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A Palaeomagnetic Analysis of Rapakivi Intrusions and Related Dykes in the Fennoscandian Shield

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Abstract. In the Fennoscandian Shield (Baltica) there are seven major rapakivi plutons and fifteen minor ones ranging in age from ca 1.66 to 1.50 Ga. These plutons are distributed in a broad WNW zone and if the most eastern pluton is excluded there is a westward trend of decreasing age of the intrusions. A palaeomagnetic study has been performed on 4 minor plutons (Rödö, Mårdsjö, Nordsjö and Mullnäset) and associated dykes in central Sweden. The results were combined with palaeomagnetic data from other rapakivi complexes in Fennoscandia in order to test if a stationary hot spot may be the origin of these anorogenic intrusions. Plotting the pole positions of this study together with poles of other complexes, poles calculated from rapakivi rocks and related dykes in Finland are located at somewhat lower latitudes and more eastern longitudes than poles of corresponding rocks in Sweden, probably reflecting an APW related to the general age differences between the plutons. The palaeolatitudes for the Fennoscandian Shield at the time of the rapakivi intrusions are restricted to a latitudinal range between ca 16° south and 27° north and there is a weak trend of increasing palaeolatitude with decreasing age of the rocks. A trend of gradually changing palaeolatitudinal positions has also been observed for the intrusion of Proterozoic anorthosite-rapakivi plutons in the Ukrainian Shield. Such differences in palaeolatitudes is not expected in case of a single stationary hot spot being the source of the rapakivi intrusions, as the rock then should carry a magnetization reflecting the same latitudinal position.

1 Introduction

In the Late Palaeoproterozoic and Early Mesoproterozoic, rapakivi granite plutons intruded in the Fennoscandian Shield. There are seven major plutons and ca fifteen minor ones distributed in a broad WNW zone from the lake Ladoga in Russia in the east , over southeastern and southwestern Finland to central Sweden in the west (Fig. 1a). The time interval for the rapakivi magmatism in the Fennoscandian Shield is from 1.66 to 1.50 Ga and apart from the most eastern pluton, the Salmi pluton, there is a westward trend of decreasing age of the complexes .

The origin of these anorogenic intrusions has been widely debated (e.g. Haapala and Rämö, 1999, DallÁgnol et al., 1999) and with this study we want to test the idea of a stationary hot spot being the source of the rapakivi complexes in Fennoscandia. A tectonic reconstruction of Fennoscandia during the time of rapakivi intrusion may give us a clue to whether the origin of the rapakivi intrusions can be a stationary hot spot. In such a case the direction of magnetization of the various intrusions will have the same inclination, since the earth magnetic field will be recorded at a stationary latitudinal position, when the shield is moving over the hot spot. This means that when reconstructing the position of Fennoscandia for the time of rapakivi intrusions we should expect a similar latitudinal position. Palaeomagnetic studies were therefore performed on rapakivi complexes and associated dykes in central Sweden and the results have been compared with palaeomagnetic data from other rapakivi complexes in Fennoscandia.

2 Minor rapakivi complexes in Sweden

In Sweden the minor rapakivi complexes have been dated at 1.50 Ga to 1.53 Ga (U-Pb; Andersson, 1997) and this study is concentrated on four of them, the Rödö (ca 1.51 Ga), Mårdsjö (1524 ± 3 Ma), Nordsjö (1520 ± 3 Ma), Mullnäset (1.526 ± 3 Ma) and on a basic dyke swarm north of Nordsjö (Fig. 1b) that has been suggested to be related to rapakivi magmatism (Gorbatschev, 1987).

The Mårdsjö , Mullnäset and Nordsjö intrusives are related to the Fennoscandian rapakivi granite complexes on structural and petrographical grounds (Andersson , 1997). The Mårdsjö complex is dominated by gabbro and syenitic rocks, while the Nordsjö and Mullnäset complexes are composed of predominantly syenitic rocks.

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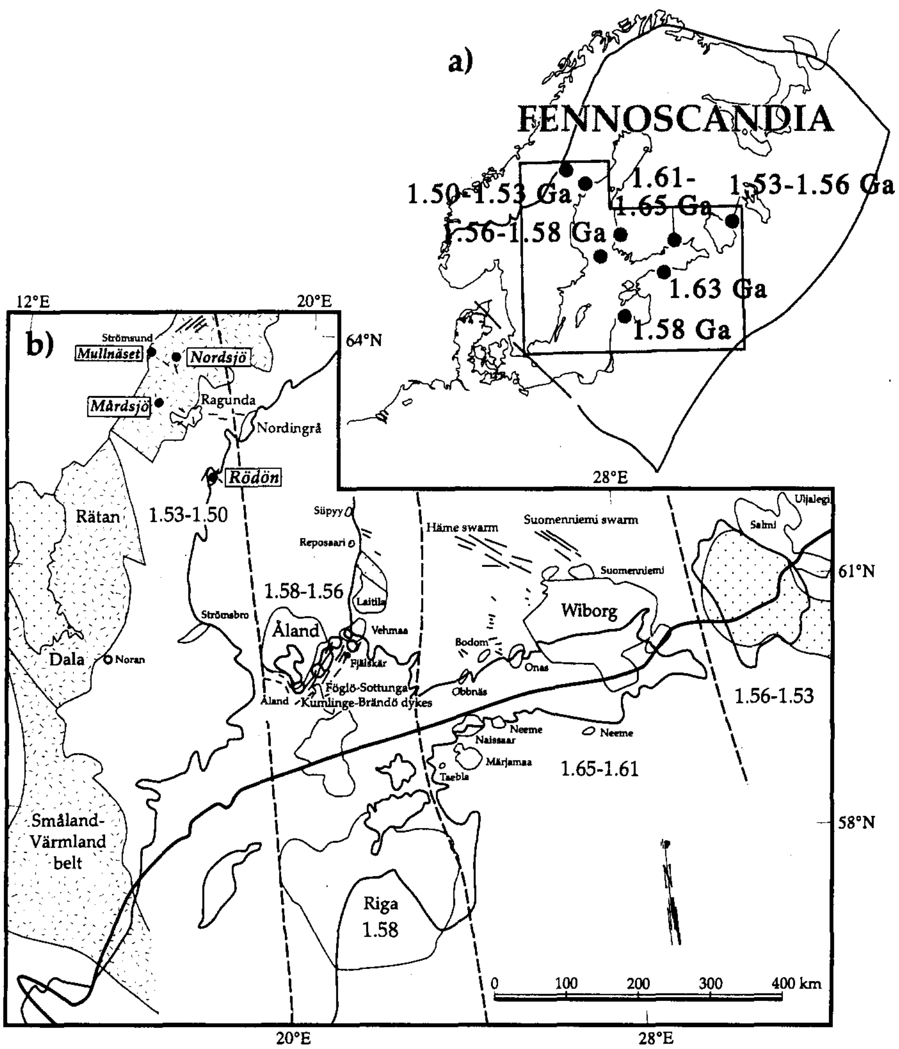

Fig. 1. (a) Rapakivi intrusions in the Fennoscandian Shield. (b)The age and geographical distribution of the rapakivis (marked by the grey areas) is shown in more detail. Note, that apart from the Salmi Pluton in the east, there is a gradual decrease in age of the intrusions from the east to the west. The rapakivi plutons and associated dykes of this study are marked by the names within frames. Basic dyke swarms are expressed as straight lines and the swarm north of Nordsjö is also included in this study. The thick line marks the northern limit of the Palaeozoic platform cover rocks.

The Rödö granite is red in color, coarse grained and with a distinct porphyritic texture with alkali feldspar phenochrysts mantled by plagioclase.

Dykes of granite porphyry and more basic porphyrite (diabase porphyrites) occur frequently in the rapakivi granite and in the country rock. Composite dykes with mingling / mixing phenomena are common , which suggests a close relation in time between the intrusion of the dykes and the granite.

Dykes with chemical compositions typical for the Postjotnian, ca 1.25 Ga, sills are found south of the granite intrusion (Lundqvist et al., 1990; Andersson, 1997).

North of the Mullnäset and Nordsjö complexes a ENE trending dyke swarm cuts ca 1.80 Ga granites. These dykes are 1.0 to 1.5 m in width and mainly composed of albite, with little apatite, opaque minerals and sericit (Lundqvist et al., 1990).

3 Palaeomagnetic results

Totally 379 samples were collected at 33 sites from the dykes and the rapakivi rocks of the Rödö , Mårdsjö, Nordsjö and Mullnäset complexes.

In the Mårdsjö complex only at one of the five sites a characteristic magnetization could be defined. This characteristic magnetization was isolated in fields ≥ 20 mT and at temperatures ≥ 560° C and had a mean direction of decl. = 32.1° and incl.= 21.1°. Also in the Mullnäset complex a stable remanent magnetization could only be isolated in one site, however, the mean direction (Decl. = 339° , Incl. = 71°) is similar to the direction of the present Earths field and a viscous origin can not be excluded.

Most of the samples collected at the five sites of the Nordsjö Complex carry a soft magnetization and no characteristic magnetization could be defined.

Susceptibility - temperature variations of the Rödö rapakivi granite indicate that mainly magnetite , titanomagnetite and some small amount of hematite are the magnetic carriers in this rock. The characteristic magnetization of the granite is best defined by thermal demagnetizations and the magnetization has a northeastern declination and a low to intermediate negative inclination at blocking temperatures ≥400°C . The mean direction is fairly well defined at decl. = 23.7° and incl. = -35°.

The palaeomagnetic pole calculated from the mean remanence direction of the Rödö granite is : Plat. = 6.2° , Plong. = 175° (RG; Table 1; Fig. 2), which is not significantly different from

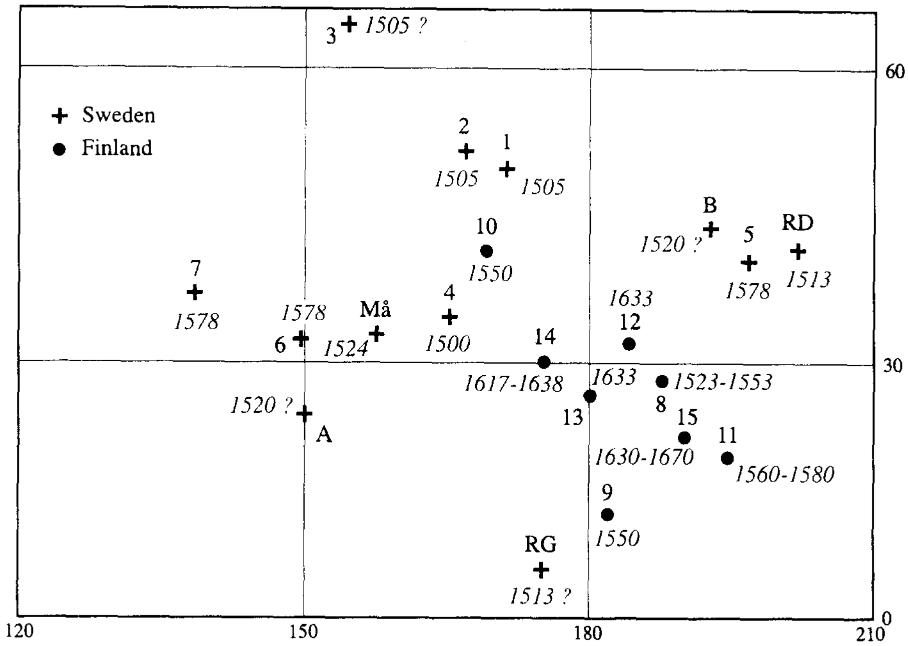

Fig. 2 . Pole positions calculated from the magnetization of rapakivi rocks and associated dykes from Sweden (+) and Finland (●).

the 1.3 Ga grand mean pole for the Fennoscandian shield (Elming et al. , 1993). Also for the basic dykes related to the granite the characteristic magnetization is best defined by thermal demagnetizations and the mean direction of characteristics magnetization for the six dykes that were sampled is at decl. = 176.8° and incl. = -26.5°. Positive contact test can be demonstrated at three of the dykes, which suggests that the magnetization of the dykes is original (Moakhar and Elming, 1998b). The palaeomagnetic pole (RD; Plat. = 41.6° , Plong. = 201.7°; Table 1; Fig. 2) calculated from the mean direction of the dykes falls close to poles calculated from other rapakivi related dykes (e.g. Nordingrå basic dykes ; Föglö dykes ; Föglö sottunga dykes ; E - W dykes; Table 1).

A dyke, with a chemical signature different from the Rödö dykes, carries a characteristic magnetization (decl. = 38.1°, incl. = 35.9°) with unblocking temperatures between 450 to 550°C. The magnetization is very resistive to AF in high fields , which suggests that the carrier of magnetization is single domain grains of titanomagnetite. The calculated pole position (Plat. = 40.1° , Plong. = 148.2°) is significantly different from those of the rapakivi related dykes in Rödö (RD) but is similar to that of an older rapakivi granite in Nordingrå (pole 6 in Table 1).

The characteristic magnetization of the dolerite sill of probably Postjotnian age has a mean direction at decl. = 45.9° and incl. = -44.1° and the calculated pole (Plat.= -5.5°, Plon. = 157.1°) is very different from that of the rapakivi related dykes. This pole falls close to the 1.25 Ga reference pole for Fennoscandia, which supports the assumption of a Postjotnian age for this dolerite.

Magnetite-titanomagnetite and occasionally pyrrhotite are the magnetic carriers in the basic dykes north of Mullnäset (Moakhar and Elming, 1998a). A characteristic magnetization is generally isolated in AF ≥ 20 mT and at temperatures ≥ 500°C. Two groups of directions can be recognized forming mean directions at (A; 3 sites) decl. = 40.8°, incl. = 14.2° and (B; 6 sites) decl. = 4.4°, incl. = 35.1°. Positive contact tests and secular variations suggest that the magnetizations are primary. The palaeomagnetic pole calculated for group A (Plat. = 26.1°, Plon. = 150°, Table 1; A in Fig. 2) is similar to that of the single site of the Mårdsjö rapakivi complex, while the pole of group B (Plat. = 45.2°, Plon.= 191.5°; B in Fig. 2) is not significantly different from the pole of the Rödö rapakivi dykes.

4 Discussion and conclusion

The palaeomagnetic pole position calculated from the characteristic magnetization of the rapakivi granite in Rödön (Plat. = 6.2° , Plong. = 175°) falls close to the 1.25 Ga reference pole for Fennoscandia. The granite is altered and the fact that the pole position of the granite is similar to the 1.25 Ga reference pole and the pole (Plat. = -5.5°, Plong. = 157.1°) calculated from the Postjotnian dolerite sill sampled 3 Km south of the Rödö island, may suggest a remagnetization of the granite. In some of the granite samples there are also traces of a high unblocking temperature magnetization with a shallow and northern direction, which may reflect a preserved original magnetization. A significantly different pole position (Plat = 41.6° , Plong. = 201.7°) is obtained from the basic dykes, which from their geochemical and petrographical signatures, as well as magma mixing, are indicated closely related with the granite. Positive contact tests suggest that the magnetization of the dykes is original. The reason for this difference in magnetization is hard to explain, i.e. if the granite is remagnetized why are not the dykes remagnetized by the Jotnian dolerites? Difference in porosity may be one ex

Table 1. Palaeomagnetic poles from rapakivi plutons and associated dykes in the Fennoscandian Shield. Lat./Long. = latitude and longitude of the sampling area, B/N/n = number of formations/sites/samples, * denotes the statistical level used in the mean calculations, Plat./Plon. = latitude/longitude of the pole, P= polarity, A_{95} = radius of the circle of 95% confidence of the pole. λ is the palaeolatitude with error bars. Age is established by U-Pb dating on zircon. Ref: (1) this work; (2) Moakhar and Elming, 1998a; (3) Moakhar and Elming, 1998b; (4) Piper, 1979; (5) Piper, 1980; (6) Fridh, 1979; (7) Pesonen and Neuvonen, 1981; (8) Neuvonen, 1970; (9) Johnson, 1979; (10) Mertanen, 1995; (11) Neuvonen, 1986; (12) Neuvonen, 1978.

Code	Rock type	Lat./Long.	B/N/n	Plat./Plon.	P	A95	λ	Age(MA)	Ref
RD	Rödö dykes	62.37/17.56	6/6*/53	41.6/201.7	r	9.5	$14.0_{7.4}^{21.6}$	1513	1,2
RG	Rödö granite	62.37/17.56	1/6*/20	6.2/175.0	n	4.8	$-19.3_{-23.1}^{-15.8}$	1513	1,2
Må	Mårdsjö gabbro	63.75/15.65	1/1/7*	32.9/157.3	n	6.5	$10.9_{7.4}^{14.6}$	1524	1,2
A	Group A dyke	64.16/16.27	3/3*/48	26.4/150.2	n	14.7	$3.8_{-6.7}^{15}$	1520?	1,3
B	Group B dyke	64.17/16.28	10/10*/60	45.2/191.5	n	7.5	$19.4_{14.1}^{25.5}$	1520?	1,3
1	Ragunda granite	63.30/16.10	1/4*/21	49.1/171.0	n	19.8	$24.1_{10.7}^{44.3}$	1505	4
2	Mean Ragunda formation	63.30/16.10	1/15*/87	51.6/166.6	c	7.1	$27.1_{21.9}^{33.2}$	1505	4
3	Ragunda dyke	63.30/16.10	4/4*/24	64.1/154.5	c	24.7	$44.1_{23.9}^{68.6}$	1505	4
4	Gävle granite	60.70/17.20	1/12*/12	34.7/165.0	n	10.0	$8.9_{2.0}^{16.5}$	1500	5
5	Nordingrå dykes	61.90/18.40	7/7*/7	40.0/197.0	n	7.1	$12.0_{7.0}^{17.5}$	1578	6
6	M. Nordingrå granite	62.90/18.60	1/28*/28	32.4/149.0	c	10.5	$13.2_{6.0}^{21.6}$	1578	5
7	M. Nordingrå gabbro	62.90/18.60	1/19*/108	36.9/138.1	c	4.7	$20.7_{17.2}^{24.5}$	1578	5
8	Föglö-Sottunga dykes	60.00/20.60	6/6*/25	27.9/187.5	n	8.8	$-1.4_{-7.9}^{5.0}$	1523-1553	7
9	Kumlinge-Brändö dykes	60.30/20.80	7/7*/25	12.2/182.0	r	6.7	$-16.2_{-21.4}^{-11.6}$	1550	7
10	Mean Åva intrusion	60.60/21.10	1/15*/15	41.0/169.0	n	12.4	$14.3_{6.1}^{24.2}$	1550	8
11	Åland granite	60.50/22.50	1/1/6*	19.5/194.4	r	16.4	$-9.7_{-21.1}^{0}$	1560-1580	9
12	Sipoo diabase dykes	60.30/25.30	4*/18/28	31.6/183.6	r	6.2	$3.3_{-18.4}^{27.9}$	1633	10
13	Sipoo porphyry dykes	60.30/25.30	3/5*/34	26.4/180.4	n	7.4	$-0.9_{-7.1}^{5.8}$	1633	10
14	SE quartz porphyry dykes	61.30/26.8	9*/9/21	30.0/175.0	n	9.4	$5.0_{-3.3}^{12.0}$	1617-1638	11
15	Kuisaari dolerite	61.20/26.70	8/8*/74	22.0/190.0	r	9.9	$-5.0_{-12.6}^{2.0}$	1630-1670	12

planation. Fluids related to the Jotnian dolerite sill could more easily have penetrated the granite than the dykes and thereby created a chemical remagnetization of the granite. The porosities of these rocks are low (< 1%) and the dykes do have a lower porosity (ca 0.3%) than the granite (ca 0.9 %). It is not clear if this difference is enough to support the interpretation of a selective remagnetization. However, apart from the somewhat higher porosity there are also cavities in the granite, which may support such an interpretation.

Plotting the pole positions calculated in this study together with poles of other complexes in Fennoscandian a scattered distribution of poles is obtained (Fig. 2), where no obvious trends in pole positions with reference to the age of the rocks are revealed. However , it seems that poles calculated from rapakivi rocks and related dykes in Finland are located at somewhat lower latitudes and more eastern longitudes than poles of corresponding rocks in Sweden , reflecting an APW related to the general age differences between the rapakivi complexes. Apart from the anomalous pole of the Rödö granite the poles of this study fall into this pattern of pole positions.

The paleolatitudes for the various rapakivi rocks , calculated from the mean inclinations of magnetizations , fall on a latitudinal range between 16° southern and 27° northern latitudes. Due to poorly constrained ages of magnetization and overlapping error bars of the palaeolatitudes , trends in

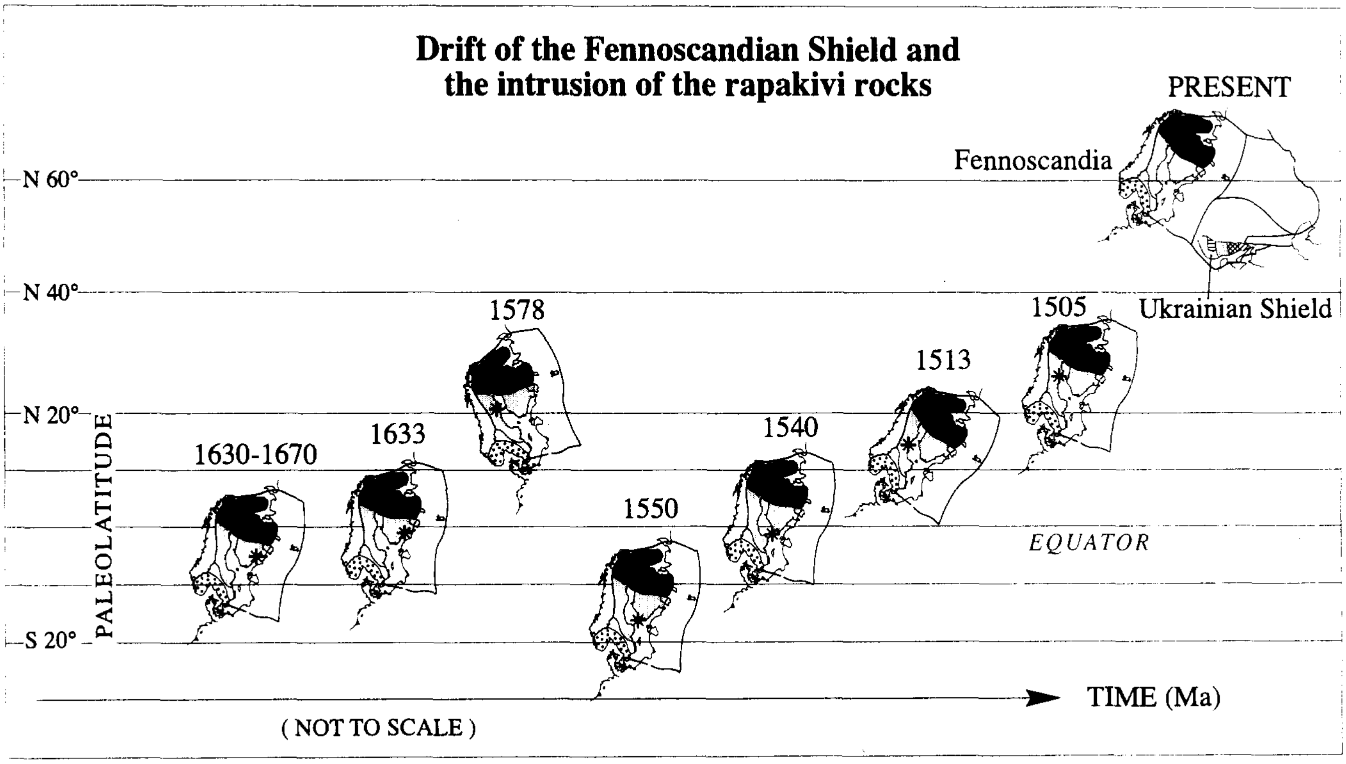

Fig. 3. The drift of the Fennoscandian Shield during the time of rapakivi intrusions. For each tectonic reconstruction the position and corresponding age of the rapakivi plutons or related dykes are given.

paleolatitudinal positions are not clearly distinguished. However, there are significant differences in the palaeolatitudes of the Fennoscandian Shield between the time of rapakivi intrusions and there is a weak trend of increasing palaeolatitude with decreasing age of the rocks. This trend is demonstrated in the tectonic reconstruction of Fennoscandia at the time of intrusion of the various plutons (Fig. 3) and it seems like the rapakivis in Sweden were intruded at times when Fennoscandia was located in higher latitudes. A trend of gradually changing palaeolatitudinal positions has also been observed for the intrusion of ca 1.79 to 1.72 Ga anorthosite-rapakivi plutons in the Ukrainian Shield (Fig. 1; Elming et al., 1999). Such differences in palaeolatitudes would not be expected in case of a single stationary hot spot being the origin of these anorogenic intrusions.

Acknowledgements

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