPS Networks of the Nordic Countries consisting of 12 stations in Finland, 10 stations in Norway, and 20 stations in Sweden.

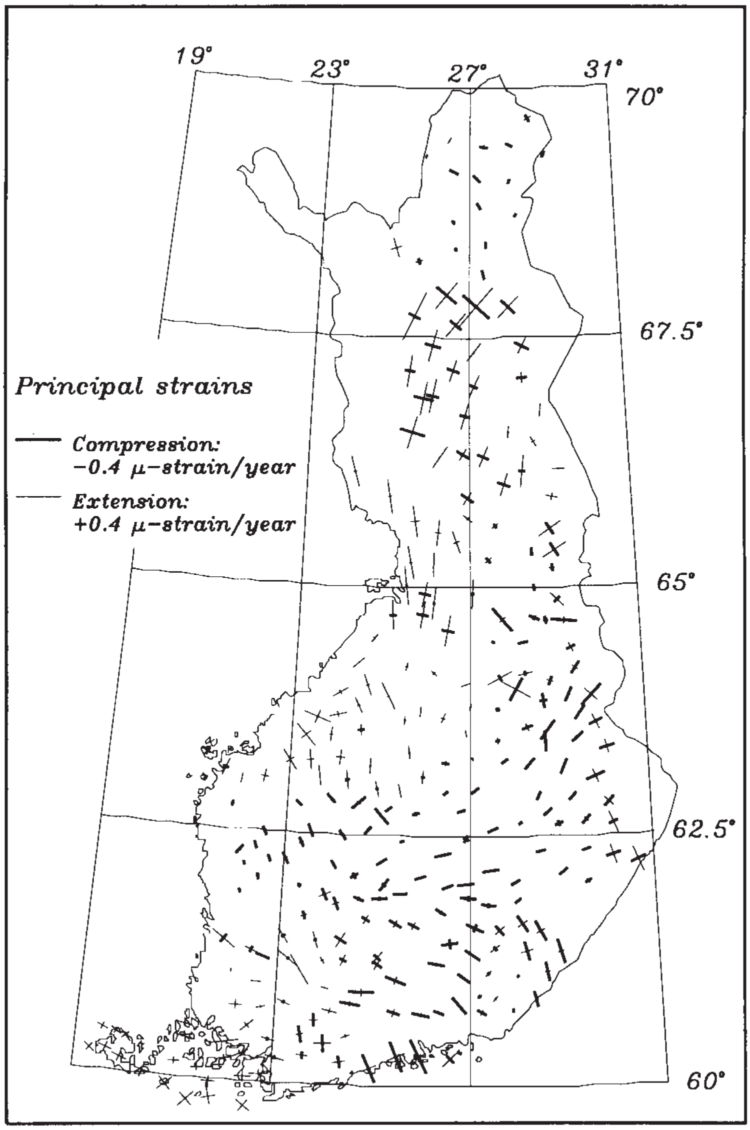

Fig. 3. Horizontal crustal strain in Finland according to *Chen* (1991).

The *National GPS Network of Finland* is shown in Fig. 4 (*Chen and Kakkuri,* 1994). The stations, which are located on different tectonic structural features of the crust, are connected to the precise levelling net for vertical control. As all 12 stations observe continuously, the operation of the network involves a huge amount of GPS data. All the data are transferred daily to a PC at the headquarters of the institute by modem and commercial telephone lines. A preliminary analysis and check of data is performed daily.

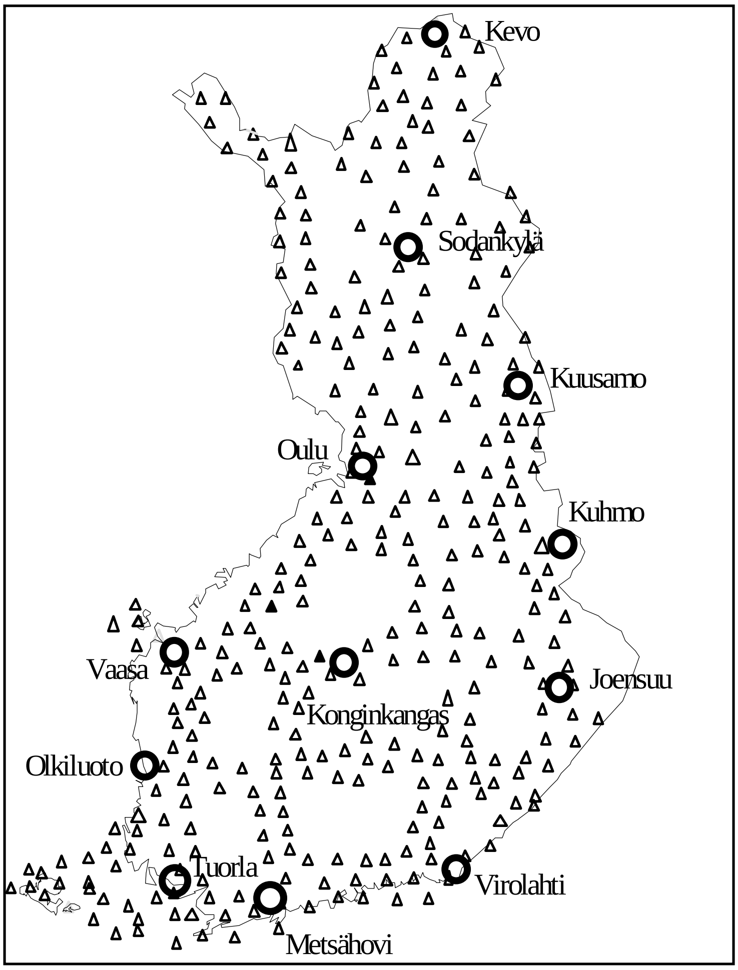

Fig. 4. Permanent GPS stations in Finland. Continuously operating GPS-stations are marked with open rings. The triangles show the first-order triangulation points used for computing the horizontal strain field for Finland.

4. *Discussion*

The Fennoscandian crust is strongly affected by two kinds of movements of subcrustal material, one being due to the postglacial rebound and the other to the convection movements in the mantle. Resulting phenomena are the land uplift, the rise of the geoid, and the ridge push from the Mid-Atlantic Ridge. The ridge push is considered to be the main cause of the horizontal stress observed.

Observed land uplift rates in the Fennoscandian Shield vary from 9 mm/yr to -1 mm/yr. Some surprisingly strong positive deviations from regularity (i.e., too great uplift values) are found, e.g. one in the South of Norway, and another at north of Lake Ladoga, etc. These can be related, if they are genuine, to the horizontal compression in the area (for details, see *Kakkuri*, 1993).

The magnitude of the horizontal strain rates, determined with repeated triangulations, is predominantly 0.1 to 0.2 μstrain/yr. Because the Fennoscandian Shield is seismically not very active, these observed strain rates seem to be too great. To confirm the correctness of the observed rates, more observations are to be made. The permanent GPS network has been established for the purpose. Because the achievable accuracy of the GPS method is as high as 1 cm for distances up to a few hundreds of kilometres, the regional deformation pattern can be determined reliably in less than 10 years.

5. *Acknowledgments*

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