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Middle Cambrian drill-core orientation with AMS in the Degliai oil structure (Lithuania) and implications of the palaeomagnetic data for palaeogeography

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The direction of anisotropy of magnetic susceptibility K_{max} is generally perpendicular to the direction of major shortening (D = 102.2°, I = 6.8°, L = 1.126, F = 1.336, P = 1.504, n = 7 specimens). The maximum axes of AMS indicated the orientation of drill-core samples. After the palaeomagnetic interpretation we got two mean directions: D = 222°, I = 50°, three specimens and D = 198.5°, I = 9°, two specimens. A comparison (four specimens) of the obtained palaeomagnetic poles with the stable European APWP indicate the Late Silurian/Early Devonian and Late Carboniferous (Late Westphalian-Stephanian) age of the remagnetization event. Our data show also that the Gargþdai fault had the maximum activity in the late Silurian/Early Devonian and Late Carboniferous time.

Key words: Lithuania, Middle Cambrian, paleomagnetism, anisotropy of magnetic susceptibility (AMS)

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INTRODUCTION

There are many oil structures in Lithuania. Magnetic and palaeomagnetic investigations of oil rocks reveal important information on oil generation.

Investigations of anisotropy of magnetic susceptibility (AMS) are widely used to solve selected geological problems. The first AMS results in Lithuania were obtained from Cambrian sandstones and shales in the Telšiai fault zone (Šliaupa et al., 2002). Results of the investigations showed a palaeostress regime in the vicinity of the Telšiai fault.

In the Baltic states, the first modern paleomagnetic studies of the Cambrian rocks were made in the Kunda quary (Estonia; Nawrocki et al. 2004). The authors obtained a paleomagnetic pole of secondary origin, which is concordant with the Late Cambrian / Early Ordovician segment of the apparent polar wander path (APWP) for Baltica.

GEOLOGY AND SAMPLING

Cambrian rocks occur almost in the whole area of the East Baltic region. The most complete Camb-

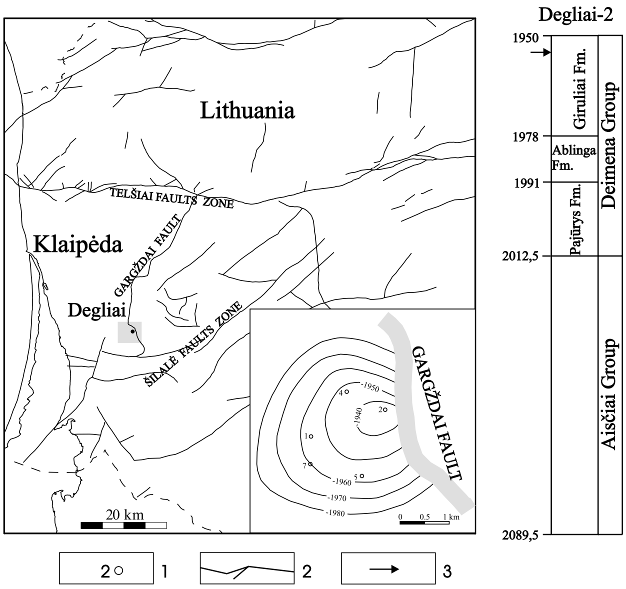
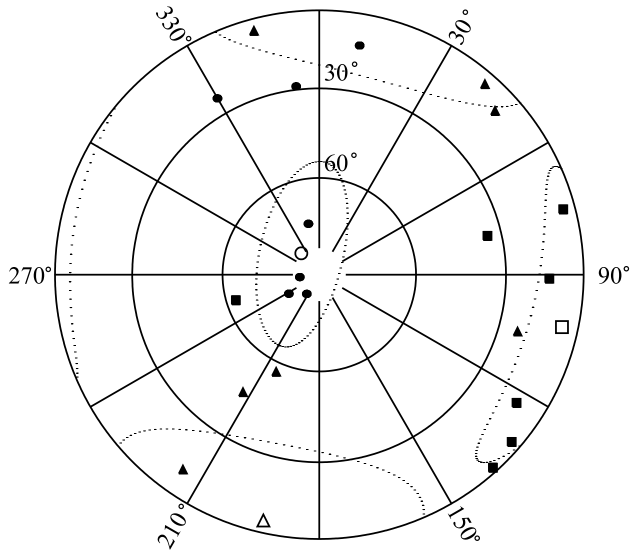


Fig. 1. Location map of boreholes with major tectonic faults (after K. Sakalauskas, 1996 and S. Šliaupa, 2003): *1* – boreholes, *2* – major tectonic faults, *3* – sampling site
1 pav. Situacinë schema su pagrindiniais lûþiais (pagal Sakalauskà, 1996 ir Ðliaupà, 2003): *1* – græþiniai, *2* – pagrindiniai tektoniniai lûþiai ir *3* – pavyzdþio ëmimo vieta



Axis		D (°)	I (°)	L	F	P
□	k_{max}	102.2	6.8	1.126	1.336	1.504
△	k_{int}	192.8	5.2	N = 7		
○	k_{min}	320.2	81.4			

Fig. 2. Stereographic projections of the magnetic anisotropy: ■ – K_{max} anisotropy axis, ▲ – K_{int} anisotropy axis, ● – K_{min} anisotropy axis, D – declination, I – inclination, N – number of samples, L – magnetic lineation, F – magnetic foliation, and P – total degree of anisotropy
2 pav. Magnetinës anizotropijos steriografinë projekcija: ■ – maksimali anizotropijos ašis, ▲ – vidutinë anizotropijos aðis, ● – minimali anizotropijos aðis, D – deklinacija, I – inklinacija, N – bandiniø skaièius, L – magnetinis linijiðkumas, F – magnetinis skalûnuotumas ir P – anizotropijos laipsnis

rian is known from East Lithuania, Latvia and Estonia. The total thickness of the beds exceeds 250 m. The Cambrian comprises there sediments of a shallow shelf sea. These rocks overlie the crystalline basement in the western part and cover the Vendian beds in the eastern part.

The stratigraphy of the Cambrian beds is based on rock lithology, marker beds, rock deposition conditions, fauna and flora, borehole and loging data. The Cambrian geological section is subdivided into regional stages, groups, formation members and strata. All three groups, i.e. Lower, Middle and Upper Cambrian, were distinguished in the area of the Baltic region

The Lower Cambrian consists of five and the Middle Cambrian of three regional stages, respecti-

Table 1. **Results of magnetic anisotropy**
1 lentelë. **Magnetinës anizotropijos duomenys**

Borehole	Depth	index	Parameters of anisotropy			Directions of anisotropy						Kappa (sum int) $0.05*10^{-6}$ SI
			Degree	Foliation	Lineation	Max axis		Int axis		Min axis		
			L	F	P	D	I	D	I	D	I	
Degliai-2	1954.5	De-1	1.172	1.132	1.327	91	14	204	57	353	29	58
Degliai-2	1954.5	De-2	1.165	1.222	1.424	77	35	213	46	330	24	21
Degliai-2	1954.5	De-3	1.189	2.028	2.410	123	12	215	11	348	74	86
Degliai-2	1954.5	De-4	1.146	2038	2.336	131	4	41	5	263	84	93
Degliai-2	1954.5	De-5	1.368	1.245	1.702	253	63	106	23	10	13	–31
Degliai-2	1954.5	De-6	1.183	1.676	1.982	138	2	47	10	238	79	298
Degliai-2	1954.5	De-7	1.065	2.599	2.769	75	5	345	5	213	83	37

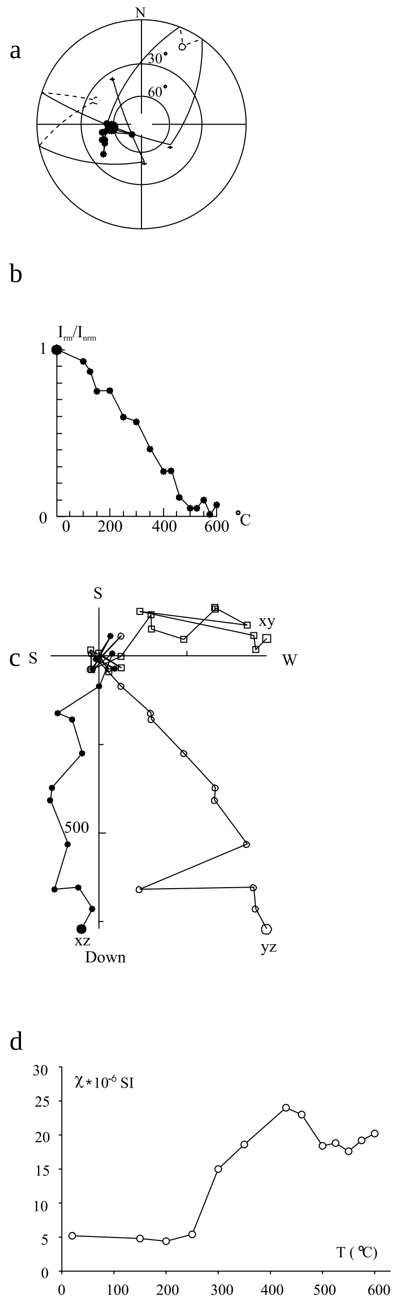


Fig. 3. Results of demagnetization of the sample de–5a: *a* – stereographic projection, *b* – I_{rm}/I_{nrm}, *c* – x,y,z projection, *d* – magnetic susceptibility

3 pav. Bandinio de-5a išmagnetinimo rezultatai: *a* – steriografinë projekcija, *b* – I_{rm}/I_{nrm}, *c* – x,y,z projekcija, *d* – magnetinis imlumas

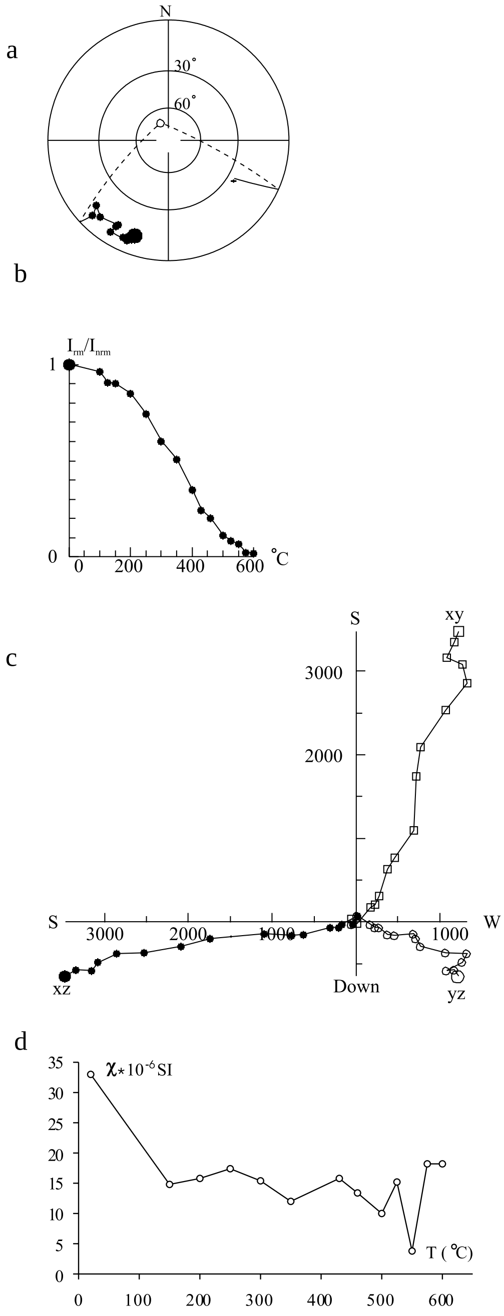


Fig. 4. Results of demagnetization of sample de–3a: *a* – steriographic projection, *b* – I_{rm} / I_{nrm}, *c* – x, y, z projection, *d* – magnetic susceptibility

4 pav. Bandinio de-3a išmagnetinimo rezultatai: *a* – steriografinë projekcija, *b* – I_{rm}/I_{nrm}, *c* – x,y,z projekcija, *d* – magnetinis imlumas

vely. The Upper Cambrian in North Estonia consists of two formations. In the study area, the Middle Cambrian Deimena regional stage is composed of the Pajûrys, Ablinga and Giruliai Formations. The Giruliai Formation is formed of six members, each being composed of greenish grey, sometimes reddish argillite, aleurolite and white sandstone with white *Solithus* relicts. Its thickness reaches 17 m (Paškevièius, 1997).

A fragment of drill-core for paleomagnetic study was taken from the upper part of the Middle Cambrian Giruliai Formation, the borehole Degliai-2 sediment. The depth of sampling was 1954.5 m. The Degliai-2 borehole is drilled in the Degliai oil structure (Fig. 1). Near the borehole, the regional Gargþdai fault with maximum activity in the Caledonian and Hercynian deformations (Sakalauskas 1996; Stirpeika, 1999; Šliaupa, 2003) was identified by seismic data. The drill-core sample consists of medium-grained sandstone. The sample has a 5° structural leaning. The hand sample was cut into several standard magnetic anisotropy and paleomagnetic specimens 2.5 cm in diameter and 2.2 cm high.

EXPERIMENTAL AND ANALYTICAL METHODS

Magnetic anisotropy. The anisotropy of magnetic susceptibility (AMS) is widely used to obtain information on the tectonic history of weakly deformed sediments. In weakly deformed sediments, the orientation of K_{min} is perpendicular to the bedding plane, while the orientation of K_{max} is generally perpendicular to the direction of major shortening (Tarling & Hrouda, 1993).

All samples were first investigated by means of the anisotropy of magnetic susceptibility. The anisotropy of magnetic susceptibility was measured with a KLY-2 susceptibility bridge (Czech Republic). The principal values of susceptibility ellipsoids and

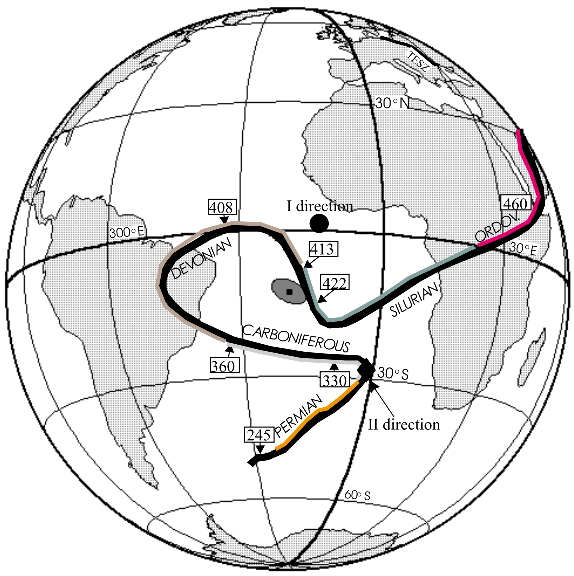


Fig. 5. Apparent polar wander path (APWP) for Baltica (after T. Torsvik et al., 1992, 1996, 2001 and J. Nawrocki et al., 2004): ● – direction I, ♦ – direction II

5 pav. Baltikos þemyno menamo pietø aðigalio kelias (pagal T. Torsvik ir kt., 1992, 1996, 2001 ir J. Nawrocki ir kt., 2004): ● – I kryptis ir ♦ – II kryptis

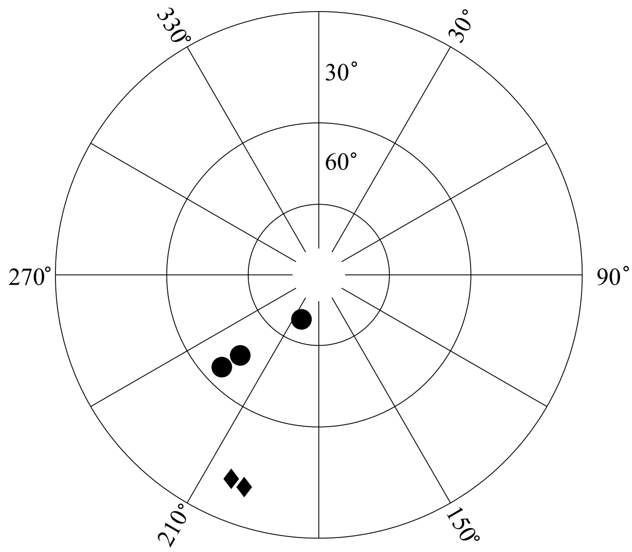


Fig. 6. Steriographic projection of palaeomagnetic investigations: ● – direction I and ♦ – direction II

6 pav. Paleomagnetiniø tyrimo rezultatø steriografinë projekcija: ● – I kryptis ir ♦ – II kryptis

the directions of their principal axes were calculated using the ANISO programme (Jelinek, 1977; Jelinek, 1978). We examined the following parameters which characterised the AMS of rocks (Hrouda, 1982; Jelenska & Kàdzialko-Hofmokl, 1990): a) the degree of anisotropy $P = K_{max} / K_{min}$; b) parameters defining the shape of anisotropy ellipsoids lineation – ($L = K_{max} / K_{int}$) and foliation ($F = K_{int} / K_{min}$); c) directions of the axes of susceptibility k_{max}; k_{int} and k_{min}.

Palaeomagnetic procedure. After the magnetic anisotropy procedures, all the standard palaeomagnetic specimens were investigated by palaeomagnetic methods. Natural remanent magnetisation (NRM) was measured with a JR-5 spinner magnetometer, and magnetic susceptibility during thermal demagnetisation was monitored with a KLY-2 bridge. The rock specimens were thermally demagnetised with an MMTD nonmagnetic oven. Demagnetisation experiments and NRM measurements were performed inside Helmholz coils which reduced the geomagnetic field by 95%. Characteristic directions were calculated using the principal component analysis (Kirschvink, 1980).

EXPERIMENTAL RESULTS

Orientation of drill-core samples according to seismic data and the anisotropy of magnetic susceptibility. The results of measurements of the anisotropy of magnetic susceptibility are presented in Table 1. The major shortening of the Degliai oil structure is concordant with the Gargþdai fault (Fig. 1). According to seismic data, the azimuth of the dip of the studied strata is about 100°. We wanted to check if this direction would be in agreement with the direction of the maximum axis of the susceptibility ellipsoid. All the specimens have an orientation with a 0° declination. The principal values of susceptibility ellipsoids and directions of their principal axes were calculated using the ANISO programme. The maximum axis of anisotropy ellipsoids K_{max} has a 102.2° declination and a 6.8° inclination. The lineation is 1.126, foliation 1.336, and the degree of anisotropy 1.504. The intermediate axis K_{int} has a 192.8° declination and a 5.2° inclination. The minimum axis K_{min} has a 320.2° declination and a 81.4° inclination (Fig. 2). The direction of the anisotropy of magnetic susceptibility K_{max} is generally perpendicular to the direction of major shortening and supports the orientation of drill-core samples by seismic data. According to the AMS investigation, the drill-core samples have a declination of 102.2°.

Palaeomagnetic investigations. Thermal demagnetization experiments allow to classify the samples into two different groups according to their unblocking temperature spectra. The first group is characterized by a rather wide range of unblocking temperature, the main body of unblocking occurring at about 400 °C (Fig. 3). The second group is characterized by the maximum unblocking temperatures of about 550 °C (Fig. 4).

Palaeogeographic investigations. Investigations of the apparent polar wander path (APWP) for Baltica are presented in the publications of T. Torsvik (Torsvik et al., 1992,1996, 2001) (Fig. 5). The updated results of palaeogeographic investigations of the

Table 2. **Results of the palaeomagnetic investigations**
2 lentelė. **Paleomagnetinių tyrimų rezultatai**

Remagnetization	n	D(°)	I(°)	Plong, (°)	Plat. (°)
● Direction I	3	222.0	50.0	346.0	2.0
♦ Direction II	2	198.5	9.0	359.0	–29.0

● – 1st direction, ♦ – 2nd direction, n – number of samples, D – declination, I – inclination, Plong – palaeolongitude and Plat – palaeolatitude
● – I kryptis, ♦ – II kryptis, n – bandinių skaičius, D – deklinacija, I – inklinacija, Plong – paleoilguma, Plat – paleoplatuma

Cambrian Baltica come from publications of J. Nawrocki (J. Nawrocki et al., 2004). The two characteristic directions were calculated after thermal demagnetisation: with 346/2 (I) (Palaeolongitude / Palaeolatitude) and with 359/-29 (Palaeolongitude / Palaeolatitude) (II) (Fig. 6, Table 2).

DISCUSSION AND CONCLUSIONS

The paleomagnetic directions were converted to palaeomagnetic poles (Table 2) which were compared to the apparent polar wander path (APWP) for stable Europe. The palaeomagnetic pole 359/-29 corresponds to the latest Carboniferous (late Westphalian–Stephanian) European poles (290–300 Ma). The palaeomagnetic pole 346/2 may come from the Silurian and Devonian boundary (413 Ma), however, it has a 15° incorrect paleo-latitude and is not well comparable with the Baltic APWP (Fig. 5).

The palaeomagnetic data indicate the Late Silurian / Early Devonian and Late Carboniferous (Late Westphalian–Stephanian) age of the remagnetization event. Our data show also that the Gargþdai fault had the maximum activity in the Late Silurian / Early Devonian and Late Carboniferous time. The Late Carboniferous time indicated the late phase of the Hercynian Orogeny, while the Late Silurian / Early Devonian time corresponds to the late Caledonian orogeny.

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VIDURINIO KAMBRO KERNO ORIENTACIJA NAUDOJANT MAGNETINIO IMLUMO ANIZOTROPIJÀ DEGLIØ NAFTOS STRUKTÛROJE IR GAUTØ DUOMENØ PALEOGEOGRAFINË ANALIZË

Santrauka

Ið Degliø-2 græþinio 1954,5 m gylyje buvo paimtas vidurinio kambro bandinys ir paruoðti septyni pavyzdþiai; pamatuota jø magnetinio imlumo anizotropija (AMS). AMS aðis K_{max} tiesiogiai statmena pagrindiniam spûdþiui (D = 102,2°, I = 6,8°, L = 1,126, F = 1,336, P = 1,504, n = 7 pavyzdþiai). Pagal AMS rezultatus ir buvo orientuotas kernas. Po paleomagnetiniø tyrimø mes gavome dvi menamas ámagnetinimo kryptis – I (D = 222°, I = 50°, n = 3 pavyzdþiai) ir II (D = 198,5°, I = 9°, n = 2 pavyzdþiai). Gauti rezultatai leido nustatyti stabilius Europos paleomagnetinius polius, kurie rodo, kad demagnetizacija vyko vëlyvojo silûro – ankstyvojo devono ir vëlyvojo karbono (vëlyvasis vestfalis – stefanis) laikotarpiais. Gargþdø lûþis buvo maksimaliai aktyvus. Parengta metodika leidþia detaliau analizuoti geologiniø struktûrø vystymàsi.

Âàëåíòàñ Êàòèíàñ, Åðæè Íàâðîöêèé

ÎÐÈÅÍÒÈÐÎÂÊÀ ÊÅÐÍÀ ÑÐÅÄÍÅÃÎ ÊÅÌÁÐÈß Â ÍÅÔÒßÍÎÉ ÑÒÐÓÊÒÓÐÅ ÄßÃËßÉ Ñ ÏÎÌÎÙÜÞ ÀÍÈÇÎÒÐÎÏÈÈ ÌÀÃÍÈÒÍÎÉ ÂÎÑÏÐÈÈÌ×ÈÂÎÑÒÈ È ÏÐÈÌÅÍÅÍÈÅ ÏÎËÓ×ÅÍÍÛÕ ÐÅÇÓËÜÒÀÒÎÂ Â ÏÀËÅÎÃÅÎÃÐÀÔÈÈ

Ðåçþìå

Èç ñêâàæèíû Äÿãëÿé-2 (1954,5 ì) áûëè ïîëó÷åíû îáðàçöû êåðíà ñðåäíåãî êåìáðèÿ è èçãîòîâëåíî 7 ïðîá äëÿ ìàãíèòíûõ èññëåäîâàíèé. Äëÿ âñåõ ïðîá èçìåðåíà àíèçîòðîïèÿ ìàãíèòíîé âîñïðèèì÷èâîñòè (AMS). Íàïðàâëåíèå îñè àíèçîòðîïèè ìàãíèòíîé âîñïðèèì÷èâîñòè K_{max} – ïåðïåíäèêóëÿðíî íàïðàâëåíèþ ãëàâíîãî äàâëåíèÿ (D = 102,2°, I = 6,8°, L = 1,126, F = 1,336, P = 1,504, n = 7 ýêç.). Ìàêñèìàëüíûå îñè AMS óêàçàëè îðèåíòèðîâêó îáðàçöîâ êåðíà. Ïîñëå ïàëåîìàãíèòíîé èíòåðïðåòàöèè ìû ïîëó÷èëè äâà íàïðàâëåíèÿ: – I (D = 222°, I = 50°, n = 3 ýêç.) è II (D = 198,5°, I = 9°, n = 2 ýêç.). Ðåçóëüòàòû ñðàâíåíèÿ (4 ýêç.) ïîëó÷åííûõ ïàëåîìàãíèòíûõ ïîëþñîâ ñ êðèâîé äðåéôà ñåâåðíîãî ïîëþñà Áàëòèêè (APWP) óêàçûâàþò íà ïîçäíåñèëóðèéñêèé, ðàííåäåâîíñêèé è ïîçäíåêàðáîíñêèé âîçðàñò ïåðåìàãíè÷èâàíèÿ. Ïîëó÷åííûå íàìè äàííûå ïîêàçûâàþò òàêæå, ÷òî ðàçëîì Ãàðãæäàé èìåë ìàêñèìàëüíóþ àêòèâíîñòü â ïîçäíåñèëóðèéñêîå, ðàííåäåâîíñêîå è ïîçäíåêàðáîíñêîå âðåìÿ.