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Paleomagnetism of Devonian dykes in the northern Kola Peninsula and its bearing on the apparent polar wander path of Baltica in the Precambrian

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ABSTRACT

Mafic dykes and large alkaline and carbonatite intrusions of Middle-Late Devonian age are widespread on the Kola Peninsula in NE Fennoscandia. These magmatic rocks are well characterized with petrographic, geochemical and geochronological data but no paleomagnetic results have been reported yet. We studied dolerite dykes from the northern part of the Peninsula and isolated three paleomagnetic components in these rocks. A low-temperature component is aligned along the present-day field, while a major constituent of natural remanent magnetization is an intermediate-temperature component (Decl. = 79.6°, Inc. = 78.5°, α_{95} = 5,9°, N = 17 sites) that is present in most Devonian dykes but is found in some baked metamorphic rocks and Proterozoic dykes too. Finally, a primary Devonian component could be reliably isolated from two dykes only. Rock-magnetic studies point to presumably primary low-Ti titanomagnetite and/or pure magnetite as the main remanence carriers but also reveal alteration of the primary minerals and the formation of new magnetic phases. The directions of a major component differ from the Middle Paleozoic reference data for Baltica but closely match those for the 190 ± 10 Ma interval recalculated from the apparent polar wander path of the craton. We assume that this Early Jurassic component is a low-temperature overprint of chemical origin. The main impact of the new results is not to mid-Paleozoic or Early Mesozoic times but to much older epochs. Analysis of paleomagnetic data shows that the directionally similar remanences are present in objects with the ages ranging from 500 Ma to ~2 Ga over entire Fennoscandia. Hence we argue that an Early Jurassic remagnetization is of regional extent but cannot link it to a certain process and a certain tectonic event. If true, this hypothesis necessitates a major revision of the APWP for Baltica over a wide time interval.

1. Introduction

On the most general scale, the modern natural sciences have similar structure: a basement of observed facts is overbuilt with theoretical constructions. For the latter to be adequate and predictive, the basement should be composed of as solid and reliable facts as attainable. Hence the permanent pursue for precision, accuracy and reliability that must go on.

Paleomagnetology that studies the "fossil" magnetism of natural objects is not an exception, and the everlasting revision never ceases. Different approaches were suggested, some tested. Now, the most widely used approach is the quality factor suggested by R. Van der Voo (1990). Of many parameters that are used to define whether a result is reliable or not, the remanence age is probably among the most important ones. Quite naturally, it is the most difficult to determine too, the problem of remanence dating being most acute for Precambrian paleomagnetic data.

This problem appears to be an internal matter of paleomagnetism. But it is not. For instance, the hot topic of modern geodynamics is the formation and destruction of supercontinents, where paleomagnetic data play a role that is difficult to underestimate. Hence refining the ages of available data is of crucial importance, and any piece of evidence that may shed some light on the conundrums that surround all so-far proposed Precambrian supercontinents, for instance, Rodinia, is welcome (compare Fig. 9f, in Li et al., 2008, and Fig. 1b, in Evans, 2009, etc.). Of course, this is a multi-disciplinary problem, which, however, crucially depends on the reliability of paleomagnetic data.

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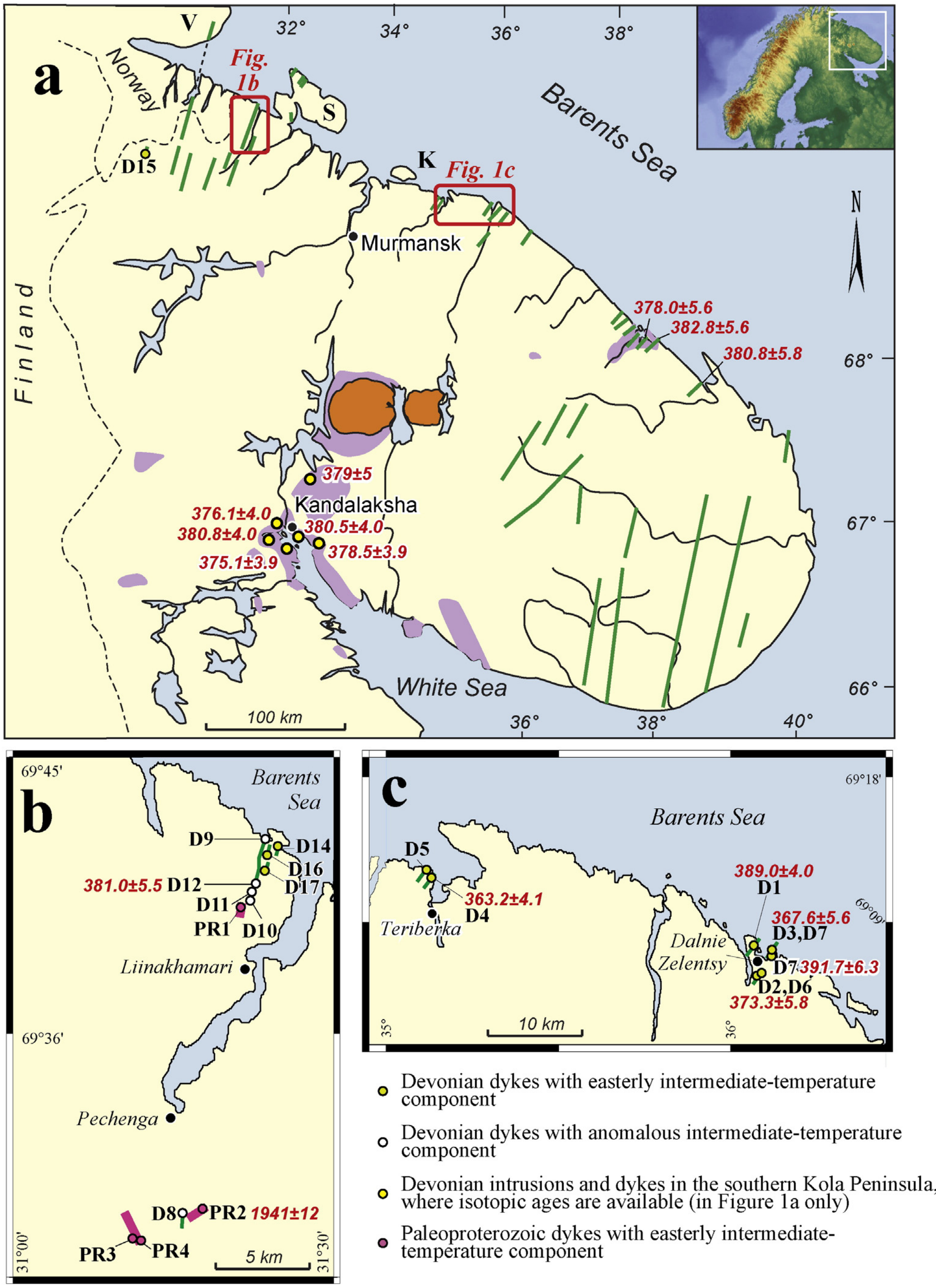

Fig. 1. Distribution of Middle-Late Devonian intrusions in the Kola Peninsula: dykes of normal composition, large alkali intrusive bodies, and the areas with numerous minor alkali intrusions are shown as thick green lines, orange and violet patches, respectively; The Liinakhamari dyke (L) with anomalous data (see text) is highlighted (yellow). Other single characters denote the objects referred to in the text: K — Kildin island, S — Sredny peninsula, V — Varanger Peninsula. Red rectangles denote the sampling areas. Some $^{40}Ar/^{39}Ar$ ages (in Ma) are shown either close to the dated dikes in the north or as orange circles in the south as the studied dykes are too small. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The original goal of a paleomagnetic study of Middle-Late Devonian dykes and large alkaline and carbonatite intrusions in the Kola Peninsula was to obtain a reliable pole of this age and to refine the still imprecisely defined 390–310 Ma segment of the apparent polar wander path (APWP) for Baltica (Torsvik et al., 2012). A large number of dykes, in the southern Kola in particular, and large intrusions, however, yielded regretfully few site-means with presumably primary Devonian remanence (Veselovskiy et al., 2013), and the resulting mean pole was classified as a preliminary by its authors themselves. Instead, a remanence with unexpected direction and of vague origin was reliably determined in the dykes along the northern coast of the Peninsula. So this paper is almost entirely dedicated to the presentation of these unexpected data and their interpretation.

1.1. Geological setting and sampling

The Fennoscandian Shield (Fennoscandia) in north-western Europe is composed of different Archean and Proterozoic major tectonic units that were mostly welded together by 1.7–1.8 Ga (Bogdanova et al., 2008, and references therein). Intense outbursts of magmatism coupled with rifting occurred in some parts of the shield in the Mesoproterozoic (ibid.); since then, all kinds of tectonic activity became subdued over most of Fennoscandia. The shield is bounded by the Caledonian fold-thrust belt in the northwest, whereas the structures of the Varanger Fjord, the Sredny and Rybachy Peninsilas and Kildin Island along the northeastern margin are the visible parts of the Late Neoproterozoic-Early Paleozoic Timan fold belt (Timanides) (Lorenz et al., 2006; Filatova and Khain, 2010).

The Kola Peninsula in northeastern Fennoscandia conforms to the above general scenario for the Precambrian (Bogdanova et al., 2008) but differs from the other parts of the shield by intense mid-Paleozoic magmatism. This Kola alkaline magmatic province comprises large plutons of agpaitic syenites, numerous carbonatite intrusions and multiple swarms of alkaline dykes. Isotopic U–Pb, Rb–Sr, Sm–Nd and 40Ar/39Ar dating consistently points to this magmatism being confined to the 380–360 Ma interval (Kramm et al., 1993; Kramm and Kogarko, 1994; Amelin and Zaitsev, 2002; Rukhlov and Bell, 2010; Wu et al., 2013; Arzamastsev and Wu, 2014) (Fig. 1), i.e., to Middle-Late Devonian time. No manifestations of post-Devonian magmatism in the Kola Peninsula have been found yet. We also know of no post-Devonian tectonics that might have affected the Kola area, apart from recent vertical motions that are connected with deglaciation rebound (Sim et al., 2011). More to the south, Late Paleozoic zones of secondary alteration and mineralization are found in southern Finland (Mertanen et al.,2008; Preeden et al., 2009)) and intense Permian to Early Triassic volcanism is well developed in the Oslo Graben in southern Norway. Still younger magmatism is confined to a suite of Early Jurassic basalt and its tuff (Scania Basalt) in a limited area in southernmost Sweden (Bergelin et al., 2011). Thus most of Fennoscandia was completely devoid of magmatic activity over the last >300 Ma.

We studied dolerite dykes up to few 10 m in thickness of mostly NNE strike in two parts of the northern Kola Peninsula, where these dykes are best exposed (Fig. 1). The Devonian age of the studied eleven dykes is either directly established with the $^{40}Ar/^{39}Ar$ method or inferred from the close similarity of their petrographic and geochemical characteristics with dated intrusions (Fig. 1) (Arzamastsev et al., 2016). According to geological data, post-emplacement tilts of the dykes are very unlikely, although some deformation, fault-conjugated one in particular, cannot be negated with full certainty. In total, twelve Devonian dykes were studied, two of them having been sampled at two sites (D2 + D6, D3 + D7) and the thick, several kilometer long Liinakhamari dyke at four sites (D9 to D12). Both baked and unheated Precambrian metamorphic host rocks were also sampled close to four Devonian dykes (sites D1-H, D4-H, D5-H и D7-H). Thus the collection comprises 17 Devonian and four contact sites, about 360 samples in total.

Samples were drilled in the field and oriented with both magnetic and sun compass. At a site, up to 24 samples were drilled across thick dykes, while 6–12 samples were drilled from thinner (<2 m) ones. In several places, the host metamorphic rocks, both from baked zones and unheated ones, were sampled at the distance of up to 100 m from the dyke contacts.

2. Methods

Drilled cores 25 mm in diameter were cut into 22 mm high standard cylindrical specimens and processed in different paleomagnetic laboratories (Geological Institute and Institute of Physics of the Earth, Russian Academy of Sciences, Moscow State University (all Moscow), and Massachusetts Institute of Technology (MA,USA)). All specimens we heated up to 630 °C in at least 12 increments in both manufactured MMTD-80 and ASC TD-48 thermal demagnetizers or home-made ovens. Also, a few pilot specimens were af demagnetized with the aid of a home-made apparatus or LDA-3A demagnetizer. On the whole, thermal demagnetization proved to be more efficient and was applied to most samples. Measurements of natural remanent magnetization, NRM, were made with Czech spin-magnetometers JR-4, JR-5, and JR-6 and a 2G Enterprises cryogenic magnetometer. Demagnetization results were plotted on orthogonal vector diagrams (Zijderveld, 1967), and linear trajectories were used to determine directions of magnetic components by a least-squares fit comprising three or more measurements (Kirschvink, 1980). The compatibility of the data from different laboratories was checked up on 20+ sister-specimens; the results of component analysis were found to agree within few degrees. Analysis of demagnetization data was made with various paleomagnetic software (Enkin, 1994; Cogné, 2003; Chadima and Hrouda, 2006).

Rock-magnetic studies were carried out in the Moscow State University, Institut de Physique du Globe (Paris), Institute of Physics of the Earth (Moscow), Institute of Precambrian Geology and Geochronology (St. Peterburg) and Borok Geophysical Observatory (Yaroslavl region). Hysteresis properties, FORC-diagrams and temperature dependence of saturation magnetization were made with a vibrating sample magnetometer MicroMag 3900 (Princeton Measurements Corporation, GB); AGICO Kappabridge with CS3 furnace apparatus (Czech Rep.) was used to measure thermal dependence of magnetic susceptibility.

3. Results

The NRM in Devonian dolerite dykes of the northern Kola ranges from 0.002 to >10 A/m, with 90% of values falling in the 0.003–7.1 A/m interval, and is accounted for by three components in widely varying proportion (Fig. 2). A low-temperature component, LTC, of ubiquitously normal polarity is isolated from ~50% of samples below 250°; its overall mean direction (Table 1) closely matches the present-day dipole field in the study area ($I_{PDF} = 79°$). We interpret this remanence as a recent viscous overprint.

No consistent component directions were isolated from dolerites at site D17, baked metamorphic rocks at sites D1-H and D4-H, and all samples of unheated metamorphic rocks. In dolerites from the other sites, the main part of the NRM, up to >90% in some samples, is accounted for by an intermediate-temperature component, ITC, that is isolated in a temperature interval from 200°–250° to 570° and decays to the origin in many samples (Fig. 2a–b). The ITC is predominantly of normal polarity (Table 1), but both normal are reverse directions are met at site D5; the polarity-means are treated as separate sites further on (D5-N and D5-R in Table 1). These eleven directions are rather well grouped (Table 1; Fig. 3a).

A directionally similar component was isolated from baked metamorphic host rocks of two Devonian dykes (sites D5-H and D7 H, Table 1) but not from unheated rocks, while no consistent data were derived from baked contacts of two other Devonian dykes. Thus, we got no baked contact test.

Demagnetization and rock-magnetic characteristics at four sites D9–D12 from the Liinakhamari dyke and site D8 at its probable continuation to the southwest (Fig. 1b) are very similar with these for the other Devonian dykes, but the ITC directions with south-westerly declinations and somewhat shallower inclinations at these sites strongly deviate (Table 1; Fig. 3b). This Liinakhamari dyke is of established Devonian age (Arzamastsev et al., 2009), hence this anomaly cannot be attributed to a disparity in ages. We cannot suggest a credible interpretation for this anomaly and exclude these sites from further analysis.

Many orthogonal plots miss the origin (Fig. 2c) and show rectilinear segments at high temperatures (Fig. 2d, f, h) and/or remagnetization circles on stereonet (Fig. 2e, g, i); thus the presence of the third high-temperature component, HTC, in these rocks is strongly indicated. This component is seen at several sites (Fig. 2d–i) but, usually, can be isolated just from one or two samples per site; thus HTC site-means can be reliably determined for two sites only (Table 1). Veselovskiy et al. (2013) have already regarded these two polarity directions together with paleomagnetic data on alkaline dykes from the southern Kola (violet patches in Fig. 1) and concluded on the Devonian age of the HTC.

Veselovskiy et al. (2013) have isolated the directionally different ITC and a HTC from three Paleoproterozoic (ca. 1950 Ma; Arzamastsev et al., 2009) dykes in the study area (sites PR1-PR4 in Fig. 1b; PR data in

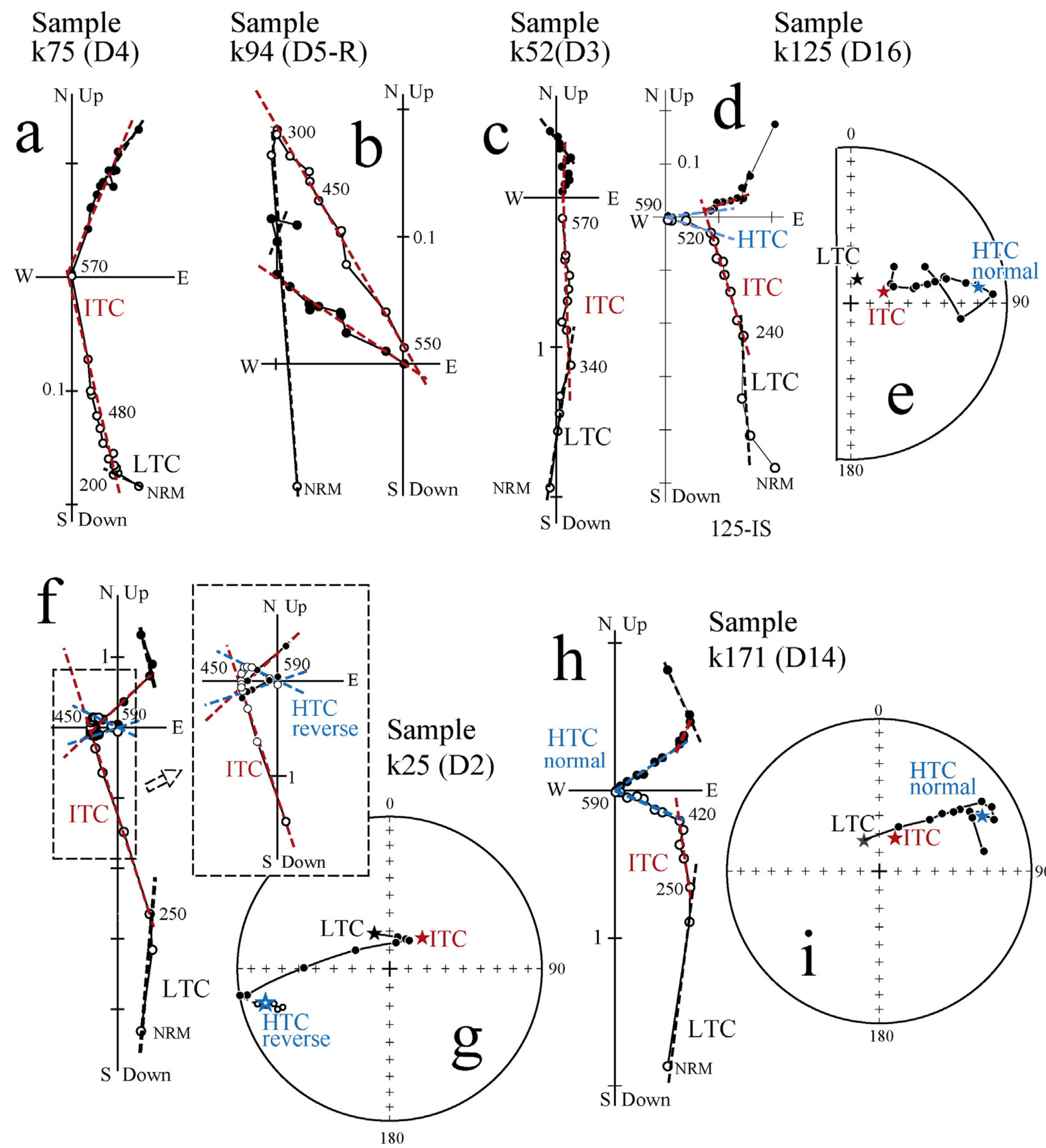

Fig. 2. Thermal demagnetization plots (a–d, f, h) and stereoplots (e, g, i) of representative samples (sites numbered as in Table 1 are in parentheses) from Devonian dykes from the northern Kola Peninsula in geographic coordinates. On orthogonal plots, solid (open) circles represent vector endpoints projected onto the horizontal (vertical) plane. Temperature steps are in degrees Celsius. Thick dashed lines denote different paleomagnetic components. Magnetization intensities are in A/m. On stereoplots, solid (open) symbols and solid (dashed) lines are projected onto the lower (upper) hemisphere. LTC, ITC, and HTC (stars) are low-, intermediate-, and high-temperature components, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1). At the same time, mean ITC directions in the Devonian and Precambrian dykes are rather similar (ITC-1 and ITC-2, respectively, in Table 1). We thus assume that the ITCs in these dykes are of similar age; consequently they were pooled and the overall mean (ITC-ALL in Table 1) was used for further analysis.

3.1. Rock-magnetic studies

Petrographic, rock-magnetic and microprobe data on representative samples coupled with remagnetization results of the entire collection can be summarized as follows (Fig. 4):

1) Low-Ti titanomagnetite and/or pure magnetite are the main remanence carriers in Devonian dykes, whereas there is no evidence of noticeable amount of maghemite and hematite;
2) Non-interacting pseudo-single-domain grains dominate in the collection;
3) Primary magmatic titanomagnetite crystals with traces of high-temperature oxidation and 1–5 μm dendritic titanomagnetite crystals are present in these rocks.

On the whole, the above features are typical for rocks with a trustworthy paleomagnetic record and are often regarded as pointing to the primary origin of remanence.

At the same time, some traces of secondary alteration are present in many Devonian dykes too. These include Fe loss in titanomagnetite grain rims and formation of new magnetic minerals, mostly low-Ti titanomagnetite, around mica crystals. The paragenesis of magnetite and rutile in Devonian dykes leads to a conclusion that secondary alteration resulted in metasomatosis by medium- to low-temperature fluids (Lindsley, 1963). Despite some signs of secondary alteration, no distinct correspondence between magnetic properties and paleomagnetic directions, e.g., the presence of the HTC, or lack thereof, can be established in the collection. Note, for instance, that no traces of the primary

Table 1
Paleomagnetic data on dykes from the northern coast of the Kola Peninsula.[a], [b]

Site	Slat °N	Slon °E	RockAge	n	D°	I°	k	α_{95}°
LTC								
D2	69.1061	36.0632	373.3 ± 5.8	10/12	352.4	81.6	19.9	11.1
D3	69.1189	36.1074	367.6 ± 5.6	9/20	6.7	74.2	7.0	21.0
D7-H	69.1189	36.1074	367.6 ± 5.6	6/11	12.4	74.6	39.4	10.8
D8	69.5023	31.2583	DEV	6/10	31.8	70.2	10.8	21.3
D12	69.6767	31.3597	381 ± 6	12/12	352.9	75.0	22.7	9.3
D14	69.6981	31.3952	DEV	12/12	343.6	77.8	16.0	11.2
D15	69.3396	29.8019	DEV	7/12	297.4	70.1	9.6	20.5
LTC				(7)	354.7	76.8	79.0	6.8
ITC								
D1	69.1234	36.0485	389.0 ± 4.0	19/19	284.3	87.9	28.5	6.4
D2	69.1061	36.0632	373.3 ± 5.8	11/12	85.1	77.5	28.5	8.7
D3	69.1189	36.1074	367.6 ± 5.6	17/20	85.1	71.4	16.0	9.2
D4	69.1939	35.1286	363.2 ± 4.1	20/21	63.5	71.4	13.3	9.3
D5-H	69.2042	35.1057	DEV	6/10	79.9	61.5	31.1	12.2
D5-R	69.2042	35.1057	DEV	6/14	331.2	−69.3	30.4	12.3
D5-N	69.2042	35.1057	DEV	5/14	328.4	82.0	143.9	6.4
D6	69.1061	36.0632	373.3 ± 5.8	12/12	174.3	79.5	63.2	5.5
D7-H	69.1189	36.1074	367.6 ± 5.6	9/11	117.0	65.2	30.3	9.5
D7	69.1189	36.1074	391.7 ± 6.3	12/12	102.1	60.3	138.5	3.7
D8[a]	69.5023	31.2583	DEV	9/10	214.4	64.6	44.5	7.8
D9[a]	69.7039	31.3810	DEV	12/12	232.5	50.6	131.4	3.8
D10[a]	69.6634	31.3422	DEV	5/6	186.6	74.8	18.6	18.2
D11[a]	69.6671	31.3463	DEV	6/9	254.9	67.1	13.3	19.1
D12[a]	69.6767	31.3597	381.0 ± 5.5	10/12	211.7	62.4	42.4	7.5
D14	69.6981	31.3952	DEV	10/12	56.6	78.8	46.0	7.2
D15	69.3396	29.8019	DEV	9/12	81.5	78.5	49.4	7.4
D16	69.6981	31.3949	DEV	12/17	72.2	75.4	40.5	6.9
ITC-1				(17/13)	93.5	77.1	38.0	6.8
ITC								
PR1	69.6627	31.3382	PR	5/10	28.6	81.1	36.7	12.8
PR2	69.5023	31.2641	1941 ± 3	8/13	57.7	83.2	16.6	14.0
PR3	69.4956	31.2018	PR	6/6	31.6	68.9	19.6	15.5
PR4	69.4954	31.2095	PR	10/11	10.7	74.4	33.5	8.5
ITC-2				(4)	28.2	77.3	116.5	8.5
ITC-ALL				(17)	79.6	78.5	37.3	5.9
PLat = 63.9°N, PLong = 87.8°E, A_{95}° = 10.5								
Comp. DEV								
D2	69.1061	36.0632	373.3 ± 5.8	10/12	273.9	−27.5	55.6	7.0
D16	69.6981	31.3949	DEV	15/17	87.1	18.9	70.1	4.6
Devon[b]				(12)	63.7	7.3	10.3	14.2
PLat = 13°N, PLong = 146°E, A_{95}° = 10								
Comp. PR								
PR1	69.6627	31.3382	PR	10/10	345.1	52.4	71.0	5.8
PR2	69.5023	31.2641	PR	12/12	7.3	52.4	204.5	3.0

Comments. Site, site names; "H" denotes the results from baked host rocks, D5-R, D5-N, reversely and normally magnetized samples, respectively, from dyke D5. ITC-all includes the data from dykes, baked metamorphic rocks and three Proterozoic dykes. Slat, Slon, site latitude and longitude. Rock Age is given in numerical form if Ar^{39}/Ar^{40} data for the studied body is available; otherwise, the age is labeled as DEV (Devonian) or PR (Proterozoic). The ages are from (Kramm et al., 1993; Kramm and Kogarko, 1994; Veselovskiy et al., 2013; Arzamastsev and Wu, 2014; Arzamastsev et al., 2016). D, declination. I, inclination, k, concentration parameter. α_{95}°, radius of confidence circle (Fisher, 1953). PLat, PLong, latitude and longitude, respectively, of paleomagnetic pole. A95°, radius of confidence circle around the paleomagnetic pole. Components are labeled as in the text.

[a] Anomalous directions from a large long dyke and its satellites that are excluded from calculation of the component ITC overall mean.

[b] Mean direction of the presumably primary dual-polarity component in Devonian minor intrusions from the entire Kola Peninsula (Veselovskiy et al., 2013).

Devonian component is found in the sample with well-developed lamellae structures that are often thought to indicate high temperature deuteric oxidation of titanomagnetite grains (Fig. 4b).

The ITC is found to be present in most Devonian dykes. Some of these dykes were dated with the $^{40}Ar/^{39}Ar$ method on plagioclase (Veselovskiy et al., 2013), but the age spectra do not indicate any loss of radiogenic argon after the dyke emplacement. As the isotope system in plagioclase becomes closed below 200°, the non-disturbed spectra also point to the lack of subsequent heating of intrusions above this temperature. This conclusion may probably be extended to all Devonian dykes in the northern Kola area.

3.2. Interpretation and discussion

As shown above, the NRM of Devonian dykes is mainly accounted for by the steep easterly component that is found in baked metamorphic rocks and some Proterozoic dykes too (Table 1). This ITC of predominantly normal polarity shows the rectilinear decay to the origin in many samples and is usually unblocked by 570° (Fig. 2). An important fact is that the ITC overall mean is significantly away from the great circle connecting the LTC and Devonian primary HTC mean directions (Fig. 3b), the latter having been taken from Veselovskiy et al. (2013); also, no smearing of ITC site means along this great circle is observed. Hence it is most likely that the ITC is not a result of an incomplete separation of the LTC and HTC because of strong overlapping of their unblocking spectra. Perhaps even more important is the ITC pole falling very close to the early Mesozoic segment (~190 Ma) of the APWP of Baltica (Fig. 5a–b).

The agreement of the observed ITC pole with the ~190 Ma reference one may be taken as an indication to an early Jurassic age of the intrusions studied. Note, however, that the ITC is a secondary component, and a primary HTC is isolated from these dykes too. The HTC

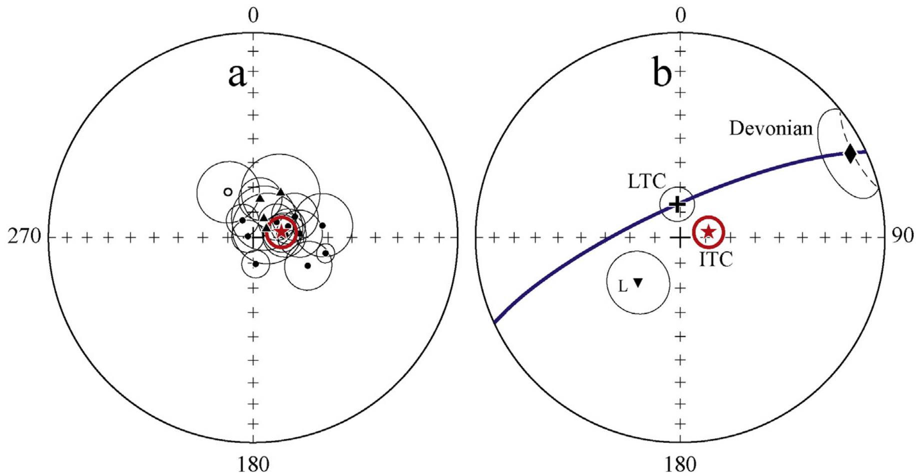

Fig. 3. Stereoplots of paleomagnetic directions. (a) ITC site-mean directions from Devonian dykes (without anomalous sites; see text) and heated host rocks (circles) and Proterozoic dykes (triangles) with associated confidence circles (black lines). Red star is the overall mean ITC direction with confidence circle (thick red line). Also shown is the anomalous ITC direction (inverted triangle) in the Liinakhamari Dyke with its confidence circle (see text for more detail). All data are in geographic coordinates. (b) Overall mean directions of the LTC (cross), ITC (star), and primary component in Devonian rocks (diamond) with associated confidence circles; the latter result is based on data from different parts of the Kola Peninsula (Veselovskiy et al., 2013). Thick blue line is the great circle connecting the LTC and Devonian data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

paleomagnetic pole, albeit regarded as a preliminary one by its authors (Veselovskiy et al., 2013), falls close to the 370–380 Ma reference poles for Baltica (Fig. 5b; Table 1). All available isotopic data on basic and alkaline dykes and large intrusions in the Kola Peninsula (Kramm et al., 1993; Kramm and Kogarko, 1994; Arzamastsev and Wu, 2014; Arzamastsev et al., 2016) indicate the Middle-Late Devonian age for these intrusions (Fig. 1, Table 1). As noted above, Early Jurassic magmatism of very limited extent is confined to southernmost Sweden (Bergelin et al., 2011) that is >1500 km away. The areas of Mesozoic volcanism in Svalbard and Franz Joseph Land is >1000 km away from our study area too. Thus one can certainly refute the hypothesis of any Early Jurassic magmatism in the Kola Peninsula.

The above facts give the solid ground for a conclusion that the ITC is an overprint of Early Mesozoic age. Some rocks in Fennoscandia and adjacent areas have already been suspected of being remagnetized. For instance, Walderhaug et al. (2007) discussed a possibility that the early Neoproterozoic magmatic complexes in southern Norway and Sweden were remagnetized by the end-Neoproterozoic, Popov et al. (2002) described strong remagnetization of Ordovician age in sediments from the White Sea region, while Mertanen et al. (2008) and Preeden et al. (2009) advocated Late Paleozoic overprinting in southern Finland. The Ediacaran Fen Complex in Southern Norway was assumed by Meert et al. (1998) to be completely remagnetized during Permo-Triassic magmatism in the Oslo Graben nearby. The main argument, sometimes the only one, for such conclusions is the "Resemblance to paleopoles of younger age" (Van der Voo, 1990).

Finding an Early Mesozoic remagnetization in an area, where it was not suspected before, made us wonder if similar remanences could be found in other parts of Fennoscandia too. Before this search, however, one should decide how to compare paleomagnetic data as the just quoted "resemblance" rule is too vague. The standard approach is to compare a problematic pole and a reference one. Note, however, that the former is based on averaging VGPs for sites, whereas the latter is the overall mean of several mean poles of similar age. Thus, they are calculated at different statistical levels, and their direct comparison may be misleading.

All ITC directions in the Kola dykes are very steep. It is well known that mapping paleomagnetic steep directions ($I > 70°$) into poles leads to a very scattered VGP distribution (compare Fig. 3a with $k = 37$ and 5a with $K \sim 10$, where k and K are concentration parameters for directions and poles, respectively). Consequently, the parameters of VGP distributions are not robust, in particular for moderate datasets, as minor angular differences in directions are transformed into much larger differences upon mapping. So we recalculated all poles to directions for a common point at 69°N, and 35°E and performed subsequent analysis in directional space.

There is a statistically rigorous procedure for comparing mean directions (poles) that is based on F-statistics (Mardia, 1972; McFadden and Jones, 1981). For this particular case, i.e., for comparing a set of reference directions (poles) with a test datum, the following approach should be used: 1) The value of F-statistics is computed for the reference data only, and this value is to be statistically insignificant; 2) Then, the test datum is added, and the F-statistics is re-computed; 3) If the latter value is insignificant, the test datum does not differ significantly from the reference dataset, and differs otherwise. The prerequisites for this procedure are that the data should be Fisher-distributed (Fisher, 1953), and the value of F-statistics for the reference data alone should be insignificant. While the first prerequisite is often met, at least approximately, it is not so for the second one. Really, the F-statistics for the reference data is larger than the critical value in most groups of coeval reference poles, and, hence the statistically rigorous procedure cannot be used.

Below, we used a less rigorous semi-quantitative method. A commonly used parameter in paleomagnetism is the radius of confidence circle α_p (A_p), where the mean direction (pole) should fall with probability *p* provided that the data have a Fisher distribution (Fisher, 1953). This parameter depends upon both concentration parameter k and n, which is the number of unit vectors used for calculation of the mean. If $n = 1$, one gets the radius of the mean-centered circle that, on average, includes *p*% of unit data (directions or poles); to avoid confusion, the circle for $n = 1$ and $p = 0.95$ (95%) is labeled β_{95} here and plotted together with the data tested to better visualize the 2D relationship between them (Fig. 6).

As the ITC pole and 190 Ma reference one are close to each other, we were initially going to calculate the β_{95} value for 190 ± 10 Ma reference poles for Baltica only. Unfortunately, just four such mean poles are given in the most recent pole list (Torsvik et al., 2012) that is too little for trustworthy estimates. The Early Mesozoic APWP segments for Baltica and Laurentia, however, are in good agreement, and the 190 ± 10 Ma interval is much better characterized for Laurentia. So, twenty 190 ± 10 Ma poles for these two cratons are pooled, following Torsvik et al. (2012), and recalculated to directions for the common point; finally, the radius of 9.3° of the β_{95} circle is calculated (orange-filled circle in Fig. 6a). We have taken Precambrian paleomagnetic poles from the

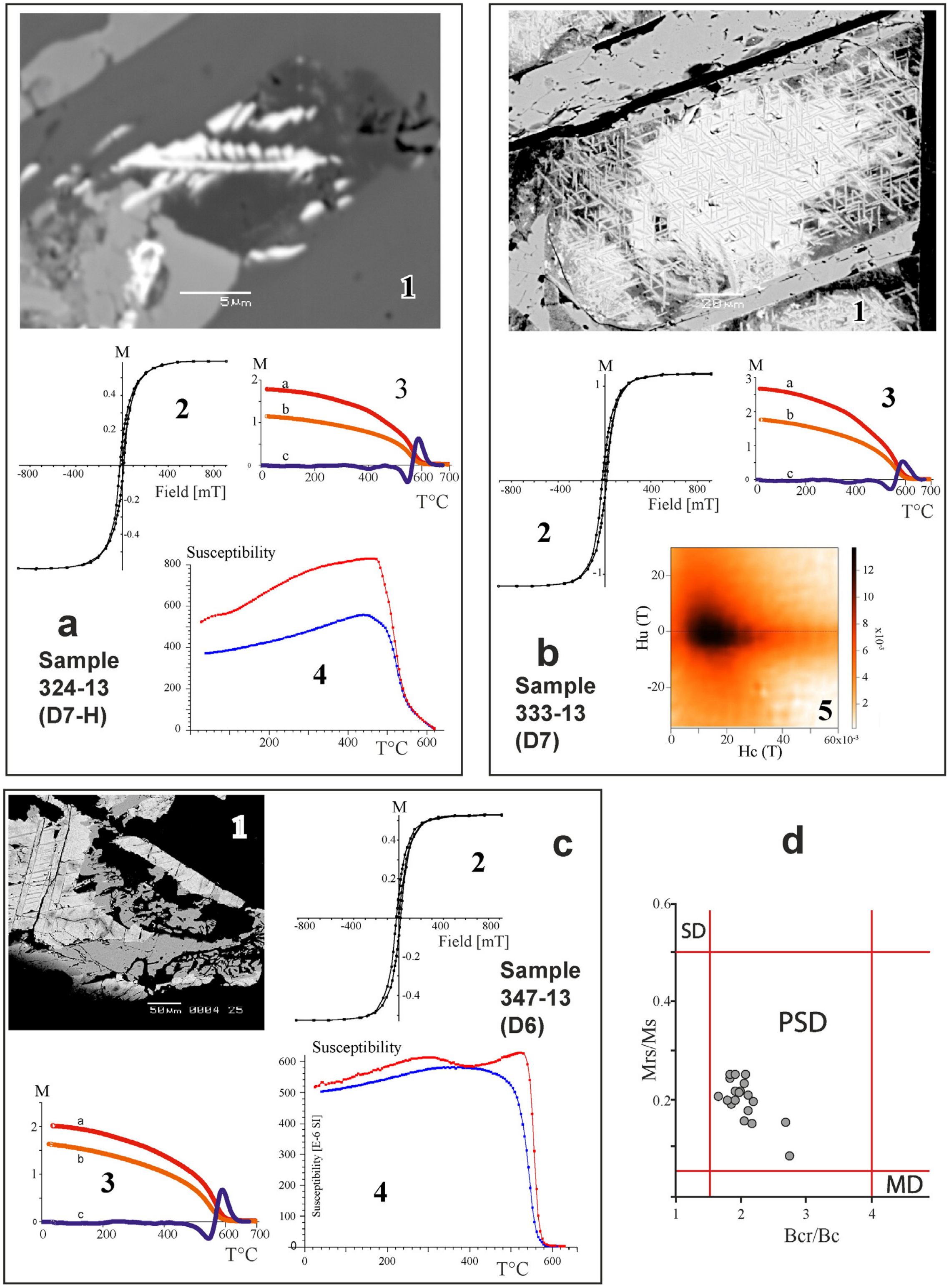

Fig. 4. Rock-magnetic and mineralogical properties of Devonian dykes: (a) sample with the ITC only; (b) sample with the LTC and ITC; (c) sample with the LTC, ITC and primary HTC; in (a–c): 1 — microphotographs, 2 — magnetic hysteresis curves (M, specific magnetization in Am^2/kg), 3 — plots of remanent saturation magnetization versus temperature: a — first heating curve, b — second heating curve, c — first-order derivative curve (M, magnetization in E-05 A/m); 4 — plots of magnetic susceptibility (in E-6 SI units) versus temperature; 5 — FORC diagram. Red (blue) lines in 3 and 4 denote heating (cooling) curves. (d) — Plot of hysteresis parameters (Day et al., 1977) with domain states indicated as SD = single domain, PSD = pseudo-single domain, MD = multi domain. Ms = induced saturation magnetization, Mrs = remanent saturation magnetization, Bc = coercivity, and Brc = coercivity of remanence. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

new PALEOMAGIA database (Veikkolainen et al., 2014) with some additions from missed or the most recent papers and recalculated them to directions. Then, the β_{95} circle is used to select Precambrian paleomagnetic directions, which fall either inside or close to this “alarm zone”. The confidence circles of the Precambrian data are taken into account (Fig. 6c) with the aid of an empirical rule that two mean

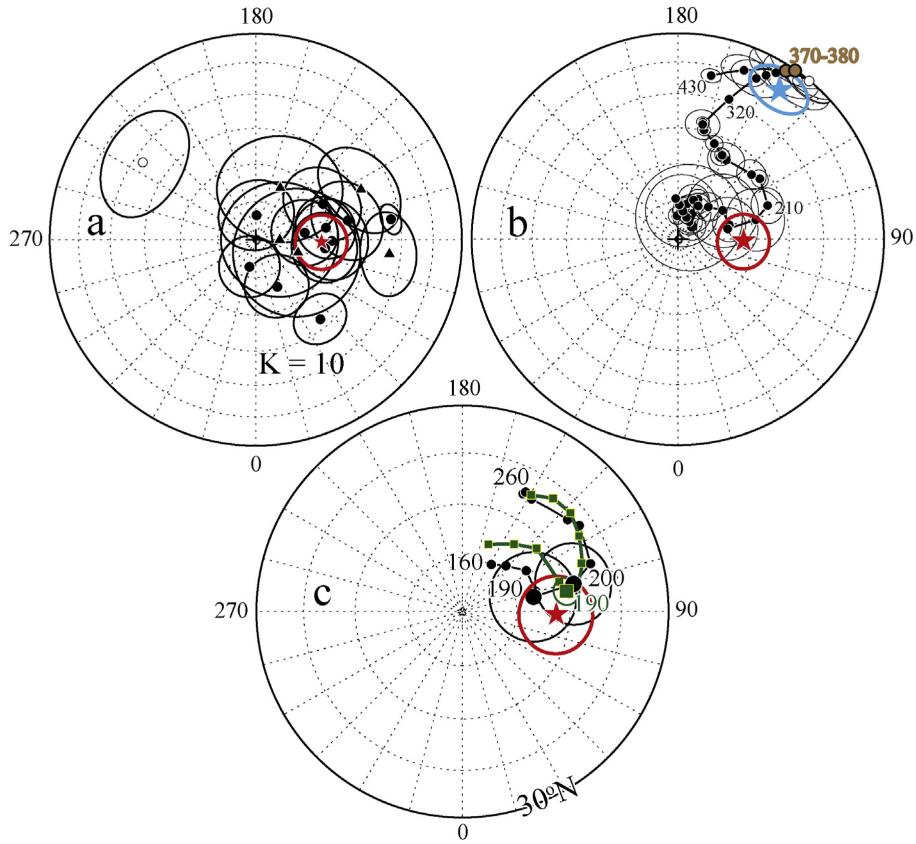

Fig. 5. Stereoplots of paleomagnetic poles. (a) VGPs for the data presented in Fig. 3a. Notation as in Fig. 3a. (b) Mean poles for the ITC data from the northern Kola Peninsula (red star and circle) and primary Devonian component for the entire peninsula (blue star and circle) (Veselovskiy et al., 2013). Black circles and lines denote the APWPs for Baltica from 0 to 430 Ma (Torsvik et al., 2012). (c) 150 to 250 Ma segments of the APWPs for Baltica (black symbols and lines) and Laurussia (green symbols and lines) after Torsvik et al. (2012) in Baltic coordinates; for clarity, the confidence circles are shown only for the reference poles (large symbols) that are closest to the ITC pole (red star and circle). Note that Fig. 5c is zoomed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

directions differ insignificantly if the smallest confidence circle is overlapped by more than half of its radius. Using this rule as a filter, the list of paleomagnetic results that fall into, or close to, the alarm circle is compiled (Table 2).

The ITC mean falls in the orange circle and is very close to the 190 Ma reference direction (purple star and cross, respectively, in Fig. 6a), in accord with the above conclusion on 190 ± 10 Ma remagnetization age of the dykes in the northern Kola Peninsula. This is the only choice, as all other post-Devonian references directions differ significantly from the ITC mean (Fig. 5b–c). Other published data from northernmost Fennoscandia fall into the orange circle too (Table 2); these include the data on sediments of the Sredny Peninsula and Kildin Island (Shipunov, Chumakov, 1991; Shipunov, 1993), some dykes in the same area (Shipunov, 1993) and some sediments on the Varanger Peninsula (Bylund, 1994; Walderhaug et al., 2012). It is worth noting that an ITC-like remanence is not omnipresent but is found in some rocks only: while gray rocks are remagnetized on the Sredny Peninsula and Kildin Island, the redbeds from the same sections show no traces of this overprint, and their NRM is dominated by a remanence with northerly declination and very shallow inclination (Shipunov and Chumakov, 1991; Shipunov, 1993). ITC-like component is found in two formations on the Varanger Peninsula too, while other parts of the section have magnetizations with quite different directions, according to Walderhaug et al. (2012). The ITC has been isolated from most Devonian dykes in the Northern Kola but is rare in the coeval dykes and intrusions in the central and southern parts of the Peninsula (Veselovskiy et al., 2013). Finally, the ITC is found in quite few Proterozoic dykes (Table 1) but not in other Precambrian rocks.

Still more interesting is a fact that paleomagnetic directions from objects with the ages ranging from 500 Ma to ~1900 Ma from other parts of Fennoscandia (Fig. 6b, Table 2) fall into the same “alarm zones” too. Of course, this does not mean that each direction in the orange circle is definitely an overprint of the same age, as the agreement may fortuitous. Really, the probability of a randomly picked direction falling into a circle with a radius of 10° is <2%, which is not large but not negligible too. So if many paleomagnetic directions from the objects of different ages fall into the same alarm zone, some results may be remagnetized at a time that is less than the youngest age of the studied object, but the others may be there by chance.

The diagnosis “Early Jurassic remagnetization” appears to be irrevocable for the ITC in the Devonian dykes and coeval datum #2 only. Let's assume that all other data in Table 2 have different ages. The close agreement of paleomagnetic poles from Table 2 implies that Baltica's location (paleolatitude and orientation) in the Early Jurassic was multiply repeated at older times; each case of agreement is to be regarded as a coincidence (numbered below as C1, C2, etc). C1 occurred in the Cambrian (##3–4). The remanences from northernmost Fennoscandia (Fig. 7), some of the demonstrably postfolding origin (e.g., Shipunov and Chumakov, 1991; Bylund, 1994), could have been acquired at ca. 560 Ma as folding in the Varanger area is assumed to have occurred at that time on the basis of Rb/Sr illite dating (Ghorokov et al. 2001; Herrevold et al., 2009). On the other hand, the age of folding does not necessarily mean the age of remagnetization, which might have taken place much later. Other coincidences occur at about 650–700 Ma (C3), 1120–1150 Ma (C4), 1500–1565 Ma (C5), ~1880–1950 Ma (C6) and even as old as ~2300 Ma (C7).

At face value, this pattern implies that Baltica has occupied very similar locations seven times during the last 2 Gyr. Between C2 and C3, Baltica just changed its orientation but remained at high latitudes, according to 616 Ma Egersund pole (Walderhaug et al., 2007). This back

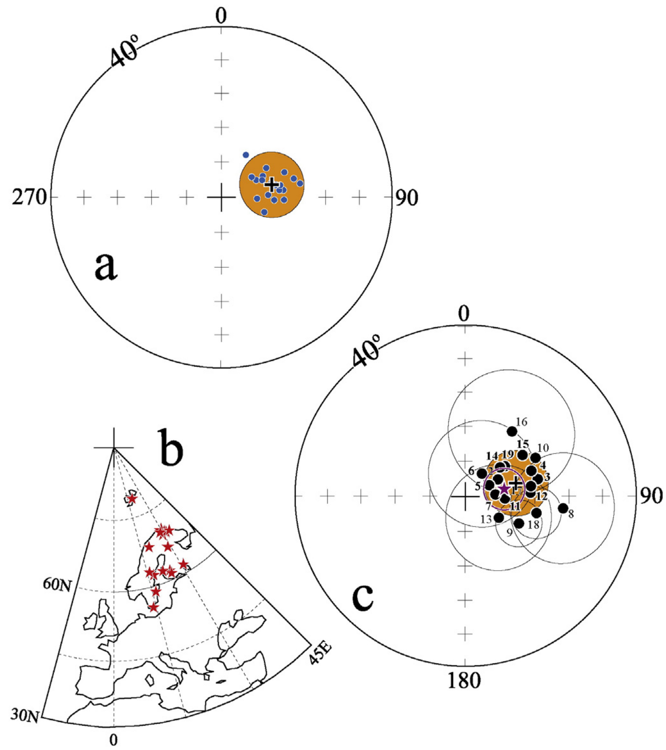

Fig. 6. (a) Stereoplot of the 190 ± 10 Ma reference directions (blue circles) recalculated to the common point at 69°N, 35°E from twenty coeval poles for Laurussia (Torsvik et al., 2012) and their overall mean (cross). Orange-filled circle denotes the confidence circle β_{95} (see text for explanation). (b) The outlines of Europe with sampling localities for Cambrian–Precambrian data (stars) that are analyzed in the paper. (c) Paleomagnetic directions (filled circles) in different Cambrian and Precambrian objects from Fennoscandia (see Table 2 for labels and detail). For clarity, confidence circles are shown only for the data outside of the orange circle. Violet star with associated circle denotes the ITC overall mean for the northern Kola Peninsula (this paper) shown for comparison. Other notation as in Fig. 6a. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and forth pattern has counterparts, in the Triassic to Jurassic or Silurian to Carboniferous, on the Phanerozoic APWP for Baltica (Torsvik et al., 2012), without noticeable changes in the velocity of pole motion. In contrast, between C1 and C2, there are several 545 to 560 Ma results, which point to the near-equatorial location of Baltica at end-Ediacaran time (Popov et al., 2002; 2005; Iglesia Llanos et al., 2005; Levashova et al., 2013; Fedorova et al., 2014), thus requiring extremely fast motions of the craton. Other coincidences (C4–C6) are bounded by at least at one side by quite different poles and thus require huge loops on the Proterozoic APWP (Salminen et al., 2009) and/or ultra-fast motion for Baltica too. These kinematic implications of most coincidences do not agree with plate motion characteristics in the Phanerozoic.

Salminen et al. (2014) identified two components in the Satakunta dykes and argued that one of them is of secondary origin (#17), as it was usually found in more weathered and/or more coarse-grained rocks. This component of inferred Early Mesozoic age mainly resides in maghemite. It is not so with the studied Devonian dykes. For instance, sample 324-13 (Fig. 4a) shows no traces of alteration, has almost pure magnetite as a carrier, and reveals the secondary ITC only. Just minor traces of maghemite and hematite are found in other Devonian dykes. In general, there is no strong evidence on the secondary origin for most Precambrian results in Table 2. Vise versa, some data sets have dual polarity, and the others are claimed to pass the baked contact test (e.g., # 14) that was regarded as evidence for the primary remanence. On the other hand, dual polarity overprints are neither too common nor very rare (Johnson and Van der Voo, 1986; 1989), whereas the baked contact test is rarely possible to carry out in full accord to canonical textbooks to make its outcome irrefutable.

Now let us assume that most data in the orange circle (Fig. 6c; Table 2) have resulted from Early Jurassic remagnetization and sum up its characteristics:

1) Regional extent and very non-uniformly developed manifestations (Fig. 7);
2) Very often, albeit not always, the main steep component shows the rectilinear decay to the origin on orthogonal plots by 550°–600°;

Table 2
Paleomagnetic data from Fennoscandia, where Early Jurassic remagnetization is suspected.

#	Rock unit	T	Site		Age		n	P	Pole		A_{95} °	D°	I°	α_{95}°	C	REF	RES#
			Lat °N	Lon °E	Low	High			Φ °N	Λ °E							
1	North Kola Devonian dikes	i	69	35	360	390	17	M	63.9	87.8	10.5	79.5	78.5	5.9	O	1	
2	Sredny-Komagnes dykes	i	70	31.3	377.6 ± 1.8	62	N	68.7	93.9	11.3	63.0	79.4	6.2	O	2, 3	100073	
3	Andrarum sandstone	s	55.7	14.0	~500	10	N	52	111	8.4	76.5	68.7	5.9	O	4		
4	Tornetrask Fm.	s	68.2	19.5	~535	43	M	56	116	13.5	68.7	69.8	9.2	O	4		
5	Sredny Peninsula diabase dyke	i	69.7	32	546	580	28	N	70.1	78.6	9.5	65.5	82.4	5.0	O	5	100155
6	Alno carbonatite complex	i	62.5	17.5	584 ± 13	27	N	77.5	84.3	28.8	37.0	81.9	15.3	O	O	100156	
7	Gotia and Polarisbreen series	s	79	20	~650	28	N	64	77	20.1	86.5	81.3	10.7	O	5	7391	
8	Tanafjord & Vestertana groups	s	70.5	30	653 ± 23	36	N	37	101	18.3	96.8	61.6	15.4	W	7	100153	
9	Janisjarvi impact melt	i	62.1	30.9	698 ± 22	22	N	45.0	76.9	10.5	116.7	72.7	6.6	W	8	100,154	
10	Mean Janisjarvi impactites	m	62	31	698 ± 22	21	M	55.3	126.6	17.6	61.5	67.0	12.8	O	8	497251	
11	Sredny Pns. gray sediments[a]	s	69.7	32.1	700	900	186	N	59.1	81.8	9.2	93.2	78.6	5.1	O	5	
12	Kildin Is. gray sediments[a]	s	69.6	34.1	700	900	61	N	51.5	99.5	11.4	86.9	71.2	7.5	O	5	
13	Vadso and Barents Sea groups	s	70.5	30	810 ± 90	35	N	52.5	66.4	27.1	122.3	78.6	15.2	W	7	7537	
14	Salla dyke & baked rocks	i	66.8	28.8	1122 ± 7	191	M	70.6	111.6	8.2	50.5	77.0	4.7	O	9	1000152	
15	Keurusselka impact structure	i	62.2	24.7	1151 ± 10	21	N	61.0	129.1	11.9	54.4	69.7	8.1	O	10, 11	497167	
16	Ragunda dykes -C	i	63.3	16.1	1260 ± 10	24	M	64.1	154.5	24.7	36.0	67.0	18.0	W	12, 13	5789	
17	Satakunta dykes, S component	i	62	21.5	1476	1565	(15)	N	53.3	103.9	13.2	81.2	71.1	7.6	O	14	
18	Almunge complex	i	59	16.4	1581	1700	32	N	43.6	90.1	10.4	103.2	68.9	7.2	W	15	100224
19	Akhmalahti & Kuetsyarvi Fm	i	69.5	29.5	2125	2330	100	N	68.4	114.8	23	53.1	75.7	13.6	O	16	7649

Comment. #, the datum number used for referring in this paper. Rock unit, the names of studied complexes taken from either PALEOMAGIA Database (Veikkolainen et al., 2014) or original publications. T, rock type: i, magmatic; s, sedimentary; m, metamorphic. Age, rock age taken from either PALEOMAGIA Database or original publications; it is given either as a number with confidence limits, or as its lower and upper limits, or as an approximate value for some sediments. n, the number of samples (sites) used. P, polarity (sign of inclination): N, normal; R, reverse; M, mixed. Φ, pole latitude. Λ, pole longitude. A_{95}, radius of confidence circle for poles. C, the color of the field in Fig. 6a, a result falls in: O, red; W, white. REF, references: 1, this paper; 2, Torsvik et al., 1995; 3, Guise and Roberts, 2002; 4, Torsvik and Rehnström, 2001; 5, Shipunov, Chumakov, 1991; 6, Meert et al., 2007; 7, Bylund, 1994; 8, Salminen et al., 2006; 9, Salminen et al., 2009; 10, Raiskila et al., 2011; 11, Schmieder et al., 2016; 12, Piper, 1979; 13, Suominen, 1991; 14, Salminen et al., 2014; 15, Piper, 1992; 16, Torsvik and Meert, 1995. RES#, reference number in PALEOMAGIA Database, if available. Other notation as in Table 1.

[a] According to Raaben (2007), the sediments on the Sredny Peninsula and Kildin Island. are roughly coeval and accumulated in the 700–900 Ma interval.

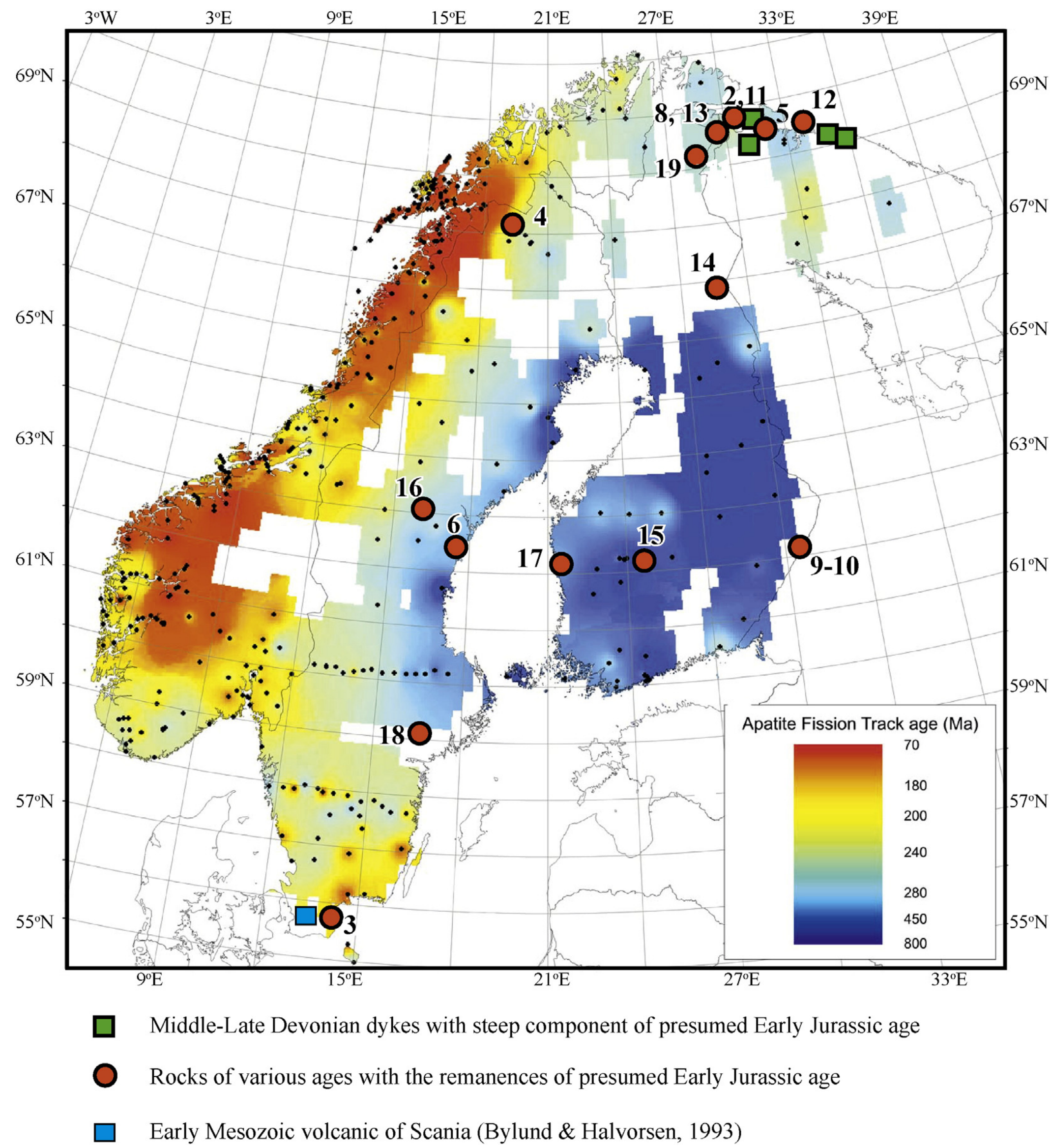

Fig. 7. Apatite fission track ages in Fennoscandia (modified after Hendriks et al. (2007)) and paleomagnetic sampling localities. Green squares — Middle-Late Devonian dykes with steep component of presumed Early Mesozoic age; red circles — objects of different ages with the remanences that are similar to the 190 ± 10 Ma reference direction for Laurussia (see text for detail). Blue square is the locality where the Scania Lower Jurassic Basalt was paleomagnetically studied (Bylund and Halvorsen, 1993). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3) This overprint is of predominantly normal, sometimes of mixed, polarity (Table 2);
4) No signs of heating above 200° and/or strong mineral alteration of Mesozoic age are reported.

In Fig. 7, the objects from Table 2 are shown together with apatite fission-track data (Hendriks et al., 2007). Remagnetized objects appear to be situated in the areas with fission-track ages of ~240 Ma or even more. As annealing in apatite takes place below 110°, these objects had already been above the corresponding isotherm at 190 Myr (Veselovskiy et al., 2015). If a remagnetization has the thermoviscous origin, it should occur at temperatures above 300° to completely reset the original remanence (Pullaiah et al., 1975) that is well before Early Jurassic time. Besides, a thermoviscous remagnetization had to affect most rocks, in sharp contrast to the observed very patchy pattern. This remagnetization could not be related to near-surface weathering too as a sedimentary cover, several hundred meters in thickness at least, had existed over most of Fennoscandia in the Late Paleozoic–Early Mesozoic interval (Arzamastsev et al., 2000; Hendriks and Andriessen, 2002; Soderlund et al., 2005). Thus remagnetization by migration of low-temperature fluids and brines appears to be the only explanation of the observed phenomena. This assumption, however, is too vague, and the above presented data and arguments are just compatible with it but do not further substantiate it.

The regional, albeit very selective, overprint distribution points to a regional character of a cause that has led to remagnetization too. Note that neither the formation of the North Atlantic magmatic province in the Early Cenozoic nor uplift and exhumation of the Norwegian Caledonides left any traces in a paleomagnetic record, as Cretaceous to Cenozoic overprints are rare, or absent at all, in Fennoscandia.

In contrast, the Central Atlantic Magmatic Province, CAMP, with the age of ~200 Myr (Ruiz-Martínez et al., 2012, and references therein) is nearly synchronous with the assumed ITC acquisition at ca. 190 ± 10 Ma. The Scania Basalts in Southern Sweden and volcanics in the Baltic and North Seas are of similar age too (Bergelin et al., 2011). To the north of Fennoscandia, coeval volcanics are reported from Svalbard and Franz Joseph Land as well as from the central and northern Barents Sea (Shipilov, Karyakin, 2011; Shipilov, 2015). The CAMP center, however, is situated near the equator with its northern margin at ca. 30°N, while Fennoscandia and the Barents Sea are between 45° до 60–65°N, i.e., 2000–4000 km from this boundary (Ruiz-Martínez et al., 2012). Some Large Igneous Provinces, LIPs, do have remote magmatic satellites; for instance, the satellites of the Permo-Triassic Siberian LIP are as far as the Polar Urals, NE Kazakhstan and the Kuznetsk Basin in SW Siberia (e.g., Reichow et al., 2009, and references therein). Still, these satellites are at least two times closer to the main LIP than in our case, and the relationship between the CAMP and volcanic manifestations around Fennoscandia remains unclear.

4. Conclusion

A paleomagnetic study of Middle-Late Devonian dykes in the northwestern Kola Peninsula showed that their remanence is mainly accounted by a remanence with steep inclination and easterly declination of predominantly normal polarity; similar components are isolated from baked metamorphic rocks and some Paleoproterozoic dykes too. The pole for this steep remanence is close to the Early Jurassic (190 ± 10 Ma) segment of the APWPs for the North Atlantic-bordering continents and strongly indicates a similar age for the remagnetization event.

The main impact of the new results is not on mid-Paleozoic or Early Mesozoic paleomagnetic data but on much older ones. Analysis of paleomagnetic data on the objects with the ages ranging from 500 Ma to ~2 Ga from different parts of Fennoscandia shows that directionally similar remanences are common in this region. Although coincidences are possible, there are about twenty directionally similar results, which is nearly impossible to occur by chance. So we conclude that remagnetization of regional extent but with selectively spread manifestations had taken place in the Early Jurassic, probably as a result of migration of low-temperature fluids. The detail of this process and its causes, however, remain vague. This is not surprising as an adequate understanding of remagnetization phenomena may take decades, and there are still too many confusing features (Van der Voo and Torsvik, 2012). Among the paleomagnetic data suspected of remagnetization, there are several results, for instance, the Cambrian ones from Sweden that will make the researchers revise the APWP of Baltica and motions of this craton over long time intervals.

The authors themselves were both surprised and confused by the phenomenon of Early Jurassic selective remagnetization, as well as its extent and profoundness. Still "worse" finding is that this remagnetization may easily pass unidentified as there are neither evident causes for it nor clear traces in rock-magnetic properties. Hence we do not expect that this interpretation will be favored by everybody, by the authors of the "suspected" results in particular. Nevertheless, we cannot see other ways to account for the observed pattern.

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