Paleomagnetism and Petromagnetism of Sedimentary Rocks of the Zhuravlevka-Amur Terrane (Junction Zone Between the Sikhote-Alin and Mongol-Okhotsk Orogenic Belts)

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Abstract This paper presents paleomagnetic data on the Berriasian-Valanginian sandstones of the Gorinskaya and Pionerskaya Formations of the Komsomolskaya Group from the coastal outcrops of the Sakhalin Bay (54.09° N, 140.05° E). Structurally, these rocks belong to the Zhuravlevka-Amur (ZhA) terrane of the Sikhote-Alin orogenic belt. Paleomagnetic studies indicate that these rocks were formed at a latitude of 10°–18° N, which is comparable to paleolatitudes (10° N–4° S) obtained previously from the Berriasian-Valanginian basalts of the Rozhdestvenskaya Formation (Sakhalin Island). The obtained paleolatitude means that after 140 Ma the Zhuravlevka-Amur terrane drifted northward by over 4000 km along the continental margin of Eurasia at an average rate of about 10 cm/year.

Keywords Continental margin · Paleomagnetism · Paleolatitude · Sikhote-Alin orogenic belt

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1 Introduction

The junction zone between two orogenic belts under consideration is represented by the Upper Triassic, Lower-Middle Jurassic turbidites of the Ulban terrane of the Mongol-Okhotsk orogenic belt (MOOB) and the Cretaceous rocks of the ZhA terrane of the Sikhote-Alin orogenic belt (SAOB) (Fig. 1). Sandstones of the Gorinskaya and Pionerskaya Formations of the Komsomolskaya Group that were sampled in coastal outcrops of the Sakhalin Bay (54.09° N, 140.05° E) form the focus of this study. Structurally, these rocks belong to the Zhuravlevka-Amur turbidite basin [4] or the Amur accretionary prism [9]. The Gorinskaya Formation with a thickness of 1100–1300 m is dominated by sandstones; less common are siltstones and their flyschoid interlayering. It is assigned a Berriasian age based on buchiids [6]. The overlying Pionerskaya Formation (900–1430 m) is divided into two sub-formations and represented by siltstone, sandstone, rarely sedimentary breccias, gritstone, and mudstone. Buchiids indicate its Berriasian-Valanginian age [6].

Despite the growing interest in tectonics and geodynamics of East Asia, the junction zone between the Mongol-Okhotsk and Sikhote-Alin orogenic belts remains poorly understood. The lack of paleomagnetic data for this area prevents the

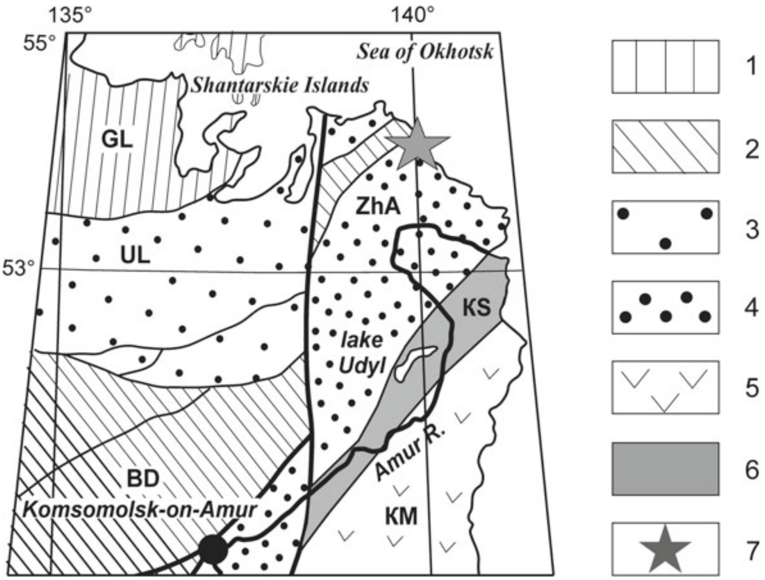

Fig. 1 Schematic map of terranes of the Sikhote-Alin orogenic belt after [4, 5] with additions. 1—Paleozoic terranes (GL, Galam); 2, 3—Jurassic terranes: 2—fragments of accretionary prisms (BD, Badzhal), 3—near-continental turbidite basin (UL, Ulban); 4 to 6—Cretaceous, essentially Early Cretaceous, terranes: 4—near-continental pull-apart turbidite basin (ZhA, Zhuravlevka-Amur), 5—Barremian-Albian island-arc system (KM, Kema), 6—Albian accretionary prism (KS, Kyselevka-Manoma); 7—region of paleomagnetic studies

paleo-latitudinal position and kinematic parameters of the Zhuravlevka-Amur terrane being quantified. The objective of the study is to obtain the first petromagnetic and paleomagnetic data on Berriasian-Valanginian sandstones of the Zhuravlevka-Amur terrane.

2 Methods

To calculate the anisotropy of initial magnetic susceptibility (AMS), the magnetic susceptibility ($\varkappa$) was measured by the MFK-1FA Kappabridge in 64 positions (AGICO, Czech Republic). The obtained data were statistically processed by the Anisoft software package (AGICO, Czech Republic). Paleomagnetic studies included: (a) thermomagnetic demagnetization in 100–5 °C steps to 680 °C involving a step-by-step measuring of magnetization on a JR-6A spinner magnetometer (AGICO, Czech Republic) inside the Helmholtz coils; and (b) cleaning with alternating field (AF) demagnetization up to 90 mT using a SQUID magnetometer (2G Enterprises, USA). Natural remanent magnetization (NRM) components were isolated by principal component analysis using R. Enkin's PMGSC (version 4.2) software [3]. The fold test was conducted on the components of magnetization to constrain their age and to determine whether the magnetization is primary or secondary. Coordinates of the paleomagnetic pole and the paleolatitude at which the studied rocks formed were calculated using R. Enkin's PMGSC (version 4.2) software [3].

A total of 95 samples were studied (51 samples from the Pionerskaya Formation and 44 samples from the Gorinskaya Formation).

3 Petromagnetic Results

The study has found that the NRM mean values of the studied specimens from the Gorinskaya and Pionerskaya Formations differ by more than two orders of magnitude: 1.4 mA/m (Pionerskaya Fm) and 331 mA/m (Gorinskaya Fm). Mean susceptibility values ($\varkappa$) are respectively 1.37E−04 SI units (Pionerskaya Fm) and 2.98E−04 SI units (Gorinskaya Fm).

The AMS of the studied specimens of rocks from the Pionerskaya Formation is both linear (predominantly) and planar (Fig. 2a–c). Rocks belonging to turbidite flows with high sedimentation rates are most probably responsible for the linear type anisotropy [4]. The average degree of anisotropy (P) is 3.5% ranging from 2 to 5%. Specimens of the Gorinskaya Formation show predominantly the planar type anisotropy (Fig. 2d, e). The degree of anisotropy for specimens of the Gorinskaya Formation is appreciably higher than in the previous case ranging from 2.2 to 22.8% with an average of 6.5%. Such high P values are most probably the result of secondary processes that affected the magnetic fabric of the material. It should be noted

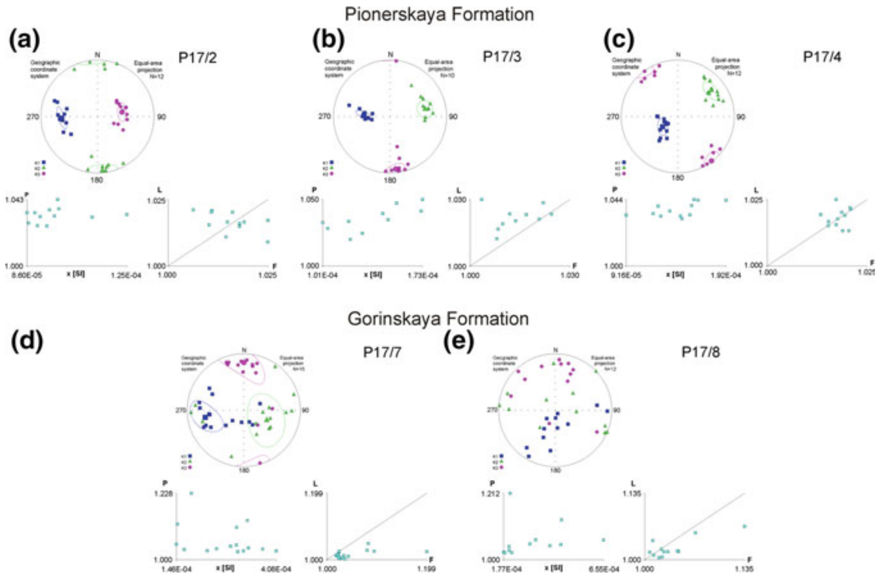

Fig. 2 Results of the initial magnetic susceptibility anisotropy analysis of specimens from the Pionerskaya (**a**–**c**) and Gorinskaya (**d**, **e**) formations. Symbols: P—degree of anisotropy; L—linear anisotropy; F—planar anisotropy; K1, K2, K3—maximum, average, and minimum axes of the anisotropy ellipsoid

that specimens from the Gorinskaya and Pionerskaya Formations, when heated to 400–420 °C, do not show changes of AMS parameters.

The *Königsberger ratio* (Qn) was calculated for the studied specimens and rock-magnetic properties were plotted on the log-log diagram (Fig. 3). Qn values of the majority of rock specimens from the Pionerskaya Formation range from 0.1 to 1, whereas for the rock specimens of the Gorinskaya Formation the Königsberger ratio is >1 and for the bulk of the studied specimens >10.

One can infer that magnetic properties of sandstones from the Pionerskaya and Gorinskaya Formations have essential differences. The log-log NRM versus magnetic susceptibility plot show clear difference in the magnetic hardness of studied specimens (Fig. 3). The appreciable difference in the rock magnetic properties of specimens from the two formations we interpret as due to the presence of different carriers of magnetic properties of rocks, as well as the different degree of secondary alteration.

High values of Qn in rock specimens of the Gorinskaya Formation (>10), as well as the behaviour of specimens during temperature demagnetization (specimens were completely demagnetized at 330–400 °C) indicate the presence of pyrrhotite as a carrier of magnetization. High coefficients of anisotropy indicate secondary (chemical) alteration in the studied rocks, which can be explained by the formation of secondary pyrrhotite.

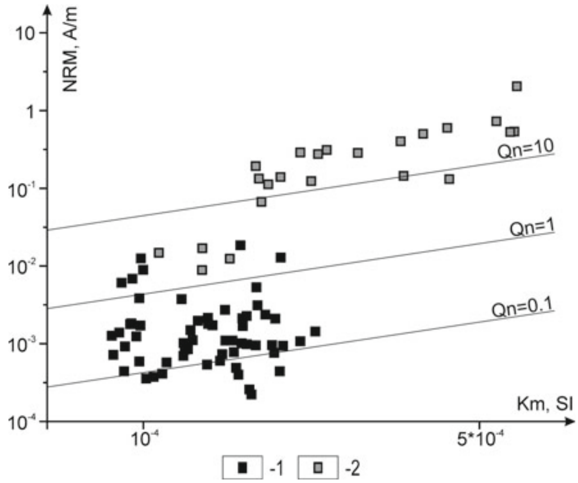

Fig. 3 Log-log plot showing distribution of rock-magnetic parameters for specimens from Pionerskaya (1) and Gorinskaya (2) formations. NRM—natural remanent magnetization, A/m; Km—magnetic susceptibility, SI units

The anisotropy coefficient in the studied specimens of the Pionerskaya Formation is not high suggesting that secondary alteration is either absent in the rock or weakly developed. Considering the obtained rock magnetic data, as well as the behaviour of specimens during temperature demagnetization (the demagnetization curve has a peak between 330 and 400 °C, while the specimens were demagnetized between 550 and 580 °C), magnetite and, to a lesser extent, pyrrhotite can be assumed to be carriers of magnetization in the studied rocks of the Pionerskaya Formation.

4 Paleomagnetic Results

4.1 Gorinskaya Formation

Detailed thermal demagnetization of rock specimens from the Gorinskaya Formation isolated one component of magnetization. All the specimens were demagnetized at temperatures between 330 and 400 °C (Fig. 4a). The isolated components of magnetization in the Gorinskaya specimens are distributed chaotically on the stereogram and shall not be used for further analysis.

4.2 Pionerskaya Formation

Detailed thermal demagnetization of specimens from the Pionerskaya Formation was carried out to 600 °C (in some cases to 680 °C) and alternating-field demagnetization

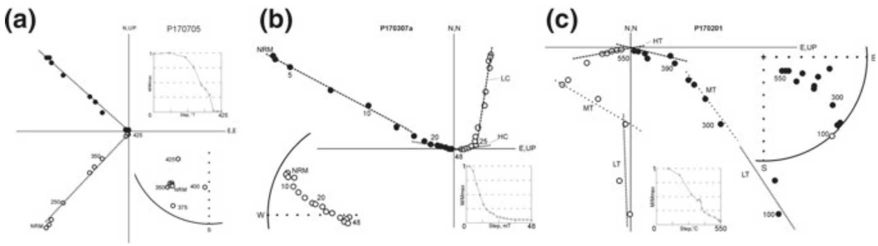

Fig. 4 Examples of orthogonal diagrams (in geographic coordinates) of alternating-field (**b**) and thermal (**a**, **c**) demagnetization data from specimens of Gorinskaya (**a**) and Pionerskaya (**b**, **c**) formations

up to 50–100 mT. The studied specimens, as a rule, display two components of magnetization (Fig. 4b) although some show as many as three components (Fig. 4c).

Directions of the isolated high-coercivity (HC) and high-temperature (HT) components are similar suggesting that they may represent primary magnetization [8]. In the Pionerskaya Formation, HT component is isolated between 380–430 °C and 540–580 °C and decays to the origin. As an example, an orthogonal diagram of thermomagnetic demagnetization is shown for sample P170201 (Fig. 4c). The NRM of this sample comprises three components, and the HT component of magnetization is isolated at temperatures ranging from 400 to 550 °C (Fig. 4c). During the Af-demagnetization, HC component is isolated between 20–25 mT and 40–60 mT and, like HT component, trends toward the origin (with an exception of a few specimens which were excluded from the statistics). As an example, an orthogonal diagram of AF demagnetization is shown for sample P170307a whose HCC is isolated in the 25–48 mT interval (Fig. 4b). These components (HT and HC) are considered to represent the characteristic magnetization (ChRM) for sedimentary rocks of the Pionerskaya Formation of the ZhA terrane.

In stratigraphic coordinates, clustering of the ChRM directions increases more than six-fold at the sample (Ks/Kg = 6.2) and by more than 100 times at the site level (Ks/Kg = 134.7) (Table 1). The best grouping is attained at about 100% (97%) untilting suggesting that the ChRM was acquired before the folding event (Fig. 5b).

Sample and site mean ChRM directions were calculated (Table 1). Coordinates of the paleomagnetic pole, as well as a paleolatitude of 14.2 ± 4° N at which the rocks under consideration formed, were calculated from the sample-mean ChRM direction (Table 1).

Table 1 Results of paleomagnetic studies

Sites	φ, °	λ, °	Rock type	N_1	N_2	Dip azim., °	Dip angle, °	Dec_g, °	Inc_g, °	K_g	a_{95}, °	Dec_s, °	Inc_s, °	K_s	a_{95}, °
P17/2	54.09	140.05	Sandstone	15	14	319	40	294.2	62.3	14.8	10.7	306.7	24.0	14.8	10.7
P17/3	54.10	140.03	Sandstone	11	6	137	110	248.1	−67.5	20.1	15.3	293.5	26.4	20.1	15.3
P17/4	54.10	140.02	Sandstone	25	15	317	87	162.6	60.3	11.1	12.0	302.8	29.4	11.1	12.0
Sample-mean (ChRM) N = 35					Kmax = 96.6%			229.3	68.0	2.2	21.8	302.7	26.8	13.7	6.8
Site-mean (ChRM) N = 3					Kmax = 97.3%			236.0	47.5	1.1	180	301.0	26.7	148.2	10.2
Paleomagnetic pole coordinates (for sample-mean)								Plat = 30.4°; Plong = 31.1°; dm = 7.4; dp = 4.0							

Note φ, λ—geographical latitude and longitude of sampling site, respectively; N1—number of collected samples; N2—number of samples used in calculating the mean; Dec, Inc—paleomagnetic declination and inclination, respectively, in geographic (g) and stratigraphic (s) coordinates; K—grouping; a95—radius of the confidence ellipse around the mean; Plat, Plong—latitude and longitude of the paleomagnetic pole, respectively; dp; dm—semi-axes of the confidence ellipse around the pole

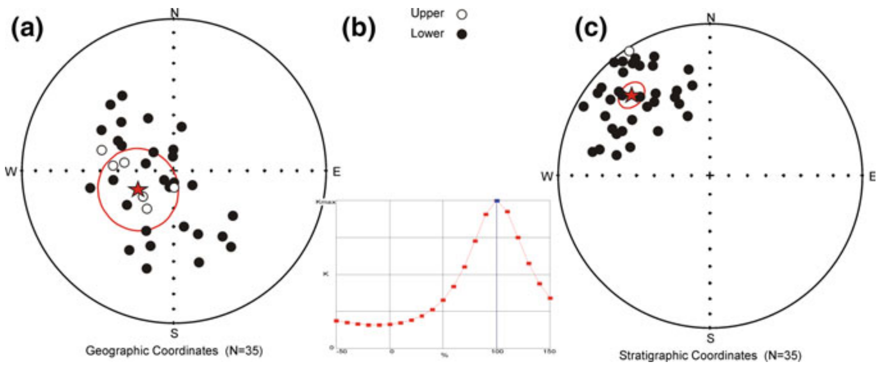

Fig. 5 Stereograms of ChRM distribution for samples of Pionerskaya formation in the geographic (**a**) and stratigraphic (**c**) coordinate systems. **b** Fold test (the relationship between the degree of clustering (K) and the degree of untilting)

5 Conclusion

Rock magnetic studies have shown that magnetic properties of rocks of the Pionerskaya and Gorinskaya Formations differ significantly. High values of the degree of anisotropy (P), and the Königsberger ratio for rocks of the Gorinskaya Formation suggest secondary alteration in these rocks attributed to the presence of secondary pyrrhotite as a carrier of magnetization, which impaired the results of paleomagnetic cleaning (demagnetization), during which attempts to isolate a primary paleomagnetic signal have not met with success. Magnetite and, to a lesser extent, pyrrhotite are carriers of magnetization in the studied rocks of the Pionerskaya Formation.

Paleomagnetic studies of rock specimens from the Pionerskaya Formation (thermomagnetic and AF demagnetization) yielded the characteristic magnetization component of pre-folding origin. Based on the direction of the characteristic component, the paleomagnetic pole was calculated for Berriasian-Valanginian rocks of the Pionerskaya Formation (Zhuravlevka-Amur terrane): Plat = 30.4°; Plong = 31.1°; dm = 7.4; dp = 4.0.

The new data are consistent with the published paleomagnetic data [2]. These data lend further support to the terrane model for the formation of the Sikhote-Alin orogenic belt and allow the tectonomagnetic model of its formation to be complemented.

The Berriasian-Valanginian sandstones of the Pionerskaya Formation formed in tropical latitudes of between 10° and 18° N, which is comparable to the paleolatitudes (10° N–4° S) earlier obtained from the Berriasian-Valanginian basalts of the Rozhdestvenskaya Formation (Sakhalin Island) [1]. The resulting paleolatitudes indicate that later on rocks of the Pionerskaya Formation moved along the Eurasian continental margin for more than 4000 km (≈4500 km). The available paleomagnetic data on Cenomanian-Turonian volcanic rocks of the Zhuravlevka-Amur terrane of the Sikhote-Alin orogenic belt [7] showing evidence of tectonic coherence of the continental paleo-margin and the above-mentioned terrane, allow the kinematic parameters of the Amur terrane to be determined. According to our estimates, the Amur terrane drifted in a northerly direction at an average rate of ≈10 cm/year.

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