ON THE THERMAL AND SEISMOTECTONIC ENVIRONMENT OF THE FINNISH PART OF THE WIBORG RAPAKIVI BATHOLITH

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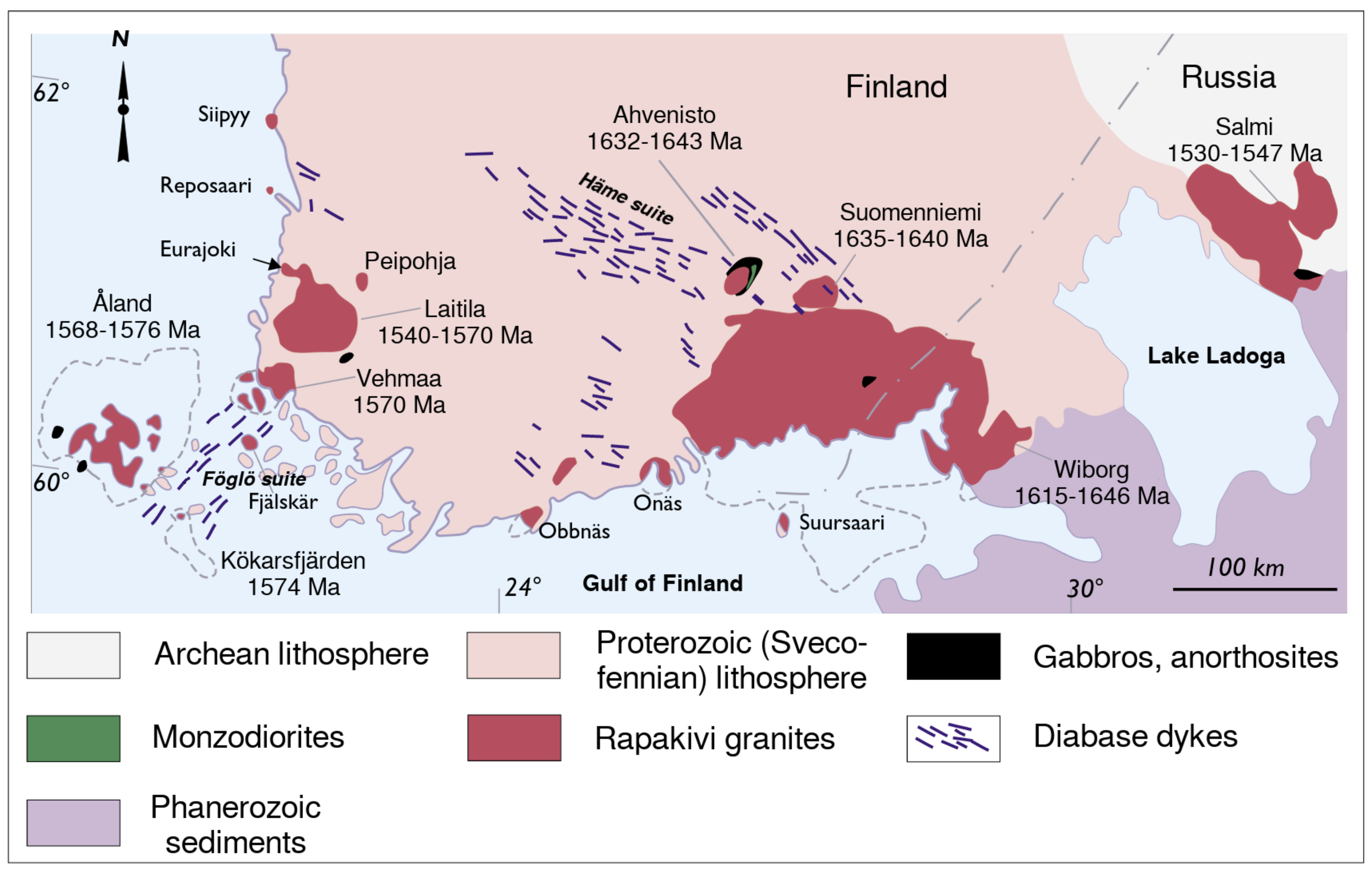
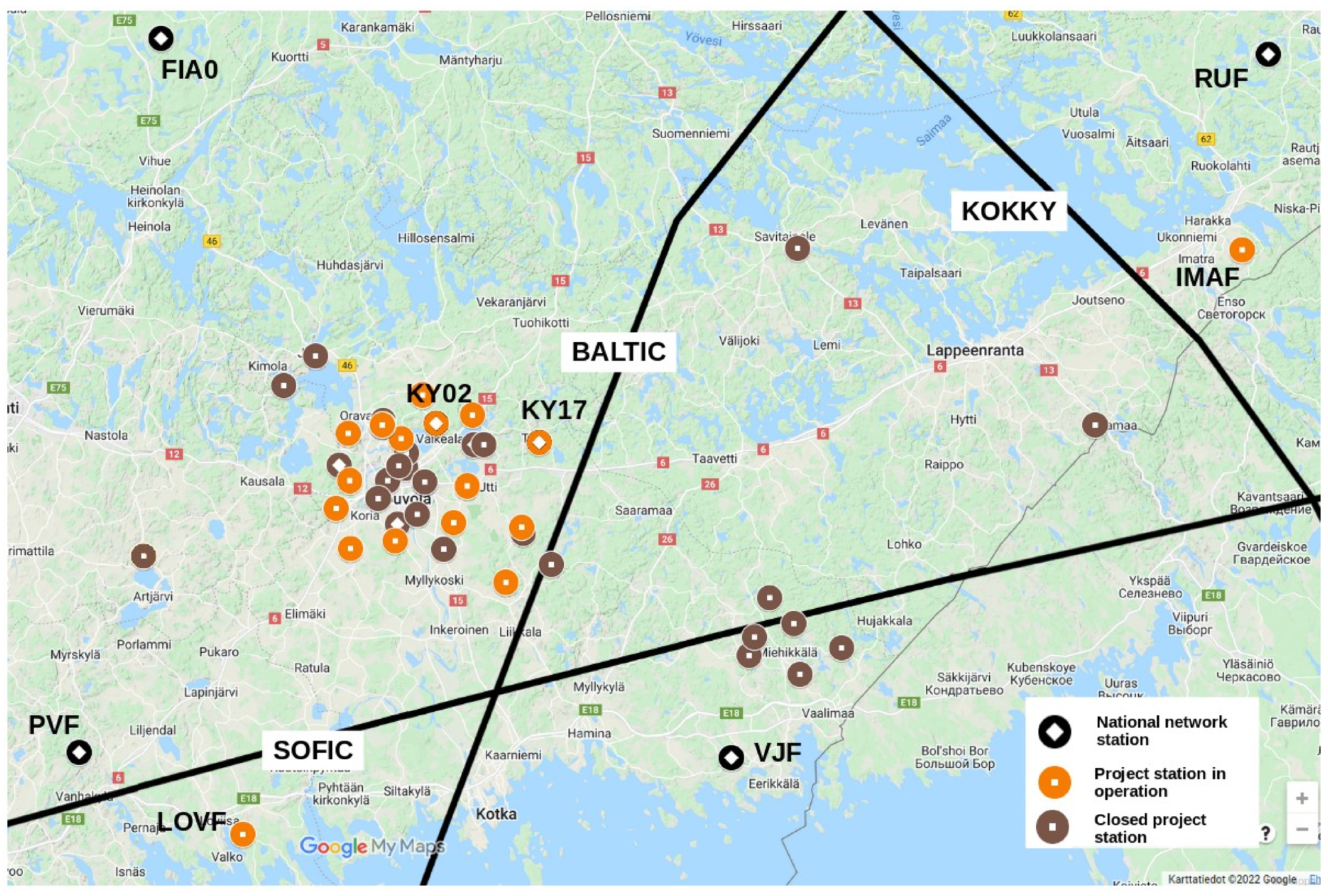


Rapakivi granite areas in Finland and NW Russia. Modified after Lehtinen et al. (1998).

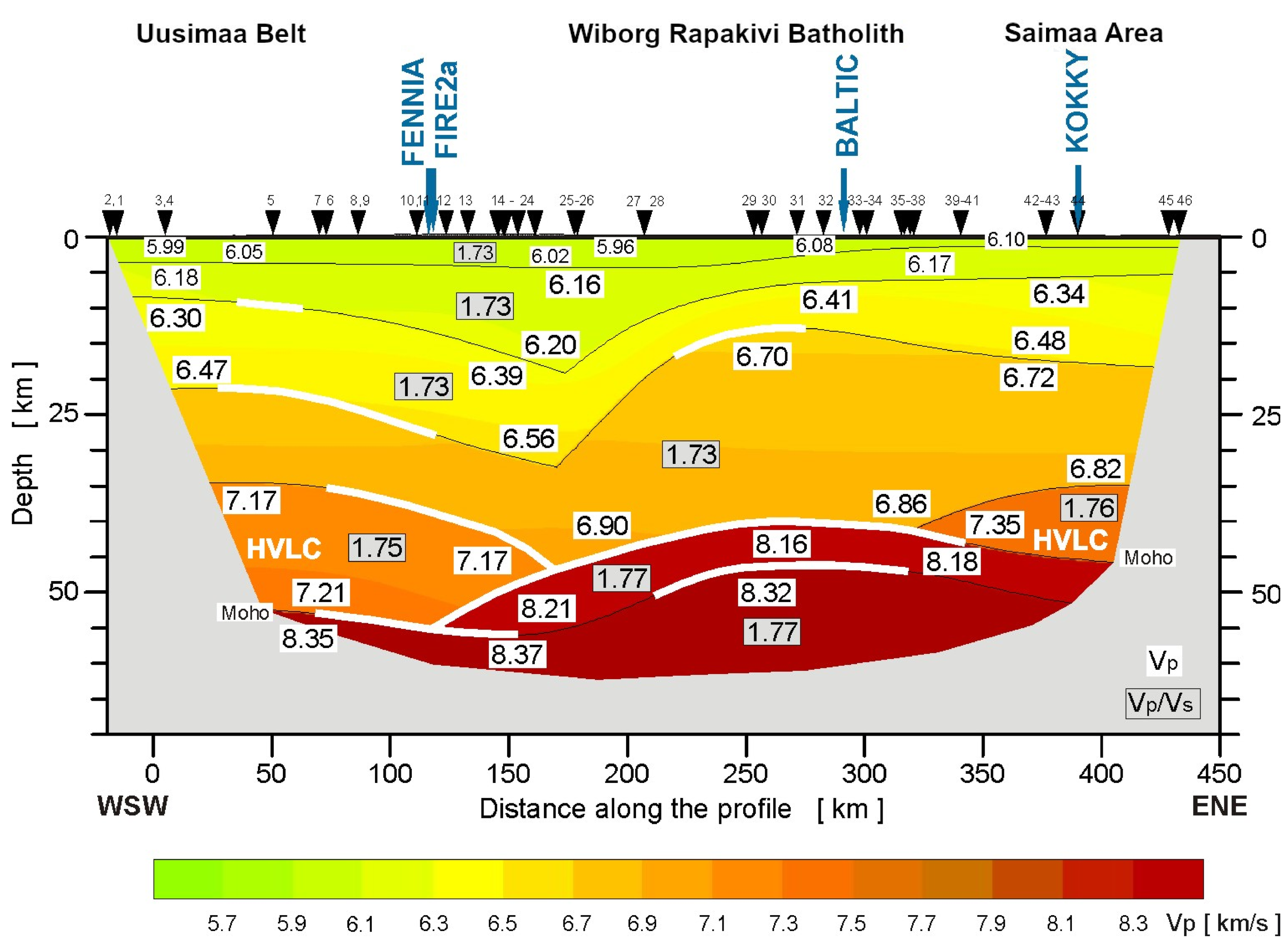
THE LARGEST RAPAKIVI AREA IN FENNOSCANDIA

The 1.646-1.615 Ga Wiborg Rapakivi Batholith (WRB) was generated by anorogenic magmas that intruded into deeply eroded Svecofennian crust. WRB covers a large part of the upper crust in the southeastern Fennoscandian shield, and is very homogeneous, mainly consisting of porphyritic rapakivi granites and to a very small extent of mafic rocks such as gabbros and anorthosites. Wide-angle deep seismic sounding (DSS) profiles BALTIC (Luosto et al. 1990, Janik, 2010), KOKKY (Tiira et al. 2021) and SOFIC (Tiira et al. submitted) cross the WRB.

Analysis of the DSS profiles has revealed that the rapakivi block is shallow, no more than 10 km. It is also seismically active despite the general rarity of earthquakes in Finland. The presence of surface waves in earthquake waveforms of the WRB indicates that earthquakes are limited to the upper 5 km of the crust (Uski et al. 2006).



Seismic stations and deep seismic sounding profiles in southeastern Finland. Ends of KOKKY and SOFIC profiles in Russia are also shown.



2D seismic model of P-wave velocity and distribution of Vp/Vs ratio from SOFIC deep seismic sounding profile (Tiira et al. submitted). The entire profile, beginning from the Turku archipelago, is visible. Confirmed crustal boundaries are displayed with solid white lines. Numbered triangles indicate shot numbers. Crossing points of FENNIA, BALTIC, KOKKY and FIRE2a profiles are also shown. HVLC means the high velocity lower crust.

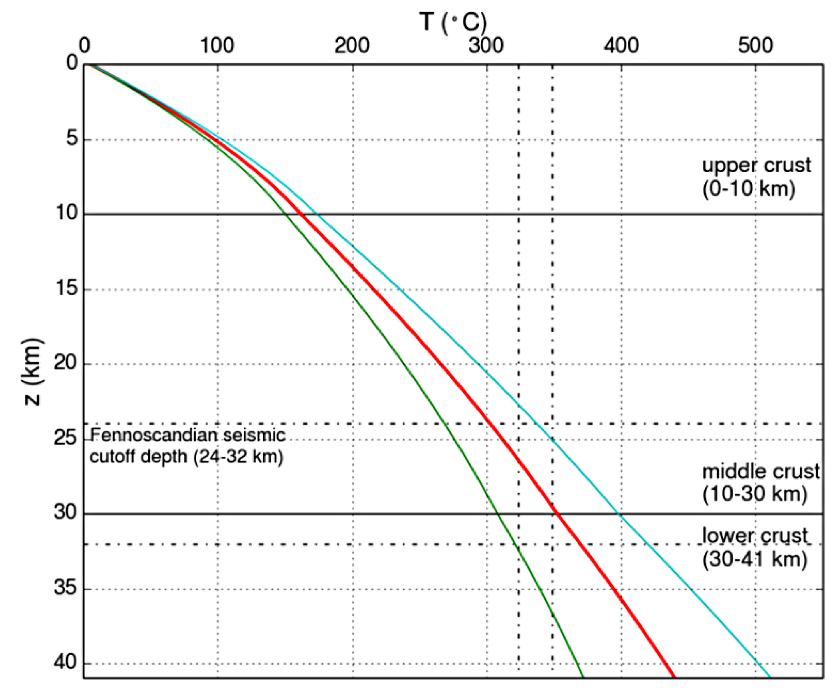
HEAT FLOW, HEAT PRODUCTION AND MODELING

Heat flow measurements from the WRB are rare. The most reliable reading is from a 200 m borehole in Loviisa, southern coast of Finland ($q = 57$ mWm^{-2} raw value, $q = 62$ mWm^{-2} with paleoclimatic correction; Kukkonen, 1989). Both values exceed the Fennoscandian average (49 mWm^{-2}; Veikkolainen et al. 2017) interpolated from paleoclimatically corrected data.

Heat production in the WRB is better known than heat flow. Lithogeochemical data from 93 rock outcrop samples from the Finnish side of the WRB, measured at the Geological Survey of Finland, provide an average heat production of 3.6 ± 1.2 μWm^{-3}. This is much more than the Finnish average 1.4 ± 1.4 μWm^{-3} and also features sharp contrasts to the neighboring Finnish areas (Veikkolainen and Kukkonen, 2019). No data from the Russian side are available.

The variation of heat production with depth greatly affects the shape of geotherms. However, direct measurements are only available for surface rocks. In WRB the dichotomy of felsic rocks above mafic ones, i.e. bimodal magmatism, supports the use of a layer cake model instead of a model with exponentially decreasing heat production.

In WRB, DSS profiles show layer boundaries in various seismic cross-sections. In a layer cake model, this information can be supplemented by using different proportions of rock types with known heat production values. In our layer cake model, we applied a decreasing thermal conductivity by temperature in three layers.



Geotherms representing the crust of WRB. Red curve shows the situation with q=60.3 mWm^{-2}, green curve that with q=57.3 mWm^{-2} and cyan curve that with q=63.3 mWm^{-2}. Seismic cutoff depth and temperature (Veikkolainen et al. 2017) are shown with dashed lines. The uncertainty over Moho temperature is as much as 70 °C.

GEOTHERM CALCULATION

For thermal conductivity λ, we used the temperature dependence

$$\lambda = \lambda_0 \left[1/(1+bT) + c(T+273.15K)^3\right]$$

where T is temperature [°C], λ_0 (2.9 Wm^{-1}K^{-1}) is thermal conductivity at the reference temperature of 25 °C and b (0.0008 K^{-1}) is a preselected empirical parameter, which depends on the lithology but is generally considered to be near the value 0.001 in crust. The factor c, representing radiative heat transfer, can be considered zero in typical crustal temperatures. Using constant heat production H within each layer, but temperature-dependent thermal conductivity, steady-state temperature T at a depth of z can be solved:

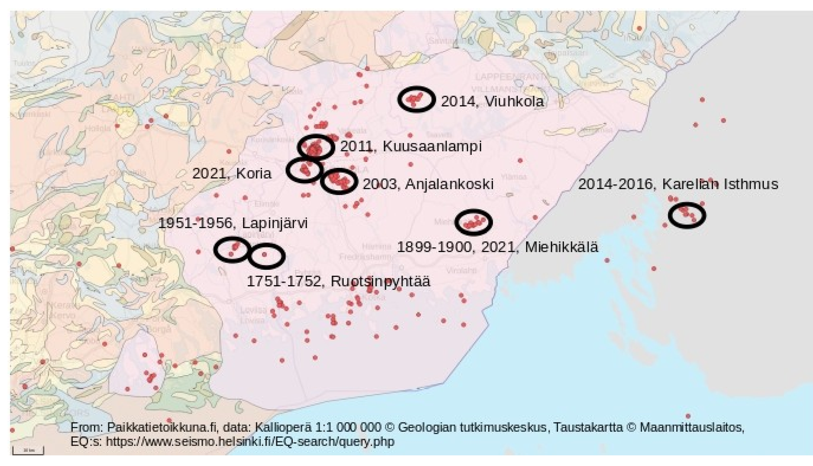
$$T(z) = (1/b)\left\{(1+bT_0)\exp\left[\left(\frac{b}{\lambda_0}\right)\left(q_0 z - \frac{Hz^2}{2}\right)\right] - 1\right\}$$

In our calculation, yearly mean surface temperature $T_0 = 5$ °C. For the composition of the upper crust (0...10 km) we assumed a mixture of rapakivi granites and gabbro-anorthosites with a very strong granitic dominance. Using heat production H = 3.5 μWm^{-3} means that 3.3% of the upper crust is gabbro-anorthosites and the rest is rapakivi granites. For the middle crust (10...30 km), we had the value H = 0.5 μWm^{-3}, and for the lower crust (30...41 km) H = 0.3 μWm^{-3} to account for the increasing gabbro-anorthositic content of the crust.

The Fennoscandian shield is almost entirely at the same erosion level. Therefore the Moho heat flow values (9...15 mWm^{-2}) determined from mantle xenoliths in the eastern Finland (Kukkonen and Peltonen, 1999; Kukkonen et al. 2003) are valid for our model despite the anorogenic origin of WRB.

To meet the thermal conditions at layer boundaries and within layers, we produced three geotherms with different surface heat flow constraints. Heat flow values appear to be clearly above the WRB value range in the heat flow map of Veikkolainen et al. (2017) which included all heat flow determinations, also poorly constrained ones. In the rapakivi area, those include the heat flow determination from a shallow well in Elimäki (Kukkonen et al. 1989).

SEISMICITY



Earthquakes in WRB and adjacent areas until June 2022. Black ovals indicate most important earthquake swarms. Rapakivi areas in southeastern Finland are shown by pink color.

Research of seismicity of WRB date back to pre-instrumental times. After the turn of the millennium, the density of seismic station network in southeastern Finland has allowed detection of small earthquakes (local magnitude $M_L<1$). In addition to the Finnish National Network stations, temporary project networks have been established in the area.

A notable earthquake swarm took place in Anjalankoski, south of Kouvola, in May 2003. The largest event had M_L2.1. The two strongest earthquakes in the WRB occurred during another swarm in December 2011-January 2012. They had M_L3.0 and M_L2.9. The latest swarms occurred in Koria in January 2021 (strongest event M_L2.0), and in Miehikkälä in May 2021 (strongest event M_L1.6).

Earthquakes in the WRB are typically shallow and laymen often mistake them for explosions. Therefore they often arouse media attention.

CONCLUSIONS

In the WRB, thermal and seismotectonic environment notably differs from that of the other Fennoscandian areas. The seismogenic zone does not cover the entire depth range of rapakivi granites. Seismic cutoff temperature is probably below 200 °C unlike the range of 300-400 °C typically assigned for granitic lithology. The rapakivi block has been highly fractured in general and earthquakes may also take place in horizontal faults within the rapakivi block.

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