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Paleomagnetism and petrophysics of the Jänisjärvi impact structure, Russian Karelia

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Abstract–Paleomagnetic, rock magnetic, and petrophysical results are presented for impactites and target rocks from the Lake Jänisjärvi impact structure, Russian Karelia. The impactites (tagamites, suevites, and lithic breccias) are characterized by increased porosity and magnetization, which is in agreement with observations performed at other impact structures. Thermomagnetic, hysteresis, and scanning electron microscope (SEM) analysis document the presence of primary multidomain titanomagnetite with additional secondary titanomaghemite and ilmenohematite. The characteristic impact-related remanent magnetization (ChRM) direction (D = 101.5°, I = 73.1°, α_{95} = 6.2°) yields a pole (Lat. = 45.0°N, Long. = 76.9°E, dp = 9.9°, dm = 11.0°). Additionally, the same component is observed as an overprint on some rocks located in the vicinity of the structure, which provides proofs of its primary origin.

An attempt was made to determine the ancient geomagnetic field intensity. Seven reliable results were obtained, yielding an ancient intensity of 68.7 ± 7.6 μT (corresponding to VDM of 10.3 ± 1.1 × 10^{22} Am^2). The intensity, however, appears to be biased toward high values mainly because of the concave shape of the Arai diagrams.

The new paleomagnetic data and published isotopic ages for the structure are in disagreement. According to well-defined paleomagnetic data, two possible ages for magnetization of Jänisjärvi rocks exist: 1) Late Sveconorwegian age (900–850 Myr) or 2) Late Cambrian age (~500 Myr). However, published isotopic ages are 718 ± 5 Myr (K-Ar) and 698 ± 22 Myr (^{39}Ar-^{40}Ar), but such isotopic dating methods are often ambiguous for the impactites.

INTRODUCTION

Interest in studying terrestrial impact structures has increased since geoscientists became aware of the geological and biological consequences of impact on Earth's evolution (Cockell et al. 2002). The impact structures have the potential to contain economic resources such as oil, gas, diamonds, metallic ores, building materials, and water reservoirs (e.g., Grieve et al. 1994; Pesonen et al. 1999). Impactites often carry a stable thermoremanent magnetization (Pesonen et al. 1992), which provides a tool to study the apparent polar wander paths (APWP), thus providing new data for paleogeographic reconstructions. Recently, paleointensity during the geological past has been successfully measured using impact melt samples (Nakamura et al. 2005).

The current impact database of Fennoscandia reveals about 30 proven impact structures with diameters ranging from 0.1 to 55 km and ages between recent and 2.4 Gyr. However, many of these structures are not only poorly dated but also lack morphological characteristics (Abels et al. 2002).

In this paper, we present new paleomagnetic and rock magnetic data for the Jänisjärvi impact structure, Karelia, Russia (Fig. 1). Petrophysical properties of the rocks were measured in order to study shock-induced effects and to provide input data for possible forthcoming geophysical modeling of the structure. We also present results of a rock magnetic investigation, scanning electron microscope (SEM) studies, and ore microscope studies, which focused on identifying the remanence carriers of the impact melt rocks and the stability of their magnetization. Paleomagnetic studies of these rocks were carried out in order to date the impact event. Paleomagnetic dating has been proven successful in cases where impact melt rocks are present and the impact test can be applied (Pesonen et al. 2001). A successful paleomagnetic dating requires that the remanence is primary. In addition, an attempt to estimate the ancient geomagnetic field intensity at the time of the impact event was performed on impact melt specimens showing the best rock magnetic features.

Finally, we discuss the implications of the new

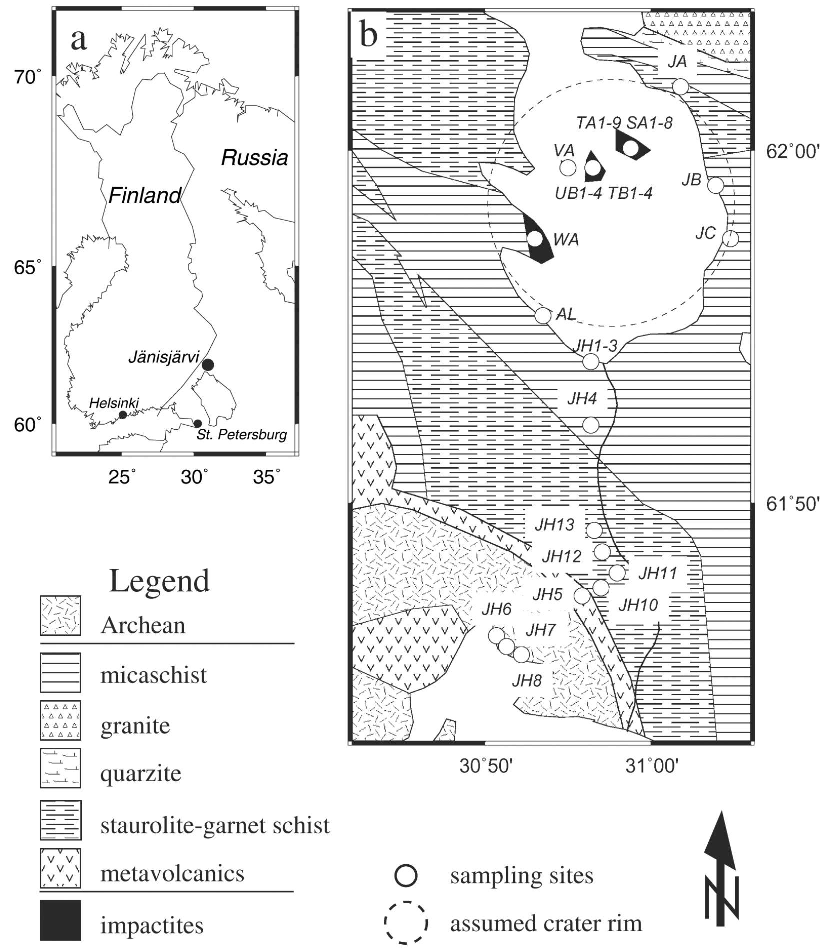

Fig. 1. a) The geographical location and b) geology and sampling sites of the Jänisjärvi impact structure, which is surrounded by Proterozoic crystalline schists of mainly Svecofenian age (1.9–1.8 Gyr). Ten minutes on the scale correspond to about 18 km.

paleomagnetic results for Jänisjärvi in light of Baltica's APWP. The age of the Jänisjärvi impact event has been previously constrained by K-Ar (Masaitis et al. 1976) and ^{40}Ar-^{39}Ar data (Müller at al. 1990) on whole rock samples to lie between 678 and 718 Myr.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The Lake Jänisjärvi impact structure (centered latitude 61°58′N, longitude 30°58′E) (Fig. 1) is located in Russian Karelia in the southeastern part of the Fennoscandian Shield, about 220 km north of Saint Petersburg. The present diameter of the structure as based on gravity data (Elo et al. 2000) is about 16 km. Figure 1 shows a geological map of the region and the sampling sites.

The present lake's shape is slightly elliptical, about 16 km long and about 14 km wide, and its deepest points reach 50 m. The lake's nearly isometrical shape is atypical for Karelia, where most lakes are elongated and shallow due to their glacial origin (Koistinen 2003). Two major, 50 m deep, NW-SE troughs delineated on the bathymetric map of Lake Jänisjärvi suggest that glacial erosion has affected the area (Elo et al. 2000). The longer trough (about 12 km) extends almost through the middle of the lake, whereas the shorter one (about 4 km) is close to the northern shore of the lake. One ridge (20–30 m high, NW-SE trending) extends across the central part of the lake and forms three islands (Iso-Selkäsaari, Pieni-Selkäsaari, and Hopeasaari).

Eskola (1921) considered a volcanic origin for the Jänisjärvi structure and particularly for the melt rocks. An impact origin for the structure was proposed by Dence (1971) on the basis of a satellite image. The discovery of shatter cones and planar deformation features (PDFs) in a quartz clast from a breccia sample (Hopeasaari Island) proved the impact origin of the structure. It was also shown that chemical composition of the target rocks and the impact melt rocks (tagamites) are almost identical (Masaitis et al. 1976). These conclusions were later confirmed by other authors (e.g., Raitala et al. 1992).

The structure is located in the Fennoscandian Shield close to the Archean-Proterozoic boundary. The Archaean crystalline basement, composed of gneissic granite and migmatites, crops out 3 to 4 km north of the lake and on the northern shore of Lake Ladoga. The Jänisjärvi impact structure is situated in Proterozoic crystalline schists (Koistinen et al. 1996). Major phases are plagioclase, biotite, and quartz, with subordinate muscovite, garnet, staurolite, and cordierite (Masaitis et al. 1976; Raitala et al. 1992). Due to the impact event, the schists around the lake are fractured.

Puura et al. (2005) claim that Jänisjärvi was formed in a composite target consisting of crystalline basement covered by Precambrian sediments during the Neoproterozoic. From the Early Paleozoic until the Mesozoic, marine sediments have been depositing over the Jänisjärvi structure. During the Cenozoic, the erosion of the structure became significant and slowly reached the actual shape, namely an eroded impact structure, where part of the impact-related lithologies are preserved. The present erosional margin of the Paleozoic sedimentary deposits (100–350 m thick) is located ~100 km to SE from Jänisjärvi, in the southern Lake Ladoga area, where the sedimentary rocks show an increasing thickness towards the north.

The impactites are mainly exposed on the three named islands, but a minor exposure of these rocks also occurs at Cape Leppiniemi on the SW coast. Similar to other impact structures (Masaitis 2005), the impact lithologies within the Jänisjärvi include impact melt rocks (tagamites), suevites, and lithic breccias. In particular, the approximately 15–20 m thick tagamite layer overlies suevites and the lithic breccias. The tagamites contain clasts of recrystallized schists, quartz, and other minerals from target rocks. Sizes of these clasts are a few centimeters across. The groundmass of tagamites consists of plagioclase, hypersthene, quartz, cordierite, small amounts of biotite, K feldspar, ilmenite, graphite, and glass. Suevite consists of fragments of schists and recrystallized glass. The schist fragments may reach about 2 m across, but most of them are not larger than 5–10 cm. The cement of this rock consists of the same comminuted and partly altered material. The lithic breccias are composed of clasts of schists and, rarely, pegmatites, and are cemented by a finely crushed matrix of the same rocks. Shatter cones up to 20–30 cm long occur in metasiltstones (Masaitis et al. 1976, 1999). These metasiltstones probably belong to the Late Precambrian cover, which was overlain by the crystalline basement at the time of impact (see also Puura et al. 2005).

PREVIOUS GEOPHYSICAL STUDIES

A circular negative Bouguer anomaly with a maximum amplitude of −7 mGal and a half-amplitude width of 8.5 km is associated with the structure (Elo et al. 2000). The center of the negative gravity anomaly corresponds roughly with the morphological center of the structure, close to the three islands situated in the middle of the lake (Fig. 1). Such negative gravity anomalies are often associated with impact structures because of the impact-induced fracturing of rocks.

The low-altitude (65 m) aeromagnetic map (Elo et al. 2000) shows the presence of some local high magnetic anomalies in the surroundings of the structure that disappear within the structure. The flat magnetic relief may be due to the low magnetization of the impactites. Such a weak magnetic relief is often a typical signature of Finnish impact structures as documented, for example, in the cases of Lappajärvi, Karikkoselkä, Paasselkä, and Suvasvesi South. This signature is interpreted by the apparent or proven lack of highly magnetic impact melt rocks in these structures (Pesonen et al. 1992, 1999).

SAMPLING

The sampling at Jänisjärvi was started in 1997. In 2003, more samples were collected along the profile from the south part of Lake Jänisjärvi to the north part of Lake Ladoga (Fig. 1) in order to study the physical properties as function of the radial distance from the center of the impact and to carry out the impact test. Altogether, 54 hand samples (of which 3 were unoriented) from 28 outcrops were taken. Standard cylinders were cored from the hand samples at the Geological Survey of Finland (GSF) in Espoo. Altogether, 546 specimens were prepared.

LABORATORY MEASUREMENTS

Petrophysical properties (susceptibility, intensity of natural remanent magnetization [NRM], and apparent density) of samples collected during 1997 were measured at the Petrophysics Laboratory of the GSF, whereas the 2003 samples were measured at the Solid Earth Geophysics Laboratory of the University of Helsinki (UH), Finland. Thermomagnetic and hysteresis properties were measured also at the UH. Susceptibility as a function of temperature was measured using AGICO's KLY-3S kappabridge. Specimens were heated in air from room temperature up to 700 °C and cooled again back to room temperature. Hysteresis properties were measured using a Princeton Measurement Corporation's MicroMagTM3900 model vibrating sample magnetometer (VSM). Measurements of the magnetic remanence were carried out partly at GSF and partly at UH mainly using alternating field (AF) treatment, only few thermal treatments were done.

Additionally, SEM (Jeol JSM-5900LV) and ore microscope analysis were performed in collaboration with the Geological Department of the UH and with the GSF in order to better define the nature of the magnetic carriers of the tagamites.

We performed paleointensity measurements of 18 stable specimens from 10 melt rock samples. To determine the absolute paleointensity, specimens were heated up to 600 °C using the double heating Thellier technique modified by Coe (1967) with standard partial thermoremanent magnetization

Table 1. Petrophysical properties of the rocks from the Jänisjärvi impact structure.

Rock type	D_a (kgm^{-3})	D_w (kgm^{-3})	P (%)	K (10^{-6} SI)	J_0 (mAm^{-1})	Q
Impactites						
Tagamite	2569	2641	2.8	3074	265	2.2
Lithic breccia	2536	2611	5.0	535	34	1.2
Suevite	2540	2555	7.2	514	18	0.9
Target rocks						
Fractured target rocks	2484	2517	7.1	215	2	0.2
Schist (unfractured)	2782	2802	0.3	378	5	0.2
Granite/gneiss/granodiorite (unfractured)	2758	2848	0.7	960	19	1.0

D_a = apparent density (dry bulk density); D_w = wet bulk density; P = porosity; K = susceptibility; J_0 = intensity of natural remanent magnetization; Q = Königsberger's ratio; B/N/n = number of sites/samples/specimens varied for each property as follows: impact melt rocks D_a 5/23/227, D_w and P 5/14/20, K 5/23/226, J_0 and $_Q$ 5/23/213; breccias D_a 1/4/49, D_w and P 1/4/30, K 1/4/49, J_0 and Q 1/4/42; suevite: D_a and Q 2/3/11, D_w, P, K and J_0 2/3/10; fractured target rocks: D_a and K 2/3/17, D_w and P 2/3/12, J_0 and Q 2/3/15; schist: D_a and K 8/11/118, D_w and P 6/8/12, J_0 8/11/106, Q 8/11/105; granite/gneiss/granodiorite D_a and K 10/10/116, D_w and P 4/4/6, J_0, and Q 10/10/105.

(pTRM) and tail checks (Riisager et al. 2001). Specimens were selected according to their petrophysical and paleomagnetic characteristics. In particular, we chose specimens showing a dominance of remanent magnetization over an induced magnetization (Koenigsberger's Q ratio higher than 1), and showing one single, stable paleomagnetic direction. The standard size specimens were oriented in the oven so that the NRM was parallel to the applied laboratory field (Blab). This setup minimizes the effects of fabric anisotropy on the paleointensity determination (Gallet et al. 2006).

RESULTS

Petrophysical Properties and Magnetic Mineralogy of the Samples

The petrophysical data include apparent density, porosity, susceptibility, NRM, and Q value as described in Table 1 and plotted in Fig. 2 as bivariate diagrams. Petrophysical data for the impact lithologies display properties distinct to those of the target rocks. For example, the susceptibility and the Q value of tagamites are higher compared to target rocks (Fig. 2), and therefore show similar trends as reported for other impact structures like Lappajärvi, Mien, Popigai, or Bosumtwi (Pesonen et al. 1999; Pilkington et al. 2002; Plado et al. 2000). The apparent density of tagamites is lower than that one of the target rocks. Also, differences between impactites exist (Fig. 2); tagamites have a higher density and one order of magnitude higher susceptibility and NRM values compared to the other impactites. Density decreases from tagamites to suevites and breccias. In addition, the susceptibility and magnetic remanence of suevites are slightly lower than those of the lithic breccias (Fig. 2). Tagamites from site WA (Cape Leppiniemi) show one order of magnitude smaller susceptibility and NRM values compared to the other tagamites, and are closer to values of suevites and impact breccias. In fact, these tagamites are more weathered than those from other sites.

We performed thermomagnetic measurements, hysteresis measurements, ore microscope studies, and SEM analysis in order to identify the remanence carriers of the impactites. Table 2 summarizes the hysteresis and thermomagnetic results of the different samples.

Thermomagnetic results suggest that most of the samples consist of two or three ferromagnetic phases based on respective Curie temperatures (T_c) defined by using the second derivative approach. The first phase occurs between 330 and 370 °C, and might be interpreted as titanomagnetite (higher Ti content) or titanomaghemite (350 °C). We exclude the possibility of pyrrhotite because the peak related to this particular T_c is not as prominent. Titanomagnetite can be observed between 520 and 580 °C, and sometimes ilmenohematite (isochemical composition with titanomaghemite, but more stable structure) was detected between 620 and 680 °C. Most curves show irreversible behavior leading to an enhancement of susceptibility during the cooling part. This kind of irreversible behavior is typical for titanomagnetites or titanomaghemites, which oxidize during heating (Dunlop et al. 1997). Figure 3a shows the thermomagnetic properties of the two tagamite specimens: TA1 and UB4. Sample TA1 exhibits two different T_c at 350 °C and 560 °C, and shows typical irreversible behavior of the tagamites, whereas sample UB4 shows one Curie temperature corresponding to titanomagnetite.

The hysteresis loops show that the tagamite specimens saturate around 0.2 T, indicating the presence of soft carriers (magnetite or titanomagnetite). Because of the different curie temperatures correlating with ilmenohematite and titanomaghemite, we would expect the presence of wasp-waisted loops. However, this could not be observed, and thus we suppose that the amounts of ilmenohematite and titanomaghemite (proved by thermomagnetic analysis) are relatively small compared with the amount of titanomagnetite. Figure 3b depicts the hysteresis loop for the two specimens TA1 and UB4. We observe that the loop is similar to that one for multidomain (MD) magnetite. All the

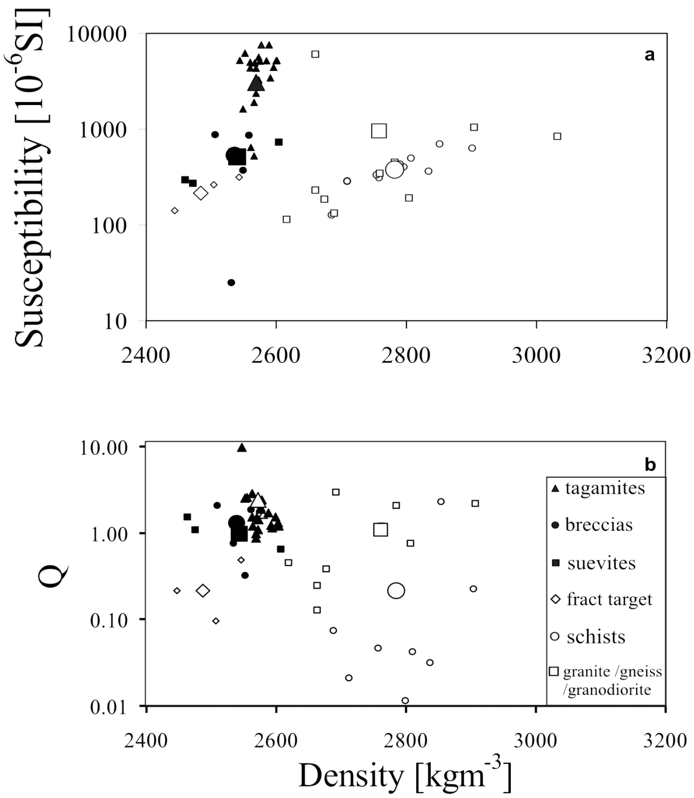

Fig. 2. Petrophysical scatter plots for the Lake Jänisjärvi rocks. The mean values for each sample (small symbol) and each rock type (large symbol) are given. a) Susceptibility versus density; b) *Q* value versus density.

other lithologies (breccias and suevites) behave paramagnetically, and therefore a separation of the magnetic material was performed using a Franz magnetic separator at GSF. The results in Table 2 represent the separated magnetic phase.

Ore microscopic and SEM studies of tagamite samples TA1 and UB4 established the presence of small, unaltered primary titanomagnetite grains (a few micrometers across). Larger titanomagnetite grains (up to a few tens of micrometers) often show cracked edges where secondary maghemite formed. The SEM analysis clearly shows that most titanomagnetites contain impurities like Al, Mg, Mn, and Cr, which is common for natural titanomagnetites. According to Dunlop et al. (1997) these impurities also affect the magnetic properties reducing Ms and the Curie temperature. Additionally, large grains of ilmenohematite (up to few tens of micrometers in diameter) were observed in both samples. Insignificant amounts of pyrite (up to few micrometers in diameter) could also be detected. Figure 3c shows that some of the titanomagnetite oxidized to titanomaghemite. Since the titanomaghemite structure is metastable, it can invert to form the isochemical, but more stable structure of ilmenohematite (Fig. 3c, right), or it can be reduced to form secondary magnetite. This whole process is normally interpreted as a consequence of low-temperature hydrothermal alteration (Dunlop et al. 1997). At the Jänisjärvi this process of alteration might have been ongoing in the marine environment during Early Paleozoic and Mesozoic.

Since we assume titanomagnetite as the dominant magnetic phase, we may interpret the hysteresis ratios of the Day plot (Fig. 4) after Day et al. (1977) in terms of grain sizes, related to domain states. In our analysis, we use the re-appraisal of the Day plot after Dunlop (2002). In general, it appears that tagamites fall close to the boundary between multidomain (MD) and single-domain (SD) mixtures. In contrast, the lithic breccia sample seems to consist of a SD-SP mixture. One suevite (sample SA8) falls in the MD area.

Paleomagnetic Results

Impactites

Most of the impactites show a relatively stable behavior during the AF demagnetization and two characteristic magnetic components were reliably isolated (Fig. 5). In some cases, a third component was present. Weighted mean paleomagnetic directions and corresponding poles of the most common components are listed in Table 3. The most common magnetic component "C" from all the impactites has a mean direction of D = 101.5°, I = 73.1° (k = 26.2, α_{95} = 6.2°)

Table 2. Hysteresis properties and Curie temperatures of impactites and fractured target rocks from the Jänisjärvi impact structure.

Sample	M_r (mAm^{2}kg^{-1})	M_s (mAm^{2}kg^{-1})	H_{cr} (mT)	H_c (mT)	M_r/M_s	H_{cr}/H_c	T_{C1} (°C)	T_{C2} (°C)	T_{C3} (°C)
Tagamites									
TA1	317.1	2232	15.5	6.5	0.14	2.38	350	560	
TA2	418.7	2052	24.2	11.2	0.20	2.16			
TA3	149.9	780.5	16.2	8.2	0.19	1.98	340	570	670
TA4	105.7	385	15.7	9.5	0.27	1.66	330	530	650
TA5	316.2	1506	18.6	9.6	0.21	1.93	350	560	640
TA6	168.6	1111	17.1	7.5	0.15	2.28	350	530	670
TA7	40.1	229.6	15.8	7.5	0.17	2.10	350	550	660
UB1	47.4	297.0	25.9	10.9	0.15	2.22	360	550	690
UB2	39.04	311.4	17.9	6.9	0.13	2.58	360	550	
UB3	30.6	186.3	24.3	10.21	0.15	2.07	370	560	
UB4	237.8	783.2	43.6	18.4	0.30	2.37		520	
TB1	52.3	252.9	29.0	12.4	0.21	2.34	300	530	600
TB2	4.5	16.2	21.1	11.4	0.28	1.86			
VA1	18.0	90.7	17.8	9.1	0.20	1.96	370	540	690
VA2	8.9	53.6	20.7	9.5	0.17	2.18	330	520	
VA3	15.5	73.8	24.0	11.3	0.21	2.12	380	560	640
WA1	3.6	14.7	32.7	14.7	0.25	2.22	330	540	
WA2	2.1	10.1	37.6	17.7	0.21	2.13	350	580	660
Breccias									
VA5*	12	28.7	134.7	36.7	0.42	3.67	360	570	
VA6*	5.9	17.9	49.5	19.1	0.33	2.60		520	
Suevites									
SA5*	0.4	2.2	60.6	22.2	0.19	2.73	360	570	660
SA8*	1.4	38.3	71.6	14.0	0.04	5.12	360	550	640
Fractured target rocks									
SA2*	1.0	23.3	12.1	113.1	0.04	0.11		550	

M_r, M_s = saturation remanent magnetization, saturation magnetization; H_c, H_{cr} = coercivity, remanent coercive force; T_C = interpreted Curie point; * magnetic material has been separated from samples using Franz magnetic separator for hysteresis measurements. In this case the results are not comparable to results for tagamites, since prior to this the whole rock samples were showing mainly paramagnetic behavior. See Fig. 1 for sampling sites.

(Fig. 6). In general, it shows a relatively stable and hard character during the AF demagnetization. Intersecting great circles also support the presence of this impact component. This component appears to be more stable in tagamites than in suevites or in breccias. From tagamites we derive a paleopole position of Plat. = 45.0°N and Plong. = 76.9°E (*dp* = 9.9°, *dm* = 11.0°).

Additionally, in about one-third of the specimens a viscous, steep positive component pointing north was isolated, corresponding to the present Earth field (PEF). We observed this component relatively more often in suevites and impact breccias than in tagamites, again showing the more stable character of tagamites.

The third component, B, was isolated from a few impact melt rock and breccia samples at the end of the demagnetization curves, mostly from site TA (cf. Fig. 1b), but also from some target rock samples. Component B has a mean direction of D = 220.8°, I = 58.1 (k = 7.5, α_{95} = 16.9°) which corresponds to the paleomagnetic pole of Plat. = 16.0°N and Plong. = 359.0°E (*dp* = 18.4°, *dm* = 25.0°). Few samples seem to trend toward B in the course of AF demagnetization. However, this component could not be isolated with certainty and, because of that, we cannot be sure of its reliability, origin and meaning. Similar kind of direction has been obtained in study by Mertanen et al. (2006) carried on shear and fault zones in Helsinki area, in Finland.

Target Rocks

Most of the target rock samples behaved erratically on AF demagnetization and no reliable component separation was possible. In spite of this we were able to isolate three or occasionally four components from the target rocks. Weighted mean paleomagnetic directions of the most common components and corresponding poles are listed in Table 3. The most common component, A, demagnetizes at high field and has a mean direction of D = 325.0°, I = 57.1 (k = 16.6, α_{95} = 11.0°, 13 sites) yielding a pole position Plat. = 57.6°N and Plong. = 268.8°E (*dp* = 11.6°, *dm* = 16.0°) (Figs. 6c and 7). Reversed directions A_R were also observed from two samples (JC1, JC3) confirming that the isolated directions most likely represents the Svecofennian direction.

The component C was isolated from 11 of the target rock

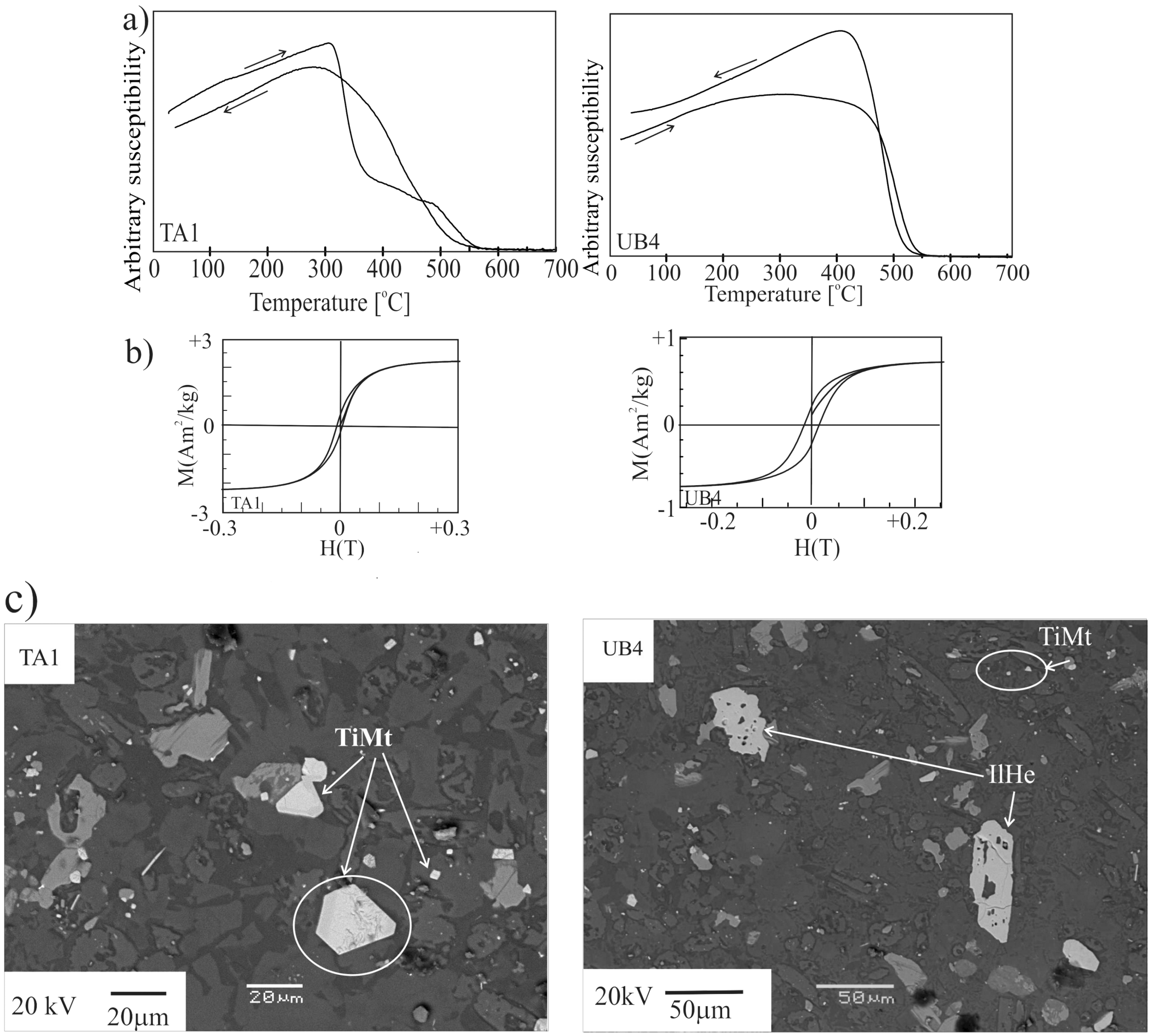

Fig. 3. a) Typical thermomagnetic curves, b) hysteresis curves, and c) SEM (Jeol JSM-5900LV) figures of magnetic minerals for Jänisjärvi tagamites (sample TA1 is on the left and sample UB4 is on the right).

samples collected closer to the impact center. This component has a mean direction of *D* = 54.9°, *I* = 60.4 (*k* = 12.5, α_{95} = 13.4°, 11 sites). Four specimens (JD1, JC1, JC3, and JH5) from three sites show a reversed direction of this component. In most cases the reversed component occurs in the target rocks as a low coercivity overprint. The two analyzed samples of shocked target rocks show a trend toward component C during the AF treatment. However, the calculated direction is highly scattered, although the intersection of great circles point to an impact overprint.

In nine of the target rock samples, we also observe a viscous component interpreted as PEF direction. Such a component is the only one present in rocks far from the impact center, proving their viscous character.

Component B, with a mean direction of *D* = 258.4°, *I* = 35.5 (*k* = 3.8, α_{95} = 75.2, 3 sites), and the paleomagnetic pole of Plat. = 11.9°N and Plong. = 320.4°E (*dp* = 50.3°, *dm* = 86.8) (also present in impactites), was isolated in 3 samples.

Paleointensity and Thermal Demagnetization

We determined paleomagnetic directions using thermal treatment based on eighteen tagamite specimens. Sample mean directions based on thermal demagnetization of ten samples give a declination of 91.7° and inclination of 77.0° (α_{95} = 11.5°, *k* = 18.6). The mean pole value is Plat. = 52.7°N and Plong. = 74.8°E (*dp* = 20.0°, *dm* = 21.4°), which correlates with the AF measurements mentioned above. We considered a

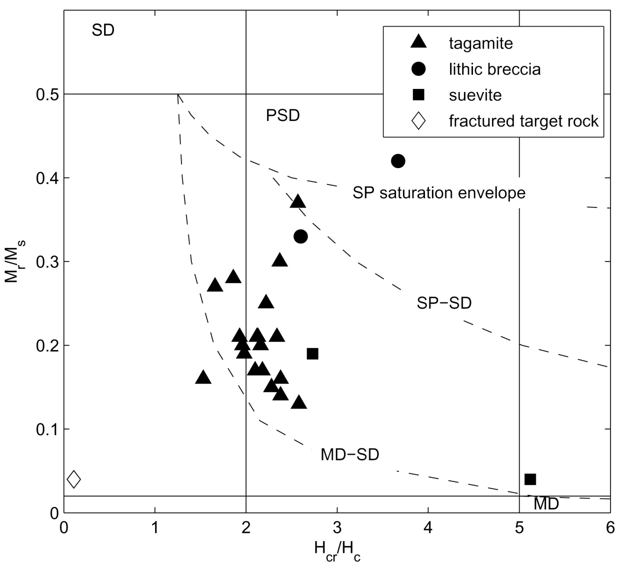

Fig. 4. Measured hysteresis ratios for the Jänisjärvi rocks plotted on Day plot (Day et al. 1977; Dunlop 2002). M_r = saturation remanent magnetization, M_s = saturation magnetization, H_c = coercive force, H_{cr} = remanent coercive force, SD = single domain, PSD = pseudo-single domain, MD = multi domain, SP = superparamagnetic.

paleointensity measurement reliable when (i) the paleointensity estimate consists of at least 5 subsequent points on the Arai diagram (Arai 1963), (ii) partial thermoremanent magnetization (pTRM) checks (e.g., Coe 1967) are less than 7% and pTRM tail checks (Shcherbakova et al. 2000) are lower than 5%. Additionally, the f factor, representing the amount of NRM used, should be at least 30%. Reliable paleointensity determination are based on 7 measurements and yielded a mean value of 68.7 ± 7.6 μT. Table 4 shows the intensity and the directional results. Most of the specimens demagnetize already at low temperatures and in some cases the mean angular deviation (MAD) is relatively high. In two other specimens, chemical alteration became significant above 430 °C. Figure 8 shows two typical paleointensity behaviors. In Fig. 8a, the Arai diagram shows the demagnetization at low temperatures for the tagamite sample TB3-3c and the behavior for sample UB4-2a. Figure 8b presents the unique direction used to determine the paleointensity, whereas Fig. 8c presents the NRM decay with respect of temperature. Finally, Fig. 8d shows the behavior of susceptibility as a function of temperature. We notice that for both specimens the susceptibility variation lies within 20% of the original value.

DISCUSSION

Paleomagnetic Poles and Age Determinations

The primary characteristic remanence direction C is obtained from impact lithologies and is believed to record the impact event. As further proof, some hints of component C were observed as overprints on fractured target lithologies farther from the center of the Jänisjärvi structure. Plotting the corresponding pole for component C, we notice that its position agrees with both Neoproterozoic (Fig. 9a; Table 5) and Early Paleozoic (Fig. 9b; Table 5) poles for Baltica. Whole rock samples of the tagamites have been dated in two different laboratories to be 718 ± 5 Myr (K-Ar method) (Masaitis et al. 1976) and 698 ± 22 Myr (^{40}Ar-^{39}Ar method) (Müller at al. 1990). These data are interpreted by the respective authors as the Neoproterozoic age of cooling of the melt and they are believed to reflect the age of the impact event for two reasons. First, regional geological activities, which could have altered the rocks, have not been reported. Second, mineralogical evidences, like the presence of cordierite crystals and the microcrystalline texture of the tagamites, favors relatively fast cooling of the impact melt.

It becomes obvious that there is a disagreement between the observed paleomagnetic age and the measured isotopic age. In fact, poles with ages close to the isotopic age of Jänisjärvi (~700 Myr) are the 750 Myr mean pole and the 616 Myr pole derived from Egersund mafic dykes (Torsvik et al. 1996; Meert et al. 2003). Figure 9b shows clearly that Jänisjärvi pole is offset compared to the 750–616 Myr APWP segment.

A closer look at Fig. 9a reveals that the Jänisjärvi pole plots close to Neoproterozoic (south) poles for Baltica (Torsvik et al. 1996; Torsvik 2003; Walderhaug et al. 1999), which have been obtained from Late Sveconorwegian massive-type anorthosites (932–929 Myr) (Pesonen et al. 1992) and from the post-Sveconorwegian Hunnedalen dyke swarm (848 Myr) (Walderhaug et al. 1999). The pole is clearly off from the Early Sveconorwegian data (1100–966 Myr) (Table 5) measured from dykes and intrusions from south Norway and south Sweden. In this respect, we would believe the paleomagnetic age for Jänisjärvi is closer to 850–900 Myr.

Since the Jänisjärvi pole can be interpreted as being of Early Paleozoic age, we compare it also to the Late Neoproterozoic–Early Cambrian APWP segment for Baltica (Table 5; Fig. 9b). When comparing the Jänisjärvi pole to the data set for Baltica (e.g., Meert et al. 2003; Torsvik et al. 1996; Torsvik et al. 2001), we notice that it plots on the Cambrian part of the APWP segment, close to the 500 Myr pole derived from Andrarum limestone. Recently, the reliability of the existing data between 750 and 500 Myr has been questioned (e.g., Eneroth et al. 2004; Llanos et al. 2005; Popov et al. 2002), mainly because the data are sparse and of ambiguous interpretation. Torsvik et al. (1996) place Baltica at very high latitudes in the southern hemisphere during the period spanning 616 to 500 Myr (Fig. 10, solid arrow). This is not the case if we include the latest paleomagnetic studies for Vendian lithologies in Baltica (e.g., Eneroth et al. 2004; Llanos et al. 2005; Popov et al. 2002), which place Baltica

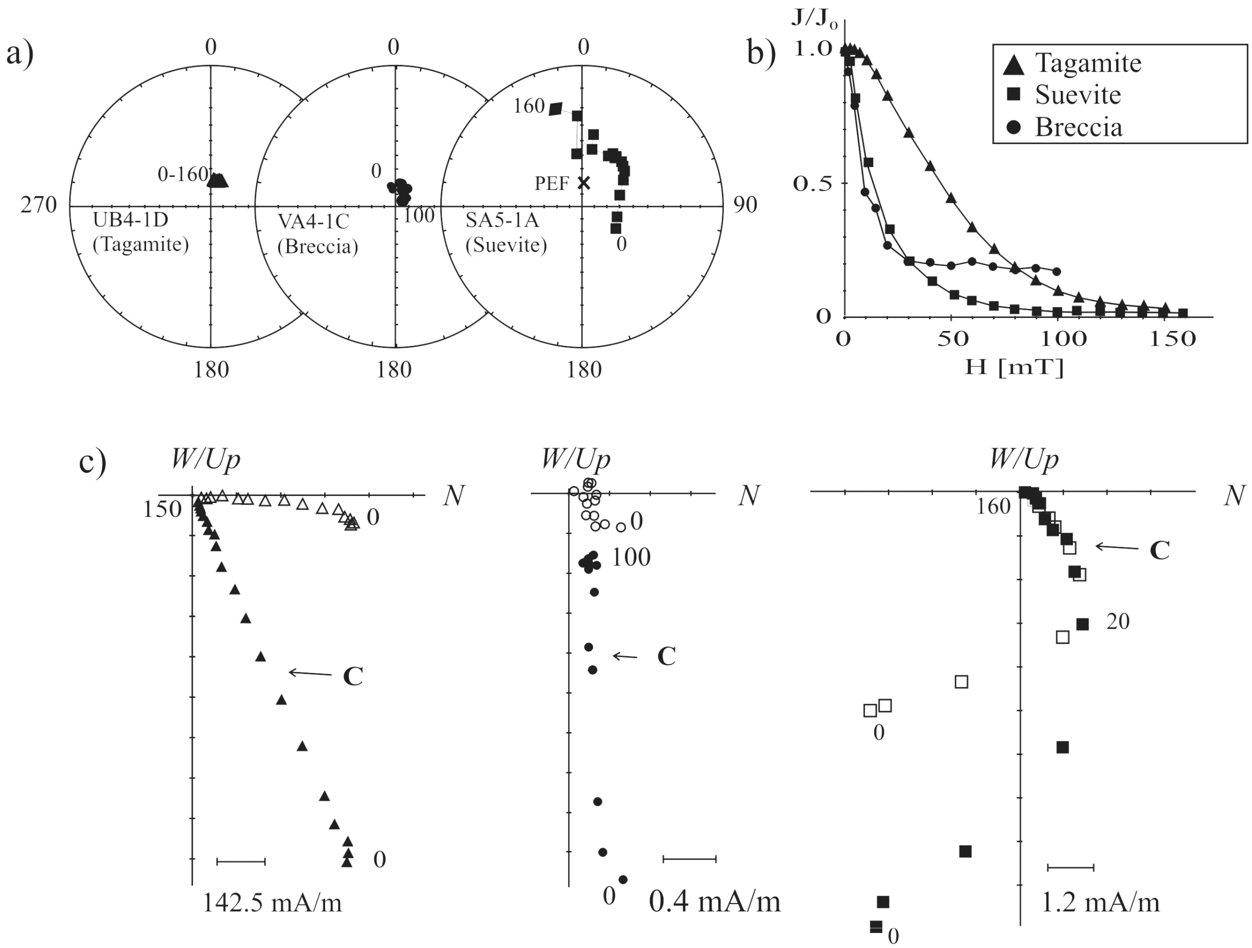

Fig. 5. Examples of AF demagnetization treatment isolating the impact component (C) as obtained from the impactite specimens' a) stereoplot, where PEF is Earth's present magnetic field direction at Jänisjärvi area is marked by cross, b) NRM intensity decay curve, and c) orthogonal vector plots where open (closed) symbols are data for N-S versus E-W (N-S versus up-down) projections.

closer to the equator (Fig. 10, dashed arrow). The discrepancy is visible also in Fig. 9b, where both APWPs are plotted; the solid line after Torsvik et al. (1996, 2001) and the dashed line after Popov et al. (2002). Regardless of which is the correct interpretation of the APWP, we notice that the Jänisjärvi pole fits well with both suggested APWP around 490 Myr.

Using Baltica's paleopoles, it appears that two possible ages for magnetization of Jänisjärvi rocks exist: 1) Late Sveconorwegian age, or 2) Late Cambrian age. If this magnetization is related to the impact event, the isotopic age of about 700 Myr given for the impact is in error (Masaitis et al. 1976; Müller et al. 1990). The question thus arises whether the isotopic data reflect inherent problems of the Ar-Ar dating technique. In fact, K-Ar and ^{39}Ar-^{40}Ar ages for whole rock impact melt samples might be ambiguous for the following reasons (Deutsch et al. 1994).

1. The post-shock loss of in situ produced radiogenic argon ($^{40}Ar_{rad}$) by devitrification and diffusional processes can result in too young ages.
2. The presence of relic $^{40}Ar_{rad}$ in the melt matrix, as well as in rock and mineral fragments, which are inherited from precursor lithologies, can cause too old ages.
3. Disturbances by secondary processes, such as incorporation of Ar from a fluid phase can lead to either increase or decrease of the ages.

Concerning the Jänisjärvi case, the data after Müller at al. (1990) show that the degassing spectra for the whole rock impact melt sample is complex and a simple interpretation is not possible. Moreover, due to the existence of two apparent isochrones and the fact that the corresponding isochron ages differ significantly on the 2σ level, the age of 698 ± 22 Myr might not reflect the age of the impact event. The general problems in interpreting Ar-Ar age data on whole rocks samples has been demonstrated on the Dellen case in detail by Deutsch et al. (1992).

The significant deviation of the Jänisjärvi pole from Neoproterozoic poles published for Baltica (Hartz et al. 2002; Torsvik et al. 1996; Torsvik 2003) might also rest on problems related to the paleomagnetic data. Four reasons may explain

Table 3. Paleomagnetic results for the Jänisjärvi structure (center point: Lat. = 61°58′N, Long. 30°58′E).

Site	Rock type	(B/)N/n	p	D (°)	I (°)	k	α_{95} (°)	Plat. (N°)	Plong. (E°)	dp (°)	dm (°)	A_{95} (°)
Impact component (C) in tagamites (af)												
TA	Tagamite	8/46	N	122.3	77.2	5.9	23.2	44.4	60.2	40.4	43.3	4.8
TB	Tagamite	4/24	N	95.3	64.1	42.2	14.3	37.1	91.5	18.2	22.8	20.4
VA(1-3)	Tagamite	3/23	N	78.2	64.7	51.5	17.4	45.1	103.1	22.4	27.9	25
UB	Tagamite	4/26	N	88.4	75.1	25.4	1.6	51.7	80.5	31	33.9	32.4
WA	Tagamite	3/18	N	108.0	71.6	20.6	27.9	40.9	75.1	43	49	45.9
Mean	Tagamite	5/22/137	N	104.0	74.0	23.9	6.3	44.5	75.0	10.2	11.3	10.7
Impact component (C) in tagamites (th)												
TA	Tagamite	6/10	N	112.0	78.9	17.2	16.6	49.3	62.2	30.0	31.6	30.8
TB	Tagamite	1/1	N	70.4	54.5			117.9	39.5			
UB	Tagamite	3/7	N	75.0	78.2	24.1	25.7	59.5	78.2	45.6	48.4	47.0
Mean	Tagamite	3/10/18	N	91.7	77.0	18.6	11.5	52.7	74.8	20.0	21.4	20.7
Mean (af+th)	Tagamite	5/22/155	N	101.5	73.1	26.2	6.2	45.0	76.9	9.9	11.0	10.4
Impact component (C) in impactites (af)												
SA	Suevites	3/7	N	106.0	78.1	336.4	6.7	49.7	66.4	11.9	12.7	12.3
VA(4-7)	Breccias	4/23	N	37.2	80.5	43.0	14.2	72.9	72.0	26.2	27.3	26.7
SA, VA	Impactites	3/3/5	R	219.2	–37.4	9.7	25.9	–40.9	339.6	17.9	30.4	23.3
Mean	Impactites	8/32/170	M	85.4	74.2	14.8	6.7	51.9	83.7	11.0	12.1	11.6
Impact component (C) in target rocks												
AL	Schists	1/2	N	89.1	68.7			44.5	90.5			
JH	Schists	2/6	N	25.9	66.5			70.7	151.2			
JA	Schists	1/2	N	82.8	58.5			37.2	105.6			
JC	Schists	3/6	N	67.4	65.8	32.7	21.9	51	109.8	29.1	35.7	32.3
JD	Schists	1/5	N	29.0	51.7			55	165.4			
JD, JC, JH5	Target rocks	3/4	R	225.0	–39.9	5.9	56.3	40.3	152.2	40.7	67.7	52.5
Mean	Target rocks	5/11/25	M	54.9	60.4	12.5	13.4	51.8	129.1	15.5	20.4	17.8
Svecofennian component (A) in target rocks												
AL	Schist	1/2	N	319.0	45.0			47.1	268.6			
JH	Schist	1/4	N	325.0	61.4	116.3	8.6	61.5	274.7	10.1	13.2	11.6
JA	Schist	2/6	N	298.5	65.9	30.8	46.7	53.8	309.9	62.2	76.2	68.8
JC	Schist	3/4	N	340.0	54.2	14.8	33.2	60.0	245.1	32.8	46.7	39.1
JD	Schist	1/5	N	346.0	55.0	25.8	13.4	62.2	236.6	13.6	19.1	16.1
JH3	Mica gneiss	1/3	N	359.2	39.6			50.5	212.1			
JH4	Mica gneiss	1/2	N	299.0	46.0			7.3	289.3			
JH13	Mica gneiss	1/1	N	313	82			69.5	356.6			
JC	Target rocks	2/5	R	132.0	–39.9	5.8	143.7	39.0	272.8	103.4	172.4	133.5
Mean	Target rocks	8/13/32	M	325.0	57.1	16.6	11.0	57.6	268.8	11.6	16.0	13.6

af = alternating field demagnetization; th = thermal demagnetization; Lat., Long. = coordinates of the Jänisjärvi impact structures center point; B/N/n = number of sites/samples/specimens; *D*, *I* = declination, inclination; *p* = polarity; N, R, M = normal, reversed, multi; k, α_{95} = Fisherian precision parameter, 95% circle of confidence; Plat., Plong. = paleomagnetic pole position; *dp*, *dm* = 95% confidence oval of the pole; A_{95} = 95% confidence circle of pole.

the apparent age discrepancy: 1) postimpact remagnetization, 2) postimpact tilting, 3) secular variation of the geomagnetic field, and 4) a poorly defined APWP due to the paucity of well-dated Neoproterozoic paleomagnetic poles.

1. A magnetization age of ~500 Myr could be explained by postimpact remagnetization, but there is no evidence for tectonic disturbances, fracturing, or igneous activity at that time in the area of Jänisjärvi, which might have affected the magnetization of the tagamites. Also, the data pass the impact test (Pesonen et al. 2001) by showing that the component C is observed in all impact rocks as well as a superimposed component over the primary Svecofennian component A in the target rocks located close to the impact structure.

   Additionally, there are no regional Paleozoic thermal events known in this area (Larson et al. 1998). One reason for 500 Myr old thermal remagnetization could be the burial of the impact area a thick postimpact cover. However, there is no evidence for such a cover, which could have caused temperatures of up to 350 °C, required to remagnetize titanomagnetite. The Cambrian to Silurian cover of Baltica has been proposed to be only

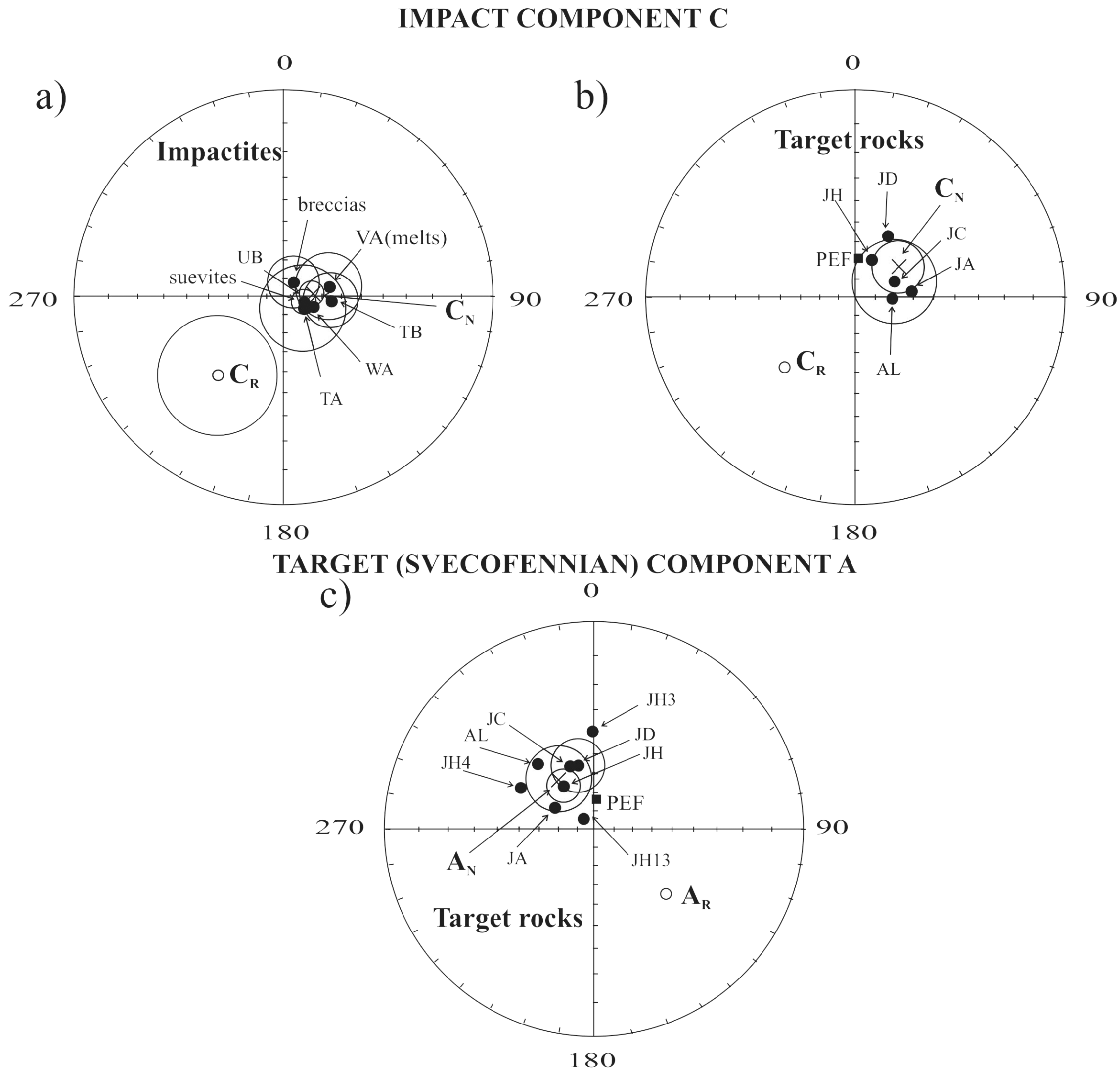

Fig. 6. Site mean directions of main paleomagnetic components for Jänisjärvi impact structure. Mean of impact component C in (a) impactites, (b) in target rocks, and (c) target component A in target rocks. PEF at Jänisjärvi area (square) and mean value of component A (cross) are shown. Circles around the direction denote the 95% circle of confidences.

few hundreds of meters thick (Larson et al. 1998). The possible post-Caledonian burial of the area would be too young to cause this 500 Myr remagnetization; Moreover, this cover and its extent are highly controversial (e.g., Hendriks et al. 2005 and references therein). The origin of a possible remagnetizations could be also chemical as according to Puura et al. (2005) the Jänisjärvi impact structure was buried under the sea 500 Myr ago. However, the fact that we again see the so-called impact component (C) as an overprint in some but not all target rocks does not support the idea of remagnetization.

2. Drilling has shown that pre-Vendian peneplain of Fennoscandian Shield dips very gently, about 0.2° to the south, suggesting that no large-scale structural movements have taken place (Laitakari et al. 1996). This tilt is negligible and does not affect the pole's position. Moreover, the impact melt layer appears on the same stratigraphic level everywhere in the structure (Masaitis 1999), and local tilting has not been reported.
3. The Earth's magnetic field undergoes secular variation (SV) due to changes in dipole (D) and nondipole (ND) components. The most important contribution of the SV to paleomagnetic data is due to westward drift of the ND field, which has a characteristic period of roughly 1800 years. This is also the time required to average out the deflection by westward drift on the paleomagnetic record (Irving 1964). In the Jänisjärvi case, the cooling of the melt body took some hundreds to thousand of years (Sazonova 1983), indicating that the SV may not be fully averaged out.

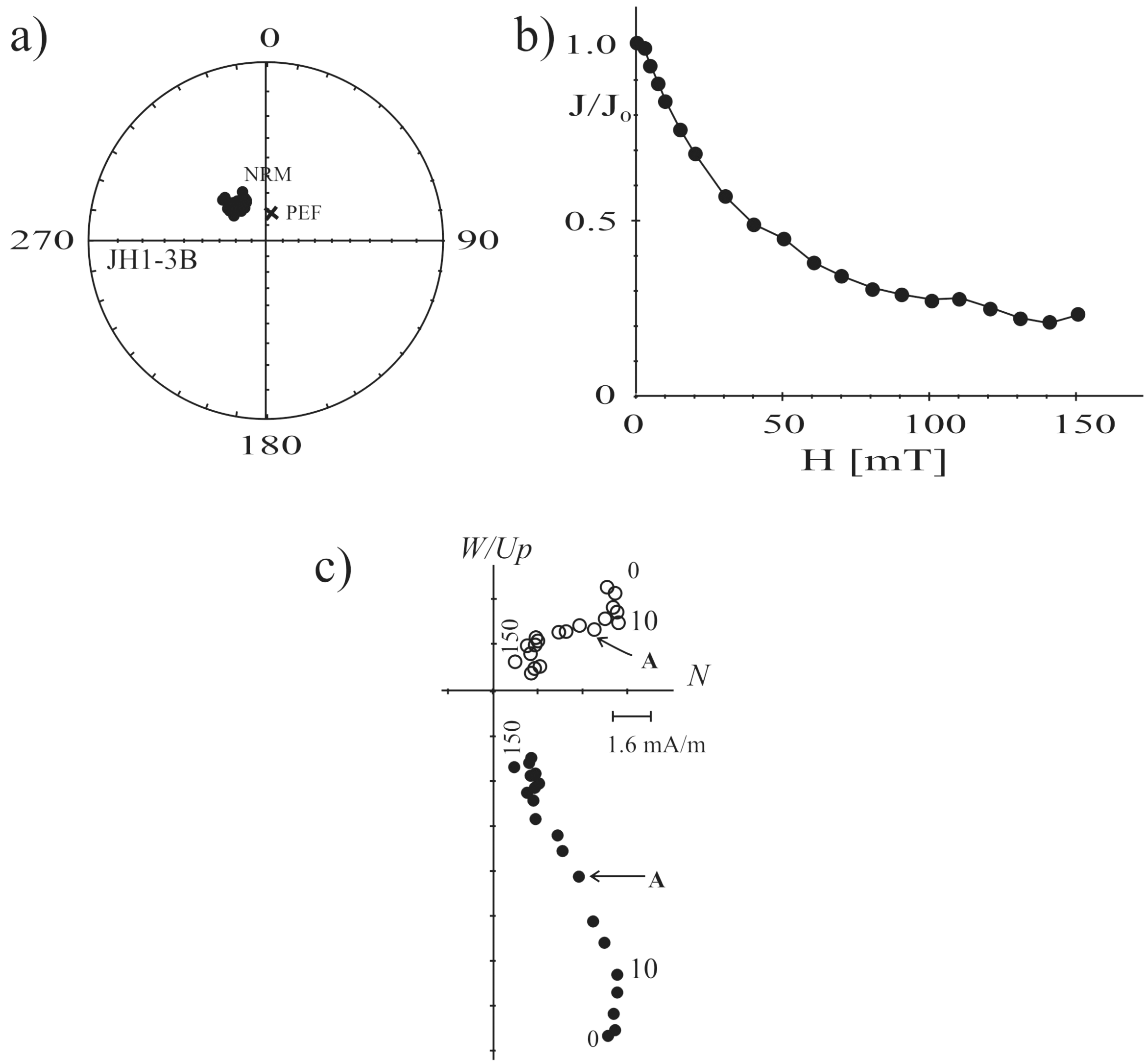

Fig. 7. AF demagnetization of the target rocks, which reveal the Svecofennian component (a) direction on a stereonet, where PEF is Earth's present magnetic field direction at Jänisjärvi area, b) intensity decay curve, c) orthogonal vector plots where open (closed) symbols are data for N-S versus E-W (N-S versus up-down) projections.

Table 4. Results of Thellier paleointensity measurements of the selected Jänisjärvi impact melt rocks.

Specimen	Volume (cm^3)	*dT* (T)	*Ba* (μT)	σ (μT)	*q*	*f*
UB4-1c	8.88	0-430	69.8	2.74	12.56	0.57
UB4-2a	10.99	0-430	74.9	3.80	6.47	0.50
TA5-2a	11.29	0-250	62.5	2.81	11.63	0.72
TA7-1c	11.19	0-250	53.2	3.71	7.43	0.70
TA7-3e	10.23	0-250	72.3	3.70	9.88	0.70
TA8-3a	11.04	0-250	65.8	6.82	4.93	0.70
TB3-3c	8.45	0-250	68.2	4.06	8.93	0.76
UB2-c	11.08	0-250	72.4	5.98	6.2	0.80
UB2-3b	11.01	0-250	79.2	5.52	8.21	0.82
Mean			68.7	7.60		

The first two letters of the specimen name refer to the site; *dT* = temperature interval used for intensity determination, *Ba* = ancient field intensity; σ = standard deviation; *q* = quality factor; *f* = the fraction of NRM.

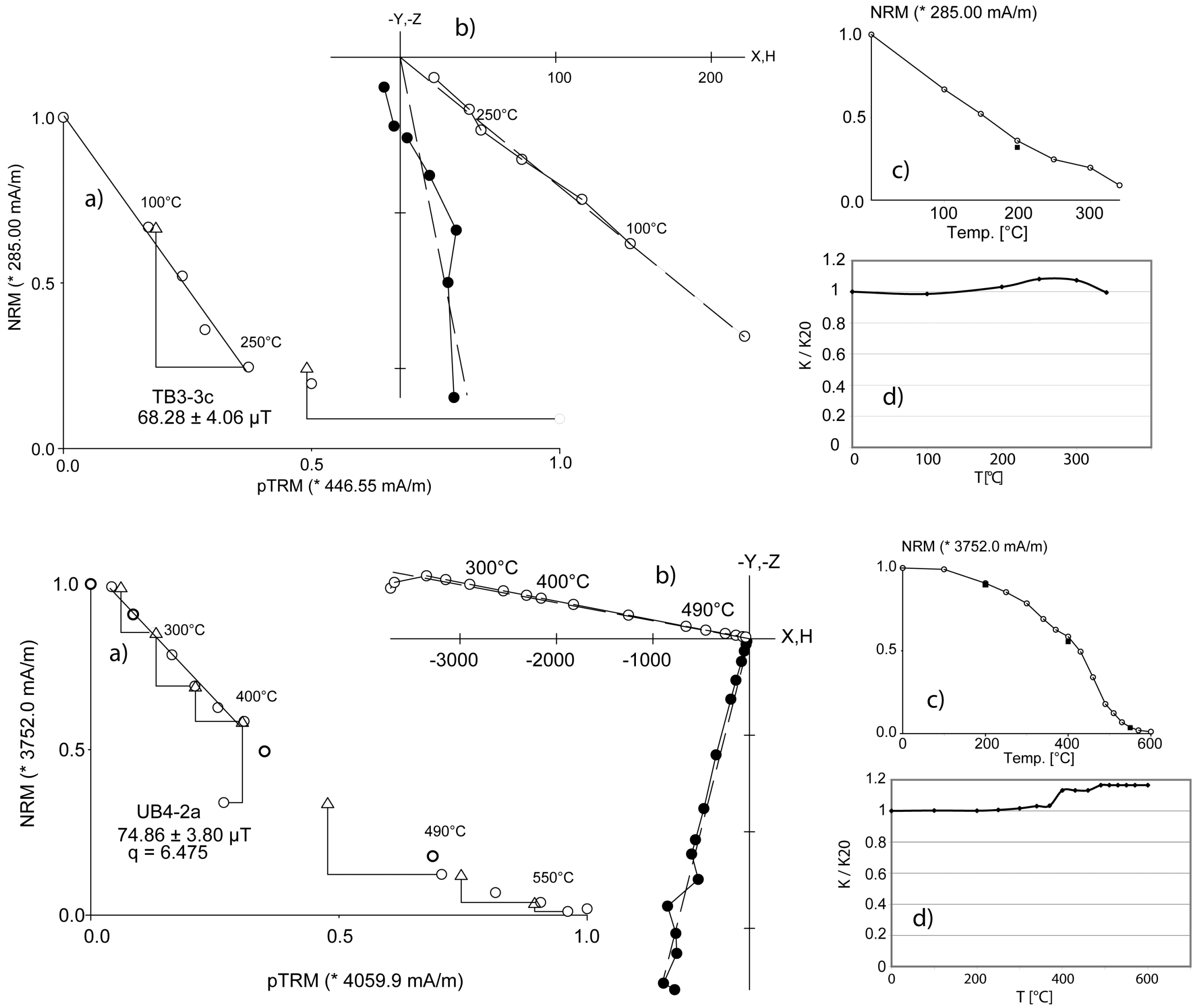

Fig. 8. Two results from Thellier paleointensity experiments (TB3-3c and UB4-2a, both tagamites). a) The Arai plot, b) the Zijderveld plot, c) the NRM intensity decay, and d) monitoring of susceptibility as a function of temperature.

We used the method given by Pesonen et al. (1992) to test if the SV of the geomagnetic field at 700 Myr ago would explain the observed discrepancy. We calculated the SV curve around the 700 Myr reference pole, assuming that the geomagnetic conditions 700 Myr ago were the same as today. Because of a lack of a 700 Myr paleopole for Baltica, we interpolated its position from the Baltica's APWP (Torsvik et al. 1996). In addition, we calculated the SV around the Jänisjärvi pole derived from the analyzed tagamites. Figure 9c shows the modeled SV curves around the interpolated 700 Myr pole and Jänisjärvi poles. As the SV curve of 700 Myr does not include the mean pole of Jänisjärvi tagamites, the Jänisjärvi pole seems to be related to a event distinct from 700 Myr.

4. When plotting the Jänisjärvi pole derived from tagamites against Baltica's ~1100–500 Myr poles, the pole position yields a Neoproterozoic (Fig. 9a) or Cambrian age (~500 Myr) (Fig. 9b). Moreover, the new paleomagnetic data from Jänisjärvi takes Baltica to high southern latitudes at the time when magnetization was acquired. If it was 700 Myr ago as the isotopic data imply, the results disagree with the latitudinal position of 750 Myr (Hartz et al. 2002; Torsvik et al. 1996, Torsvik 2003) (Fig. 10). If both these positions (750 and 700 Myr) are correct and the Jänisjärvi tagamites acquired magnetization at 700 Myr, it would indicate rapid latitudinal movement of the shield (13.2 cm/pal) combined with ~150° rotation (Baltica upside down at 750 Myr, Torsvik 2003) between 750 and 700 Myr. Considerable latitudinal movements of Baltica during the Neoproterozoic has been proposed, in particular between 970 and 900 Myr (e.g., Brown et al. 2004; Elming et al. 1993; Weil et al. 1998), although the velocity of the movement is much smaller than that

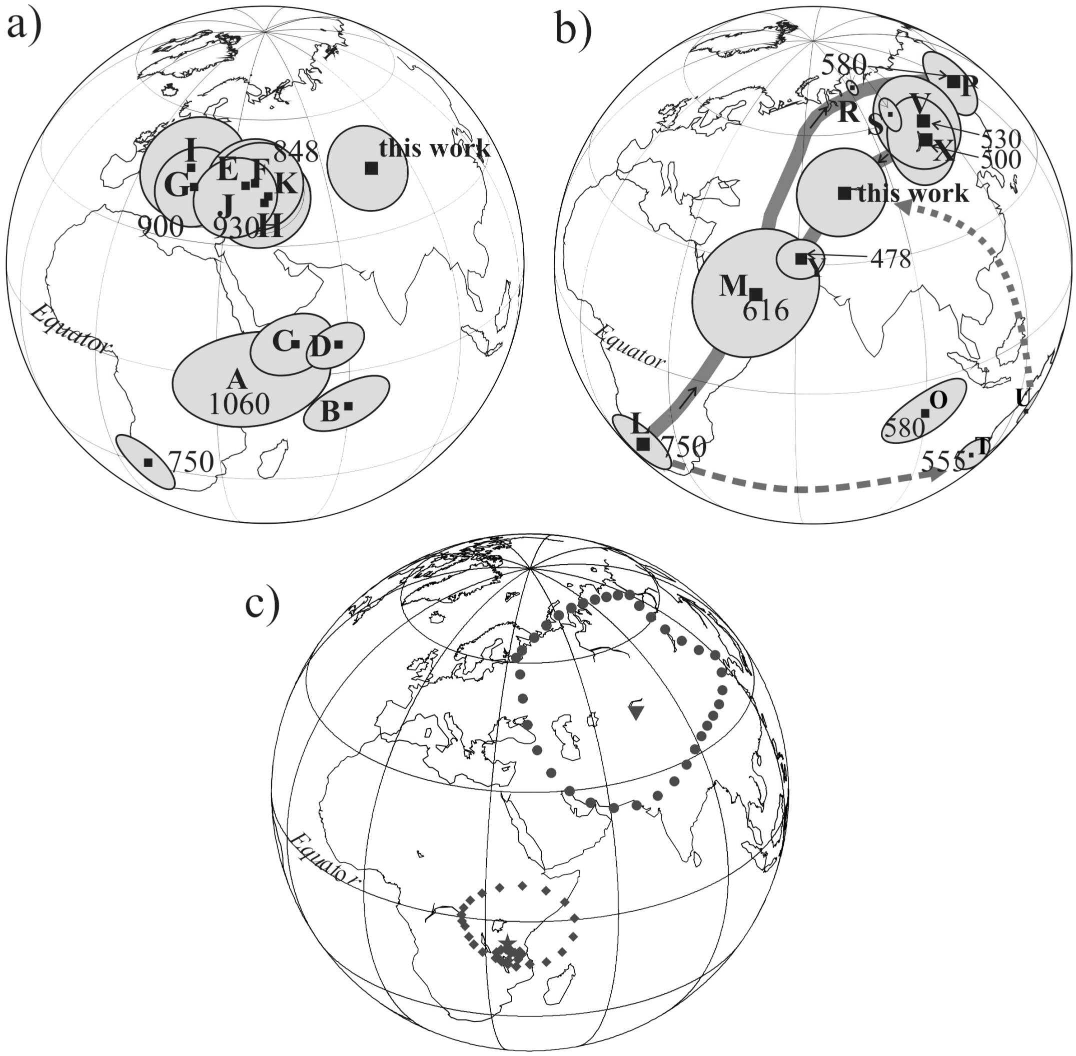

Fig. 9. A comparison of the pole from this study to the proposed paleopoles for Baltica between ~1100–500 Myr shows that the pole C is clearly off from 750–616 Myr segment of Baltica's APWP. In (a), the pole is plotted with Neoproterozoic poles, mainly Early and Late Sveconorwegian poles; b) is plotted with poles between ~750 and 500 Myr. Shown are two different APWP curves after Torsvik et al. (1996, 2001) (solid line) and after Popov et al. (2002) (dashed line). Numbers denote the age of the pole in Myr and lettering is the key for poles and references in Table 5. c) The dots around the 700 Myr reference pole and this work's mean pole from Jänisjärvi tagamites show the calculated secular variation curve (SV), which would be observed if the Earth's magnetic field had a westward drift around the mean pole similar to the present one.

discussed above (Fig. 10). Walderhaug et al.'s (1999) data places Baltica at a high southern latitude at ~848 Myr ago. Again it requires rapid movements to take Baltica from high southern latitudes up to the equator at 750 Myr (Torsvik et al. 1996) and back to high southern latitudes again at the possible age of 700 Myr (Fig. 10). On the other hand, the absolute age of the rock formations used to calculate the 750 Myr pole (average) is not well constrained.

In summary, the explanations discussed in points 1–4 cannot solve the discrepancies concerning the age and position of the Jänisjärvi pole. Since the magnetization direction of the tagamites is clear can be interpreted without further assumptions to record the impact event, we suggest new isotopic date to solve the age discrepancy.

Paleointensities and Virtual Dipole Moment

As mentioned before, the paleointensity estimate is based on seven reliable measurements. One of the main problems with these reliable estimates is the fact that they are mainly associated with low temperatures and demagnetize completely at 250–320 °C. Based on the rock magnetic investigations, we believe that this temperature is associated with primary titanomagnetite. This idea is supported by the good directional agreement with AF measurements as well as

Table 5. Selected paleomagnetic poles for Baltica, ~1100–500 Myr.

Pole name	Key[a]	Age (Myr)	Pole Lat./Long.[a]	A_{95}[a]	Reference
Bamble mean	A	~1100–1040	–3/37	15	Meert et al. 2003
Nilstorp dolerite	B	~980	–9/59	11	Patchett et al. 1977
Årby dolerite	C	~995	7/47	8	Patchett et al. 1977
Falun dolerite	D	~966	6/58	6	Patchett et al. 1977
Bjerkheim-Sogndal intrusion mean	E	~930	44/38	4	Stearn et al. 1984
Rogaland anrthosites mean	F	~930	44/34	3	Stearn et al. 1984
Egersund-Ogna anorthosites	G	~900	42/20	2	Brown et al. 2004
Garsaknat body	H	~902	40/41	11	Stearn et al. 1984
Åna-Sira Massif	I		46/17	13	Stearn et al. 1984
Håland-helleren Massif	J		41/33	9	Stearn et al. 1984
Hunnedalen dikes	K	~848	41/42	6	Walderhaug et al. 1999
Mean	L	~750	–28/17	8	Torsvik et al. 1996
Egersund dikes	M	~616[b]	22/51	14	Poorter 1972
Egersund dikes	N	~616[b]	48/20	14	Meert et al. 2003
Alnö complex	O	545–589	–8/92	7	Piper 1981
Fen complex	P	~583	56/150	8	Meert et al. 1998
Sredny dyke	R	~580	73/95	2.3	Torsvik et al. 1995
Komagnes dyke	S	~580	63/103	4.5	Torsvik et al. 1995
Zolotica River	T	~556	–28/110	4	Llanos et al. 2005
Winter Coast	U	~555	–25/132	3	Popov et al. 2002
Torneträsk Fm	V	~535	56/116	13	Torsvik et al.2001
Andrarum limestone	X	~500	52/111	8	Torsvik et al.2001
St. Petersburg limestone	Y	~478	34/59	6	Smethurst et al. 1998

[a]Key refers to letters given in Fig. 9; Pole Lat./Long. are latitude and longitude of the pole position; A_{95} is the 95% confidence circle about the mean pole.
[b]Age from Bingen et al. 1998.

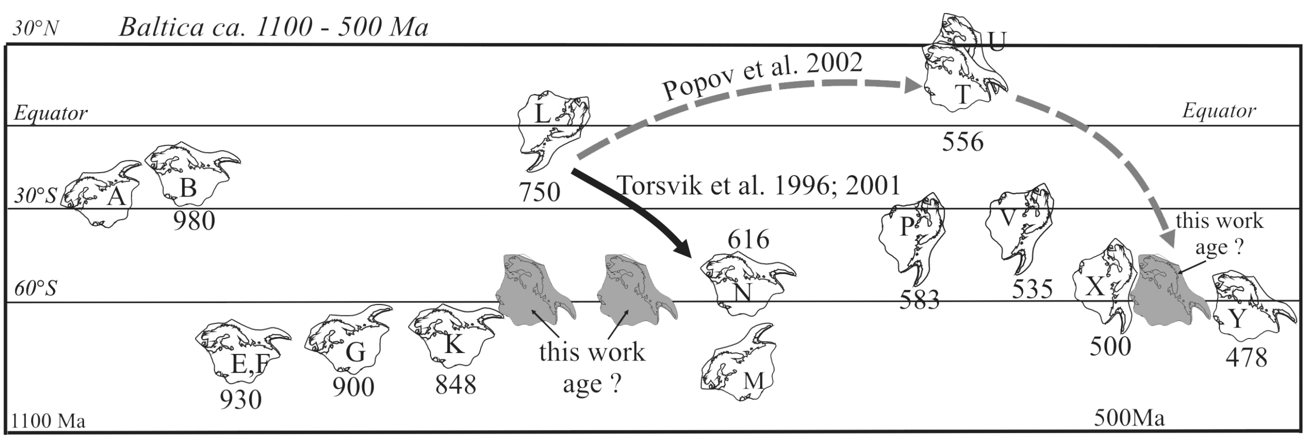

Fig. 10. Baltica's schematical latitudinal movement between about 1100 and 500 Myr ago. Used data is listed in Table 5. According to data set of Torsvik et al. (1996, 2001), Baltica moved from the equator to high southern latitudes between 750 and 616 Myr and stayed there up to Early Ordovician. However, Popov et al. (2002) proposed that Baltica stayed on low latitudes between 750 and ~500 Myr (gray dashed = line arrow). Data from this work takes Baltica to high southern latitude, but since the age is controversial, the continent is shown in three possible locations on time scale. According to isotopic dating the age is ~700 Myr, but when comparing the magnetization direction and paleomagentic poles to other poles of Baltica two ages were obtained: Neoproterozoic age and a Cambrian age. Note: continent's size is reduced; letters are keying to Table 5, and numbers refer to ages in Myr.

the presence of impurities, which could lower the T_c of this magnetic phase. Additionally, the fact that the impact direction (C) can be observed in some target rocks makes us suppose that it is of primary origin. The only two specimens that cover a broader temperature spectrum were drilled from sample UB4. In this case, the paleointensity can be determined from the first part of the plot (0–430 °C), before occurrence of alteration, and the corresponding *f* factor is 0.5–0.6. A closer look at the Arai diagram (Fig. 8) shows us that the diagram is concave, and the estimate might be biased toward higher values. In fact, the paleointensity obtained using the whole spectrum would be about 50% lower.

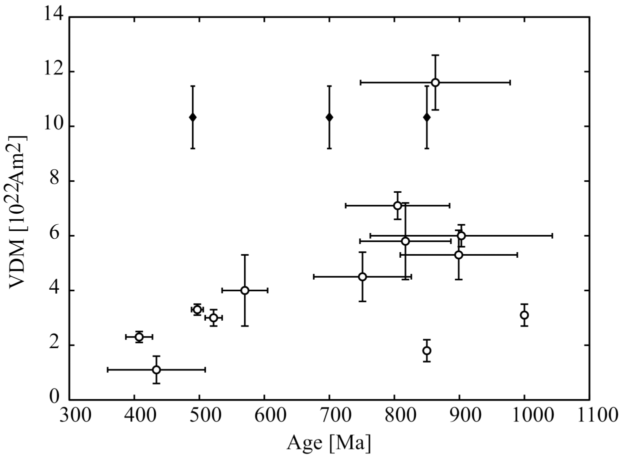

Fig. 11. VDM variation between 1000 and 400 Myr ago. Open circles are data from PINT03 database. Closed diamonds show the VDM for Jänisjärvi according to the paleomagnetic age (500 Myr or 850 Myr) and the isotopic age (700 Myr).

Nevertheless, there is good agreement between the values obtained from the different specimens.

Taking into account the problems discussed above, we can plot the virtual dipole moment (VDM) of 10.3 ± 1.1 10^{22} Am^2 obtained from the mean ancient field value for Jänisjärvi using the suggested ages of 500, 700, and 850 Myr (Fig. 11, closed diamonds). Compared with data from PINT03 database (open circles) (Perrin et al. 2004) collected for the interval 400 to 1000 Myr, Jänisjärvi shows remarkable higher paleointensities, and correlate only with a point by Schwarz et al. (1969) for Canada, dated 863 ± 115 Myr. The ambiguity of the data by Schwarz et al. consist in the fact that they did not use any pTRM check in their experiments, and hence alteration might play an important role in the intensity estimate itself. Additionally, the data consist of one single measurement only. At the same time, the data is in obvious contrast with reliable results recently obtained for the Cordova Gabbro (850 Myr) by Yu et al. (2002), showing a VDM of 1.8 ± 0.4 10^{22} Am^2. The comparison with the other PINT03 data suggests that the intensities determined from Jänisjärvi are considerably biased towards higher values. Hence, the problem of concave Arai diagrams, which has been discussed by other authors (e.g., Coe et al. 2004), seem to lie at the basis of the discrepancy.

CONCLUSIONS

The following conclusions are drawn from this study:

1. Petrophysical properties of the rocks from Jänisjärvi impact structure are characteristic of impact craters formed in a crystalline target. That is, the porosity of the impactites is higher than target rocks, whereas the apparent density of the impactites is lower. Moreover, there are also differences between impactites, with melt rocks showing clearly higher density, susceptibility, and NRM values than suevites and breccias. All the samples show fairly weak NRM and low susceptibility values.
2. Optical, SEM, rock magnetic, and paleomagnetic studies indicate the presence of primary titanomagnetite. Some secondary maghemite and ilmenohematite were also observed and could be associated with hydrothermal processes following the impact event.
3. The paleomagnetic investigation shows that the impact-related component is well defined in tagamites and can be partly observed as overprint in target rocks. This observation supports a primary origin of the impact related component.
4. The main result from this study is the pole derived from Jänisjärvi tagamites, which is directly associated with the impact event. A comparison with paleomagnetic poles from Baltica shows that two possible magnetization ages exist, namely a Late Sveconorwegian one (about 850 Myr) and a Late Cambrian one (around 490 Myr). Both paleomagnetic ages disagree with the isotope data of 700 Myr. Our observations support the idea that the Jänisjärvi paleomagnetic pole is of good quality and primary origin. Therefore, we believe that a new, accurate isotope dating would help solving the discrepancy.
5. Paleointensity studies of tagamites show remarkably higher paleointensities compared to other studies on Neoproterozoic-Cambrian rocks. Despite their reliability (i.e., positive alteration checks and intensity determined using the ChRM), the intensity measurements could be biased toward higher values because of the concave-shaped Arai diagram.

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