Quaternary Science Reviews 30 (2011) 2054–2068

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

The Brunhes-Matuyama boundary in Western Beringia: a review

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ARTICLE INFO

Article history:
Received 24 September 2009
Received in revised form
31 May 2010
Accepted 3 June 2010
Available online 22 July 2010

ABSTRACT

Early-Middle Pleistocene deposits have been studied in Central and Northern Yakutia, the Magadan region, and Chukotka. The Brunhes-Matuyama boundary occurs in the Ozheleznenye Galechniki (=Ferruginated pebblestones) beds of Central Yakutia that belong to the Talagay horizon of the Early-Middle Pleistocene. These layers include classic Aldan mammal fauna. In Eastern Yakutia sediments of Early-Middle Pleistocene belong to the Akan horizon, and the Early Pleistocene sediments are from the Chukochya horizon. These sediments which belong to the Olyor Formation and its age-equivalents yielded numerous mammal remains, termed the Olyor faunal complex. The Brunhes-Matuyama boundary is located in Akan horizon. In the upper reaches of the Kolyma River, the Brunhes-Matuyama boundary occurs in sediments of the Middle Pleistocene Belichan horizon. The boundary of the Brunhes-Matuyama is characteristic within the Elhkakvun and Enmakay formations of Chukotka. In Kamchatka, the boundary of Matuyama and Brunhes is evident in volcanic sequences. In the eastern part of the peninsula, this boundary is located in the Tumrok or Iult volcanic complex and in Central Kamchatka in the Kreruk volcanic complex.

1. Introduction

Brunhes-Matuyama represents the last major reversal of the Earth's magnetic field. $^{40}Ar-^{39}Ar$ dating and astronomically calibrated ages place this event at approximately 780 ky (Shackleton et al., 1990; Baksi et al., 1992; Singer and Pringle, 1996; Tauxe et al., 1996; Carlut et al., 2000; Horng et al., 2002; Channell et al., 2004; Coe et al., 2004; Singer et al., 2005). The Brunhes-Matuyama transition is recorded within an interglacial period during marine Oxygen Isotope Stage (MIS) 19 (Tauxe et al., 1996; Channell et al., 2004; Liu et al., 2008). The reversal has been used as a key time horizon for determining chronologies and for correlating marine and continental Quaternary sediments, especially in the absence of accurate radiometric ages or biostratigraphic data. Furthermore, this level marks the boundary of the Early and Middle Pleistocene as defined by the international geologic time scale (Gibbard and Van Kolfschoten, 2004).

In the Russian stratigraphic scheme, the Pleistocene is divided into the Eopleistocene, equivalent to the Early Pleistocene Subseries, and the Neopleistocene, equivalent to the Middle and Late Pleistocene Subseries (Borisov, 2007). In this paper we will use international classification units (Gibbard and Head, 2009).

The Russian stratigraphic scheme developed 30 years ago considered the lower Quaternary boundary at the Brunes-Matuyama horizon, as discussed in many works (Sher, 1981, 1984; Virina et al., 1984) the lower part of Olyor Formation was considered to belong to the Late Pliocene – in this article this unit belongs to the Early Pleistocene.

2. Study area

The boundaries of Beringia extend eastward from the Lena River of eastern Yakutia to the Mackenzie River of northwestern Canada (see Elias and Crocker, 2008 for more history on the term "Beringia"). The Russian part of this vast area, which stretches from Bering Strait to the Lena River, is referred to as Western Beringia, and Early and Middle Pleistocene deposits are widespread here. These sediments are located in many of the large river valleys and in the coastal lowlands, as well as buried in tectonic depressions. In interior areas of Western Beringia alluvial and lacustrine facies dominate, whereas in some coastal depressions marine facies are more common. On the other hand, Kamchatka is characterized by volcanic sequences and not discussed here. These deposits have been studied in Central and Northern Yakutia, the Magadan region, and Chukotka (Fig. 1).

3. Method

The area of Western Beringia is located in the permafrost zone. Sampling was conducted in outcrops of thawed sediment by core

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doi:10.1016/j.quascirev.2010.06.008

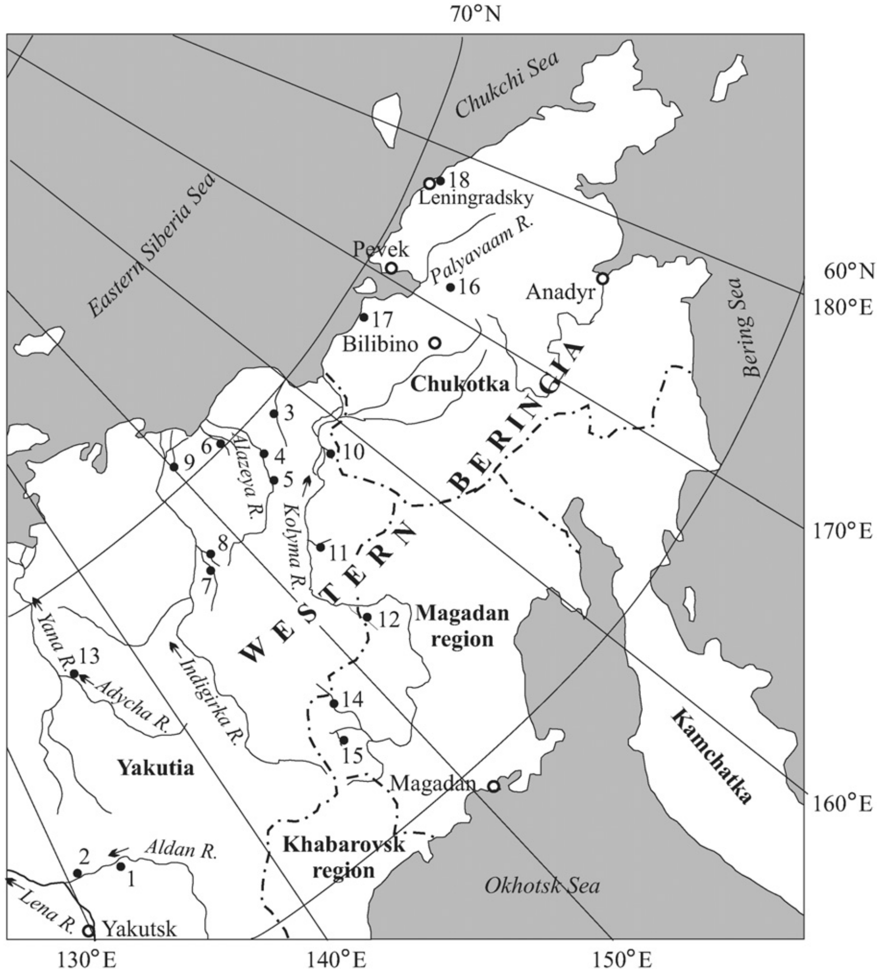

Fig. 1. Map of Western Beringia, showing the locations of sections and sites discussed in the text: (1) Tanda; (2) Chuya; (3) Bolshaya Chukochya sections – Svyatoy Nos, Svyatoy Nos-3, Kuropartochye, 22-II, 22-IV, 23, 24; (4) Alazeya sections – Obmanchivoe-1, Obmanchivoe-2, Alazeiskoe, Tumus-Yar, Zabytoe; (5) Alazeya, 2079; (6) Bolshoy Khomus-Yuryakh, P-182; (7) Badyarikha sections – Badyarikha-1, Badyarikha-2; (8) Ogorokha sections – Ogorokha-1, Ogorokha-2; (9) Keremesit – section 2; (10) Krestovka; (11) Slezovka – B-24; (12) Popovka – section 309; (13) Adycha – 2, 3, 4, 7; (14) Berelekh, Malyk-Sien sections – 71, 311, 312, 313, 157, 159, 181, 216, 201, 186; (15) Ongkachan; (16) mine172; (17) borehole 10; (18) Enmakay sections – mine 255, 151, 206, site 267, quarry 15.

sampler with internal cardboard containers, focusing on fine-grained deposits of clay, silts, and fine-grained sand. Sampling excluded deposits influenced by solifluction and ice wedges, both of which deform the direction of magnetization (Minyuk, 2004). Samples from frozen deposits in sediment cores and from mines were taken by core sampler after thawing. Borecore samples were oriented "up-down".

Magnetic remanence was measured using JR-4 and ION-1 spinner magnetometers. Magnetic susceptibility was measured on a KLY-2 kappabridge. To isolate a characteristic remanent magnetization (ChRM) direction, samples were mainly subjected to progressive demagnetization in AF at 5 mT steps up to 40 mT and to thermal demagnetization up to 300 °C. Almost all deposits contain siderite. Therefore, heating is not held above 300 °C because of neoformation of magnetite. Most of samples carry essentially a single component of magnetization, observed both upon thermal or alternating fields treatments (Fig. 2). A small secondary component, probably of viscous origin, was sometimes present and was easily removed.

4. The Brunhes-Matuyama boundary

4.1. Central Yakutia

In Central Yakutia, Quaternary deposits within the Lower Aldan depression were the main focus of study (Fig. 1). These deposits are represented by alluvial, lacustrine, eolian, cryogeniceolian, glacial and fluvioglacial facies. The Ozheleznenye Galechniki beds, assigned to the Middle-Early Pleistocene, were first described by Vangengeim (1961) from the Tanda section (131°48.0′E, 63°18.5′N), located on the left bank of the Aldan River 130 km upstream from its mouth. Sediments of the same age are known from the bottom of the Chuya section, also on the Aldan, but only 35 km upstream from the river's mouth (130°12.5′E, 63°23.0′N). Paleomagnetic analyses were done for both sections. In the Tanda section, Ozheleznenye Galechniki deposits consist of alluvial yellow–gray cross-bedded sand and pebbles within a sandy-gravel matrix. The thickness of these beds is 5 m. Paleomagnetic samples were taken from lenses and thin layers of fine-grained sand and sandy loam frequently occurring in these deposits. The Ozheleznenye Galechniki deposit directly overlies Miocene Mamontova Gora Formation and in turn, is overlain by the Middle Pleistocene Bestyakh Formation (Fig. 3). Ozheleznenye Galechniki deposits were studied in a few sites located along the outcrop. Fig. 2 shows a composite section.

The Ozheleznenye Galechniki beds have yielded specimens from the Aldan mammal fauna: *Palaeoloxodon* ex gr. *namadicus* Falc.et Cautley, *Equus* sp. (ex gr. *sanmeniensis*), *Alces latifrons* Johns, *Canis* cf. *variabilis* Pei., *Trogontherium* cf. *cuvieri* Fisch., *Bison* aff. *schoetensacki* Freud., *Allophaiomys pliocaenicus* aut *Microtus* (*M.*) sp., *M.*

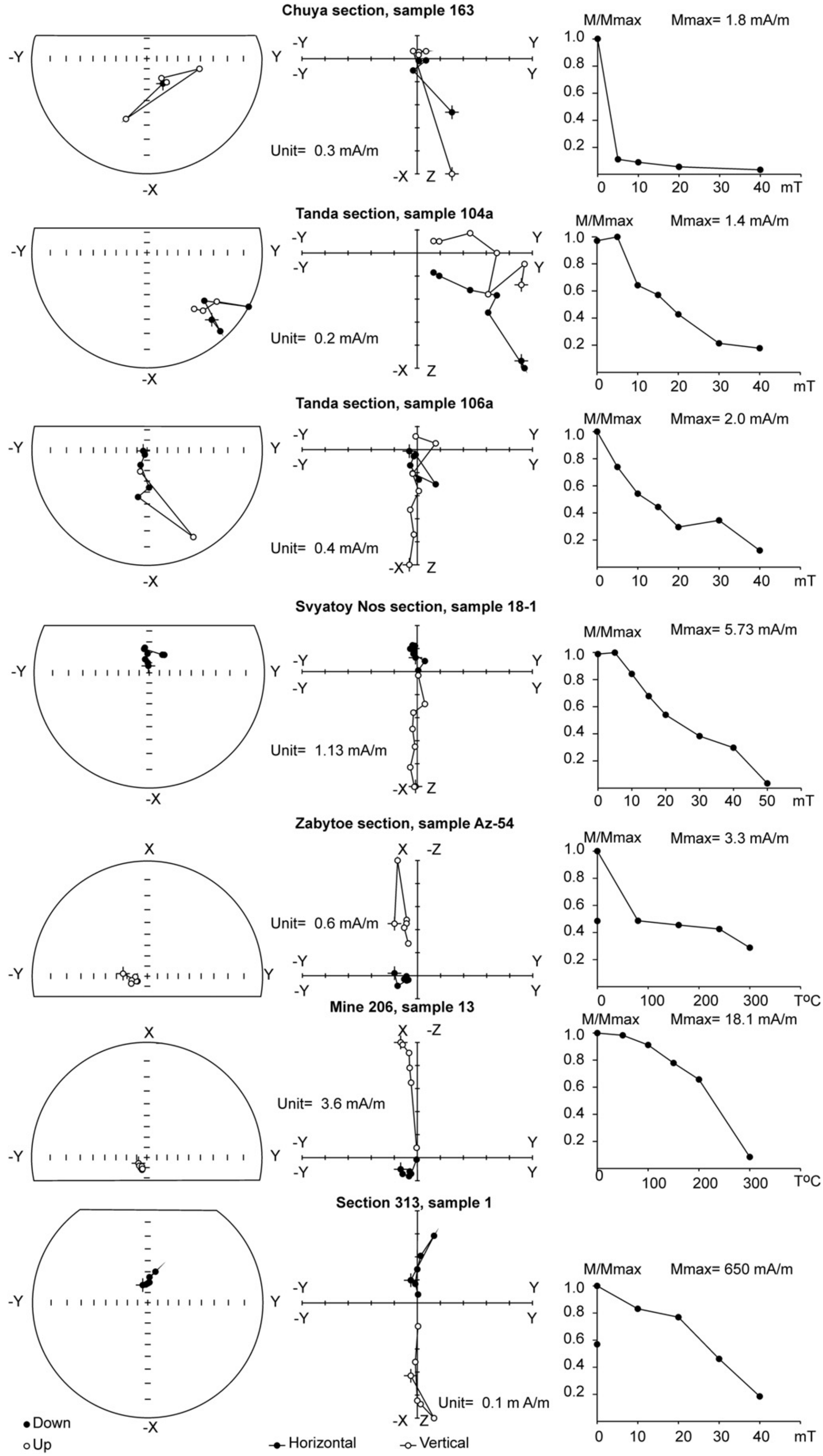

Fig. 2. Typical AF and thermal demagnetization plots of sediments. (on the left-hand side) Stereographic projections with closed (opened) symbols indicating normal (reverse) component. (centre) Orthogonal plots with solid (open) data points indicating vector end points projected onto the horizontal (vertical) plane. (on the right-hand side) Demagnetization intensity plots.

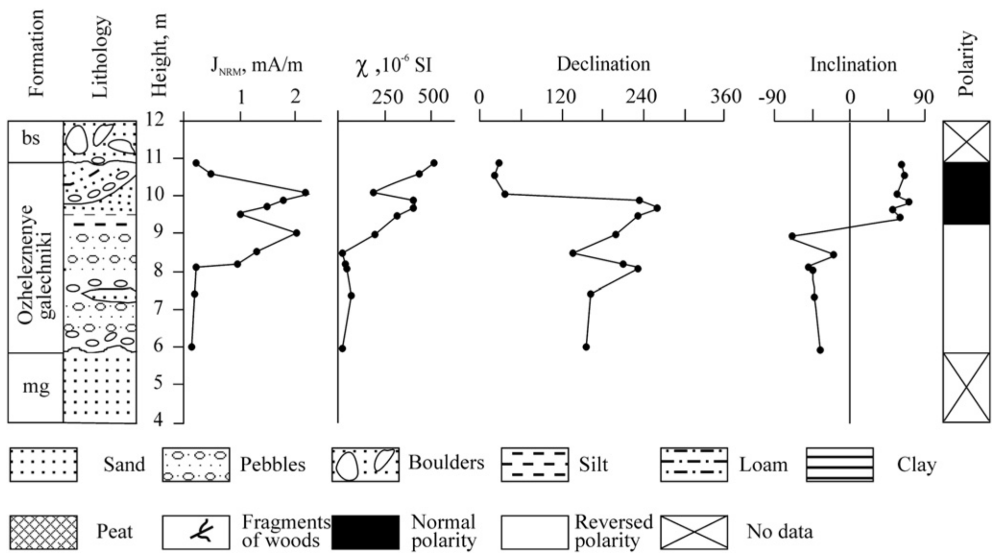

Fig. 3. Magnetostratigraphy of the Tanda section: bs – Bestyakh Formation, mg – Mamontova Gora Formation, I_{NRM} = Intensity of natural remanent magnetization, χ = magnetic susceptibility.

ex gr. *arvalis* Pall., *M.(P.) gregaloides* Hinton (Vangengeim, 1961, 1977; Rusanov, 1968; Alekseev et al., 1982, 1984). This fauna is considered age-equivalent with either the Tamanian fauna or the somewhat younger Tiraspolian fauna of Eastern Europe (Vangengeim and Zazhigin, 1982). The Brunhes-Matuyama boundary occurs in sediments containing the Tiraspolian fauna (Shantser, 1982a,b).

Palynological data indicate the presence of forest during this period. The spectra are dominated by arboreal taxa, particularly *Betula* and *Pinus* (48–92%). Pollen of thermophilous plants does not exceed 2%. Poaceae, *Ericales*, Brassicaceae, Ranunculaceae, and *Thalictrum* are typical of the herb taxa. Sphagnales, Polypodiaceae, Osmundaceae, *Filicales*, *Bryales*, *Lycopodium*, and *Selaginella* characterize the spore group (Alekseev et al., 1982; Kamaletdinov, 1982).

In the Chuya section, the Ozheleznenye Galechniki beds are composed of ochre-colored pebbles with coarse-grained sand and gravel matrix. Thin layers of fine-grained sand with subhorizontal laminae or cross-bedding are also described for these deposits. The thickness of the beds varies from 0.2 to 2 m. They occur above the Mamontova Gora Formation of the Middle Miocene and are overlain by gray fluvial pebbles of the Middle Pleistocene.

The associated palynological assemblage is dominated by tree taxa (42%) such as *Larix*, *Picea*, *Pinus*, *Betula*, *Alnaster*, and *Salix*. The spectra contain up to 10% herb pollen with spores having maxima values of 48%. Cyperaceae, Compositae, *Artemisia*, Chenopodiaceae, and Caryophyllaceae dominate the herb types (Alekseev et al., 1984).

The polarity sequences within these sections are the same. The upper part of the sections has normal polarity, whereas lower portions show reversed polarity (Figs. 3, 4). We assume this reversal represents the Brunhes-Matuyama boundary, which agrees with the available biostratigraphic data. The shallow inclination of some samples apparently is due to the specific sedimentation of alluvial facies.

4.2. Northern Yakutia

In Northern Yakutia (Figs. 1 and 3), sediments representing the Lower–Middle Pleistocene boundary are known as the Olyor Formation, which was defined by Sher (1971) from the middle part of the Bolshaya Chukochya River basin. The Olyor Formation and equivalent deposits have been studied in the basins of the Bolshaya Chukochya, Alazeya, Bolshoy Khomus-Yuryakh, Indigirka (Badyarikha, Ogorokha, Keremesit), and Kolyma (Krestovka, Popovka, Slezovka) rivers. Neotectonic uplift in the lowlands accounts for sediments exposed along the rivers (Patyk-Kara et al., 1982).

4.2.1. Bolshaya Chukochya River basin

Olyor sediments are exposed in the middle part of the river where they are eroding off the Chukochya uplift. The type section for the formation is section 21 or Svyatoy Nos (156°52.0′E, 69°27.3′N) (Virina et al., 1984; Minyuk, 2004). Sediments consist of gray to brownish-gray silt and sandy silt, including sand layers and peats. The numerous cryogenic structures observed in these deposits are typical for this formation (Sher, 1971).

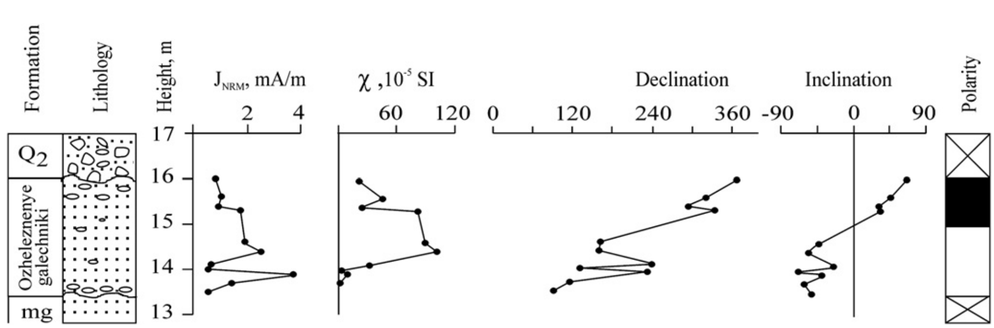

Fig. 4. Magnetostratigraphy of Chuya section: mg – Mamontova Gora Formation, Q_2 – Middle Pleistocene sediment.

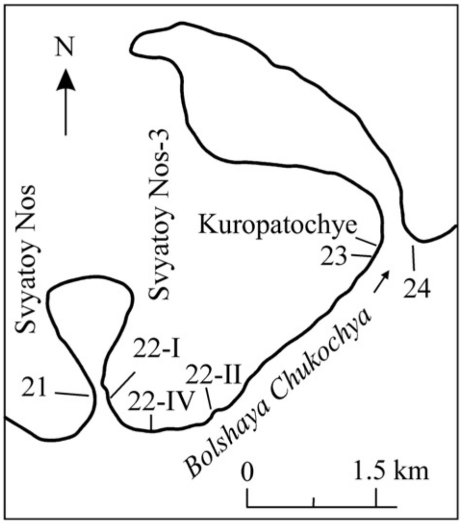

Fig. 5. Map showing the locations of studied sections in Bolshaya Chukochya basin.

These sediments yielded numerous mammal remains, termed the Olyor faunal complex (Sher, 1971). The older fauna within this complex, including such taxa as *Lemmus obensis* Brants, *Predicrostonyx compitalis* Zazh, *Allophaiomys* cf. *pliocaenicus* Korm., *Clethrionomys* ex gr. *rutilus* Pall., *Citellus* ex gr. *parryi* Rich., *Equus* (*Plesippus*) *verae* Sher, *Praeovibos beringiensis* Sher, *Sorex* sp., and Leporinae gen., correlates with the Razdolean (Siberia) or Tamanian (Eastern Europa) faunas of the Early Pleistocene. *Microtus* sp., *M.* ex gr. *oeconomus*, *Dicrostonyx renidens* Zazh., *Praealces* aff. *latifrons*, *Soergelia* sp., and *Equus* (*Plesippus*) sp., which compose the younger Olyor fauna, correspond to the Tiraspolian (Eastern Europe) fauna of the Middle Pleistocene (Virina et al., 1984).

Magnetostratigraphic analyses have been done on 7 sections from the Chukochya basin: Svyatoy Nos, Svyatoy Nos-3, Kuropartochye sections (Minyuk, 2004) and 22-II, 22-IV, 23, 24 sections (Virina et al., 1984) (Figs. 1, 5).

The Brunhes-Matuyama boundary was found in the upper part of the Olyor Formation in the following sections: Svyatoy Nos, 21, 24, 23, and 22-II and Svyatoy Nos-III. These horizons also contain the biozone characterized by *Dicrostonyx renidens*, which correlates with the Eastern European Tiraspolian fauna (Sher, 1984). The Jaramillo subchron also was recognized in the 23 and 22-II sections with mammals belonging to the biozone characterized by *P. compitalis*, being comparable to the Tamanian fauna of Eastern Europe. In the other sections, samples from the Olyor Formation have reversed polarity but samples were only taken from the lower parts of the formation (Fig. 6). So, the type section for the Olyor Formation area occupies the upper part of Matuyama chron, including the Jaramillo event and the lower part of Brunhes chron.

Two different vegetation types are represented by the pollen data from the Olyor sediment (Grinenko and Zharikova, 1982).

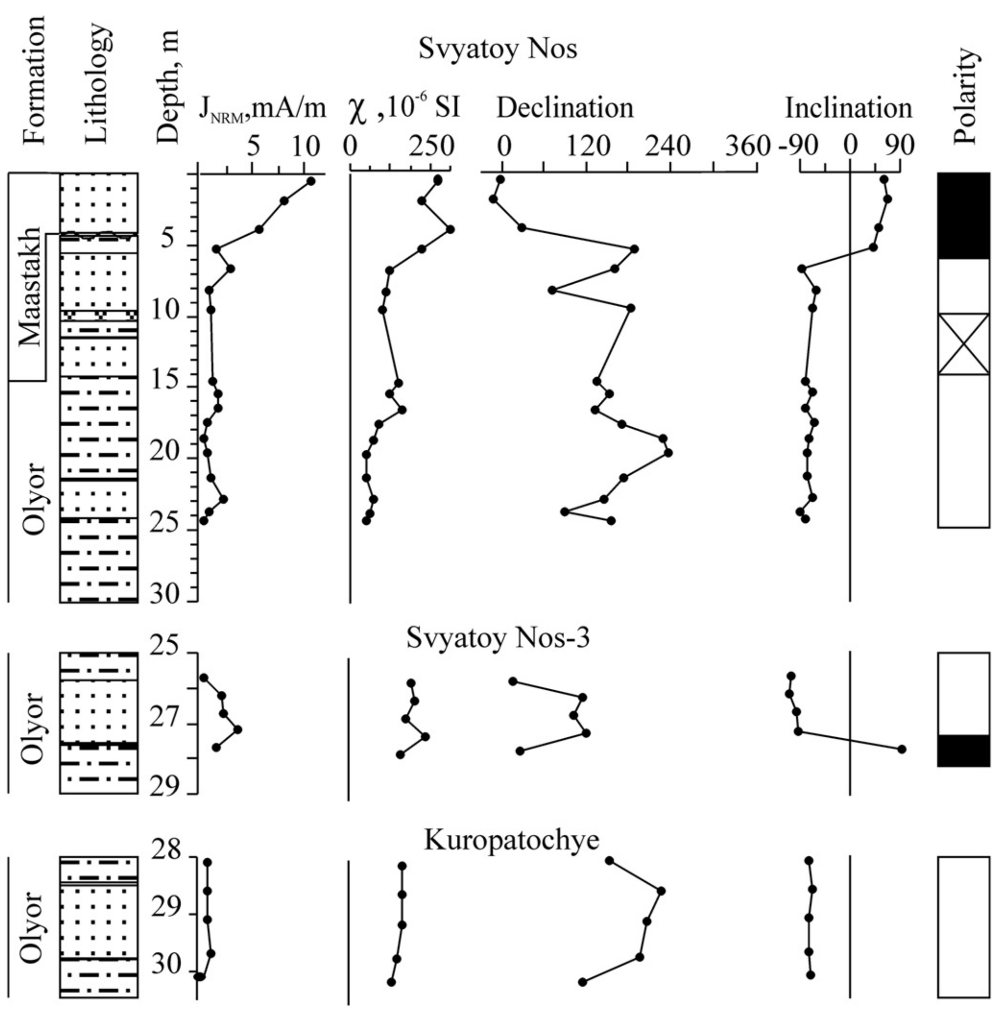

Fig. 6. Magnetostratigraphy of Olyor and Maastakh formations from Bolshaya Chukochya basin.

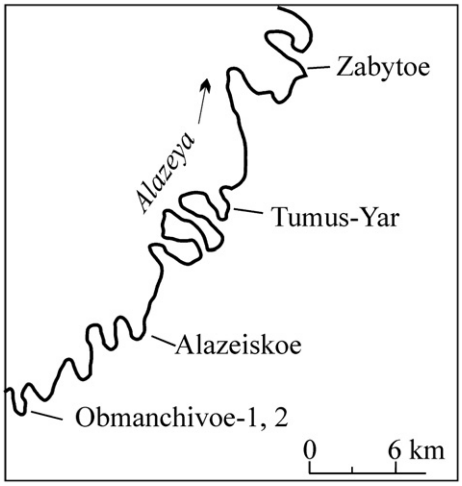

Fig. 7. Map showing the locations of studied sections in Alazeya basin.

Pollen spectra from below the Brunhes-Matuyama boundary are dominated by spores (42–78%) including *Bryales* (30–75%), *Sphagnum* (7–8%), and Polypodiaceae (3–5%), with trace amounts of *Lycopodium* and *Selaginella*. Herb pollen is also relatively abundant (14–51%) and diverse (15–20 taxa). Trees and shrub pollen occur in minor amounts (4–7%), key among these woody plants being *Betula*, *Alnus*, and *Larix*. Tree taxa vary from 4 to 7%, whereas shrub pollen is 0.7–4%. Pollen spectra from above the boundary represent *Artemisia*-Chenopodiaceae dominated vegetation, as these taxa are prevalent. *Bryales* (7–29%) are the most common spores in this younger assemblage. Percentages of tree and shrub pollen do not exceed 0.6–1.5%.

4.2.2. Alazeya River basin

In the Alazeya basin, Olyor sediments are exposed in the middle section of the river (155°00′E, 69°21.0′N) between Andryushkino village and the mouth of the Rassokha tributary (Kaplina et al., 1981; Minyuk, 2004). Here the sediment consists of alluvial-lacustrine sandy silt with horizontal and undulating laminae (Figs. 1, 7). The Olyor Formation also is exposed in a few rare localities along the river, upstream from the village (section 2079, 154°16.5′E, 68°54.4′N). Here the sediments are silty and include thin layers of peat and polygonal ice-wedge casts, which are located in different horizontal levels. It is possible that these ice-wedge casts represent a stratigraphic unconformity (Kaplina et al., 1981). The associated mammal fauna belongs to the Olyor complex and includes *Equus* (*Plesippus*) cf. *verae* Sher, *Praealces* sp., *Archidiskodon* (aut) *Mammuhtus* sp., *Praeovibos* sp., *Soergelia* sp., and *Trogontherium* sp. (Kaplina et al., 1981; Sher, 1981).

Pollen preserved in these deposits is dominated by herbs, including abundant mesic taxa of Ranunculaceae, Rosaceae, and Apiaceae. Pollen from *Artemisia* and Chenopodiaceae, generally indicators of drier substrates, occurs consistently in these records. Spores, primarily from *Sphagnum* and *Bryales*, are common throughout, while *Selaginella* appears only in the upper parts of the formation. Nonarboreal pollen occurring in trace amounts is represented by shrub *Betula*, *Alnus*, *Pinus pumila*, and tree *Betula*, *Larix*, *Picea,* and *Pinus* sub gen. *Diploxylon*. Pollen in the lower part of the sediments is dominated by tree taxa (Kaplina et al., 1981).

Quaternary lacustrine ostracodes are found in the nearby Tumus-Yar section. Key taxa include *Ilycypris gradii*, *Limnocythere sanctipatricii*, *Limnocythere inopinata*, *Candona candida*, *Candona nyalina*, *Candona obtusa*, *Candona*. cf. gr. *crogmaniana*, *Candoniella subellipsoida*, *Candoniella* ex gr. *susuni*, *Candoniella* ex gr. *detecta*, and *Candoniella lactea* (Kaplina et al., 1981).

The Brunhes-Matuyama boundary is recognized in all of the studied sections (Minyuk, 1989, 2004). The boundary is located in the following sections: 1) at 5 m above river level (2079); 2) 4.5 m at Obmanchivoe-1; 3) 7.7 m at Alazeiskoe-2; 4) 27 m at Tumus-Yar (Fig. 8); and 5) 12 m at Zabytoe. The varying position of this boundary relative to water level has been caused by recent tectonic movements. The Jaramillo subchron was found in the Tumus-Yar and Zabytoe sections, with a 9 and 2.5 m thickness, respectively.

4.2.3. Bolshoy Khomus-Yuryakh River basin

The focus of study in the Bolshoy Khomus-Yuryakh basin (Fig. 1) was the P-182 section, which is located on the right bank of this river, 43 km upstream from the Okulya tributary (153°36.0′E, 70°00′N). An analogue to the Olyor Formation occurs in the bottom of the section. These sediments consist of interbedded gray silty sand and sandy silt with horizontal and cross-bedding, with a thickness sediment of 16 m. The 25-m-thick Maastakh Formation of the Middle Pleistocene overlies the Olyor Formation. The representative of the Olyor fauna complex, *Equus* (*Plesippus*) *verae* Sher, was discovered in this basin. The Brunhes-Matuyama boundary was established at a depth of 37 m from the top of the section (Fig. 9) (Minyuk, 2004).

4.2.4. Badyarikha River basin

Analogues to the Olyor Formation were exposed 14 km upstream from the mouth of the Ogorokha tributary (146°30.0′E, 68°15.0′N). Here the Badyarikha River (Fig. 1) eroded a 60 m uplift. The Olyor sediments lay on gray–brown consolidated clays of Miocene age and are overlaid by the Ice Complex of the Late Pleistocene. The base of the Olyor Formation is 2 m above river level. The formation was studied in two sections, Badyarikha-1 and Badyarikha-2. The sediment is gray to dark gray sandy silt that is either massive or with horizontal bedding, including thin layers of fine-grained sand, peat, and detritus. Polygonal ice-wedge casts, which are typical for these deposits, are filled by sandy silt with pieces of wood, organic detritus, and shells. The thickness of the Olyor Formation in this basin is up to 25 m. *Praeovibos* sp. (determination by A. Sher) was found in the Badyarikha-1 section at 13 m above river level. The magnetic properties of the Olyor sediments do not differ from those from other sites in the Kolyma lowland. In general, reversed polarity was predominant in both sections. The Jaramillo subchron was found at 13–16 m and 9–11 m depths in the Badyarikha-1 and Badyarikha-2 sections, respectively. The Brunhes-Matuyama boundary was not documented in these sections, because cryogenic displacements and solifluction prevented sampling in the upper Olyor Formation where the boundary would likely be located.

4.2.5. Ogorokha River basin

The Ogorokha River is the right tributary of the Badyarikha River. Here sediments correlated to those of the Olyor Formation were studied in two sections along the middle part of the river between the Tirehteh and Sobognuur tributaries (146°26.0′E, 68°19.0′N) (Fig. 1). Here the Olyor Formation consists of green–gray to gray, poorly sorted sand and silt with organic detritus. The thickness of the Olyor sediments is ~10 m. Ice Complex deposits overlie the Olyor Formation. In the Ogorokha-1 and in the upper part of the Ogorokha-2 sections, sediments have normal polarity. The lower part of the Ogorokha-2 section reveals reversed polarity (Fig. 10). The change in polarity in the Ogorokha-2 section at 11 m above river level was identified as the Brunhes-Matuyama boundary (Minyuk, 2004).

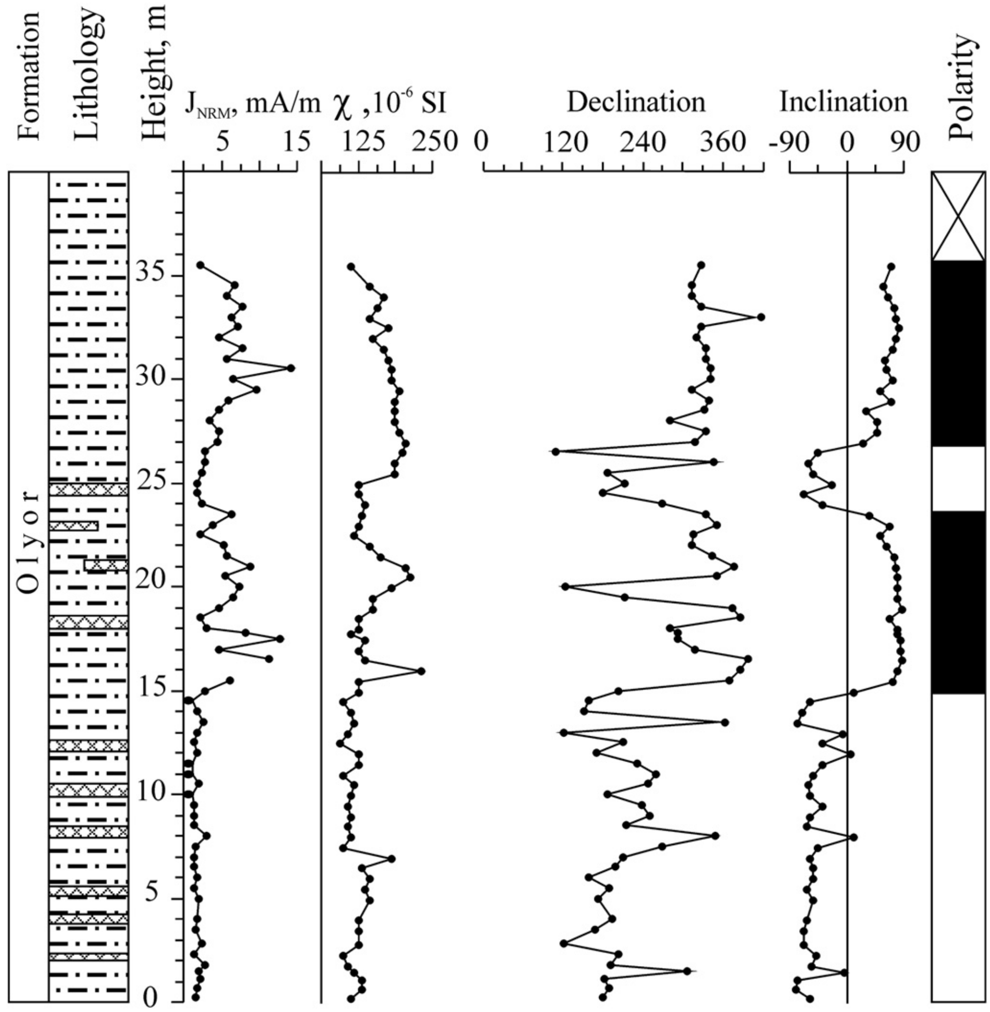

Fig. 8. Magnetostratigraphy of Tumus-Yar section.

4.2.6. *Keremesit River basin*

Outcrops and cores within the Keremesit basin expose deposits corresponding to the Olyor Formation (Bashlavin et al., 1986). These sediments, found in the middle part of the basin (150°00′E, 71°00′N) (Fig. 1), consist of interbedded alluvial sands and silt with layers of clay and lenses of gravel. The thickness of the sediment is 8 m. Mammal remains from the Olyor faunal complex were found in debris at the bottom of the outcrops. These remains included

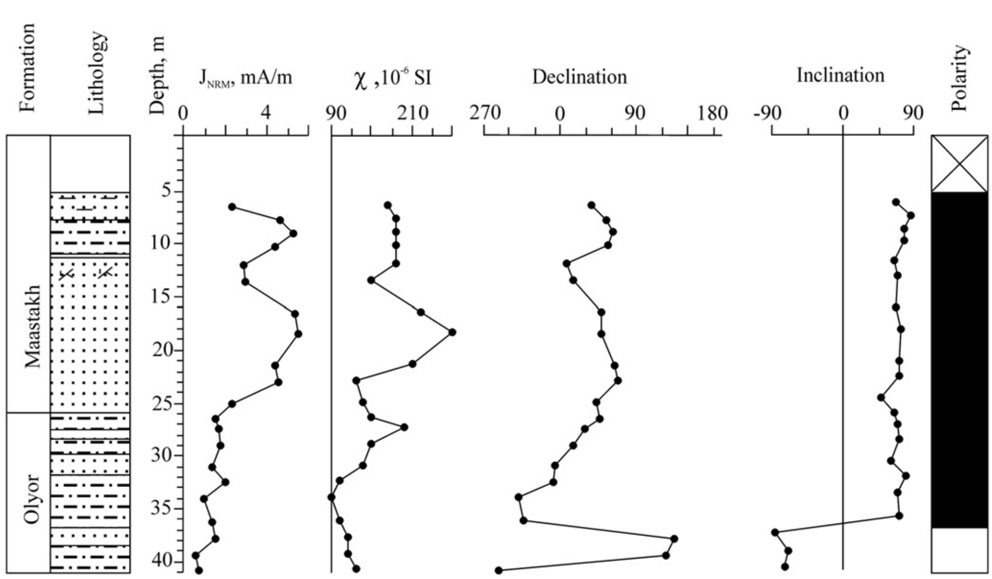

Fig. 9. Magnetostratigraphy of P-182 section.

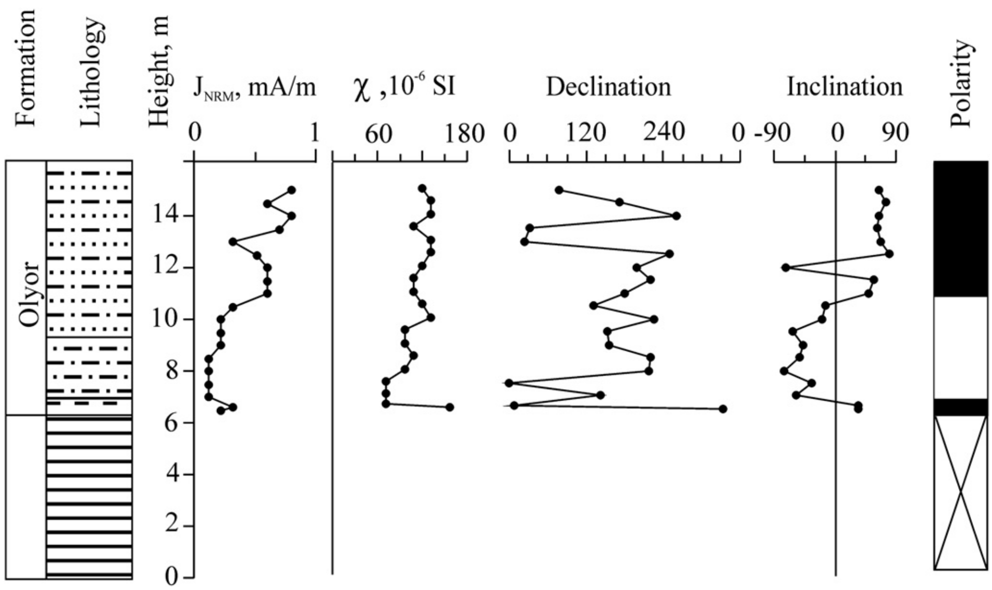

Fig. 10. Magnetostratigraphy of Ogorokha-2 section.

Equus (*Plesippus)* cf. *verae* Sher, *E.* (*Plesippus)* sp., *Ovibovini* (cf. *Praeovibos*), *Mammuthus* sp. (archaic form), and *Rangifer tarandus* L. The Brunhes-Matuyama boundary was established at 2 m above the bottom of the section 2. A sharp climate warming is associated with this boundary. Above this boundary, the palynological content of the sediments is up to 46% trees and shrubs, up to 40% herbs, and 13% spores. Pollen spectra below the boundary are dominated by herbs (up to 60%), with 25% spores, and 14% arboreal pollen (Bashlavin et al., 1986).

4.2.7. Kolyma River basin

In the Kolyma basin the Olyor sediments were studied along the Krestovka, Popovka (site 309) and Slezovka (B-24 section) tributaries (Fig. 1).

The Olyor Formation in the Krestovka River valley is divided into upper and lower parts (157°28.0′E, 68°00′N). The sediments consist of silt and fine-grained sand with layers of peat and lenses of gravel. The upper portion of the formation has yielded a mammal fauna with *Dicrostonyx renidens* Zazh., *Lemmus* cf. *obensis* Brants, *Clethrionomys* ex gr. *rutilus* Pall., *Microtus* (*Microtus*) sp., *Arctelephas* sp., *Equus* (*Plesippus*) sp., and *Equus* sp., whereas the lower part of the formation includes *Lepus* sp., *Ochotona* sp., *P. compitalis* Zazh., *Lemmus* cf. *obensis* Brants, *Allophaiomys* cf. *pliocaenicus* Korm., *Clethrionomys* ex gr. *rutilus* Pall., *Gulo* cf. *schlosseri* Korm., *Arctelephas* sp., *Equus* (*Plesippus*) *verae* Sher, *Equus* sp., *Cervalces* sp., *Rangifer* sp., *P. beringiensis* Sher, *P.* cf. *priscus* Staud., *Ovibovini* gen., and *Bison* sp. (Sher et al., 1977; Shilo, 1987). *Larix* and arboreal *Betula* pollen dominate in the upper part of the formation. Pollen data from the lower part of the formation represents hypoarctic tundra, with isolated stands of *Betula* and *Larix*, and Poaceae-Chenopodiacaea tundra. The Brunhes-Matuyama boundary at this site is situated in the upper part of the Olyor Formation (Sher et al., 1977).

In the Slezovka River valley, the Olyor Formation is exposed in section B-24 (153°00′E, 66°59.5′N) where it overlies Early Pliocene sediments of the Begunovka (bg) Formation. Sediments from the Late Pleistocene Ice Complex cover the Olyor deposits (Minyuk, 2004). These sediments are composed of silt and sandy silt (thickness ~13 m) and are predominantly of reversed polarity (Matuyama chron) with normal polarity in the middle part (depth 4.5–9.5 m) that correlates with the Jaramillo subchron (Fig. 11).

In the Popovka River (left tributary of the Kolyma River) basin, 14 km downstream from the mouth of Belaya Noch creek (151°42.0′E, 64°42.0′N), brownish-gray, gray, compacted, massive silts containing humus were found under Ice Complex deposits (section 309). The thickness of the sediments is 16 m. According to the structure and composition of the section, these deposits are similar to the Olyor Formation. They overlay Pliocene sediments represented by brownish silts with lenses of coarse gravel and by compact greenish-brown silts with erratic pebbles and charred wood. The Olyor sediments display mostly normal polarity. In the lowest part of the sequence, a change in polarity occurred, characterized by a gradual shallowing of the inclinations with the transition to the opposite direction. This portion of the section is assumed to include the Brunhes-Matuyama transition (Fig. 12).

4.2.8. Adycha River basin

The Adycha beds have been assigned to the Middle Pleistocene. Originally, these beds were defined by Biske (1978) in the bottom of the fourth terrace of the Adycha River (Fig. 1) near Betenkes village. These beds are overlain by the Ulakhan-Sular Formation of the Late Pleistocene (Kaplina et al., 1983). Magnetostratigraphic samples were taken from four sites within the Ulakhan-Sular section on the right bank of the Adycha River. Alluvial facies of different lithologies characterize these beds. Paleomagnetic samples were taken from four sites located along the outcrop. At site 2, the Adycha beds consist of detrital material with sandy–silty matrix and layers of sand and silt. The thickness of the sediments at the studied section is 2.6 m.

In site 3, 260 m from site 2, the lower part of the beds consists of yellow-grayish sands with subhorizontal laminae. They are overlain by sands, silts and clays having planar and trough cross-bedding. The sediment includes plant macrofossils (e.g., wood fragments and branches) and pebbles. The top of the beds is 8 m above river level.

In site 7, 500 m from site 3, the lower portions of the beds consist of pebbles overlain by silts. In site 4, 1760 m from site 7, Adycha beds contain silt-sandy material.

Based on their lithology and stratigraphic positions these sediments belong to the same unit, which is overlain by the Middle-Late Pleistocene Ulakhan-Sular Formation characterized by yellow–gray sands.

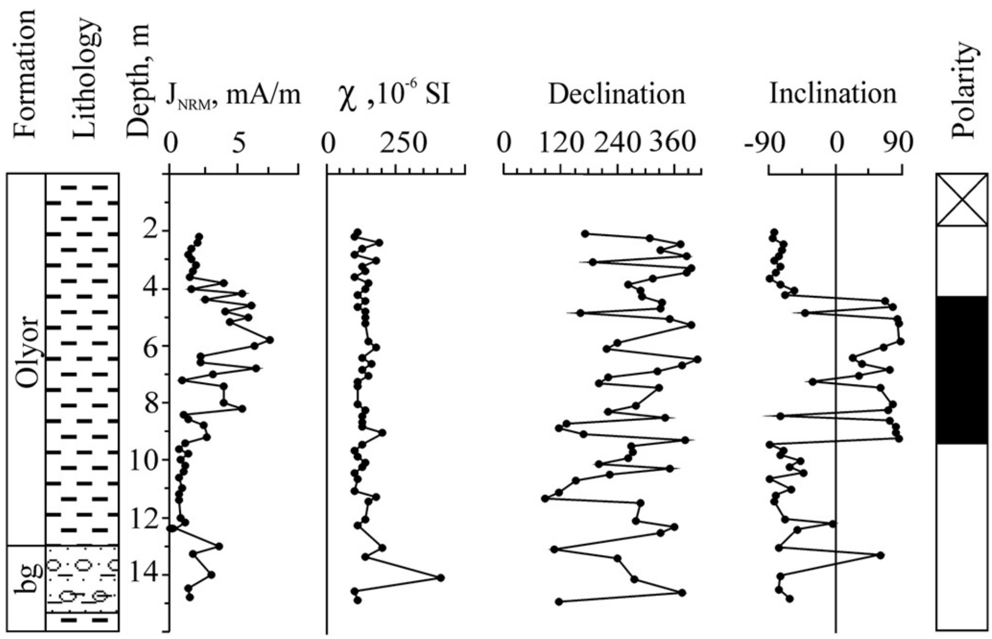

Fig. 11. Magnetostratigraphy of B-24 section.

The correlation between sites is unknown.

Archidiskodon cf. *wusti* Pawl., *Archidiskodon* (aut) *Mammuthus* sp., *Equus* (*Plesippus*) sp., *E.* ex gr. *mosbachensis* Reich., *Soergelia* sp., and *A. latifrons* mammal fossils have been recovered from the Adycha beds (Kaplina et al., 1983). As a whole, this fauna is younger than Olyor-type fauna from the Bolshaya Chukochya River. Sediments that include the Adycha fauna belong to the Middle Pleistocene (Sher, 1984). The Adycha sediments have normal polarity and are correlated with the Brunhes chron. Magnetic properties and paleomagnetic directions are shown in Table 1.

General correlations of Pleistocene sediments from Northern Yakutia are shown in Fig. 13.

4.3. Chukotka

In Chukotka (Fig. 1), Quaternary deposits have been studied within the Chaun and Valkaray depressions.

4.3.1. Chaun depression

Early-Middle Pleistocene deposits are widespread in the western part of the depression, where they are named the Elhkakvun Formation. The type section for this formation is found between 8 and 23 m depth in mine 172 (Kyshtymov et al., 1988) (Fig. 1). The mine is located on the left bank of the Elhkakvun River in the upper reaches of the left tributary, Chaanayveem, 170 km to the East of Bilibino town. The formation occurs above Early Pliocene sediments and is overlain by Late Quaternary deposits. Sediments consist mainly of pebbles with coarse gravel and gravel–sand matrix, which include lenses and layers of silt, sand, gravel, and wood debris. The pollen assemblage of the Elhkakvun sediments is characterized by relatively low percentages of arboreal pollen (10% tree *Betula*; up to 6% *Alnus*; up to 47% *Pinus* subgen. *Haploxylon*). There is a significant increase in palynomorphs of shrub *Betula* (up to 47%), *Alnus* (15%), *Bryales* (10– 15%), and Poaceae (10–25%). Representatives of thermophilic and dark-coniferous species are very low (Kyshtymov et al.,

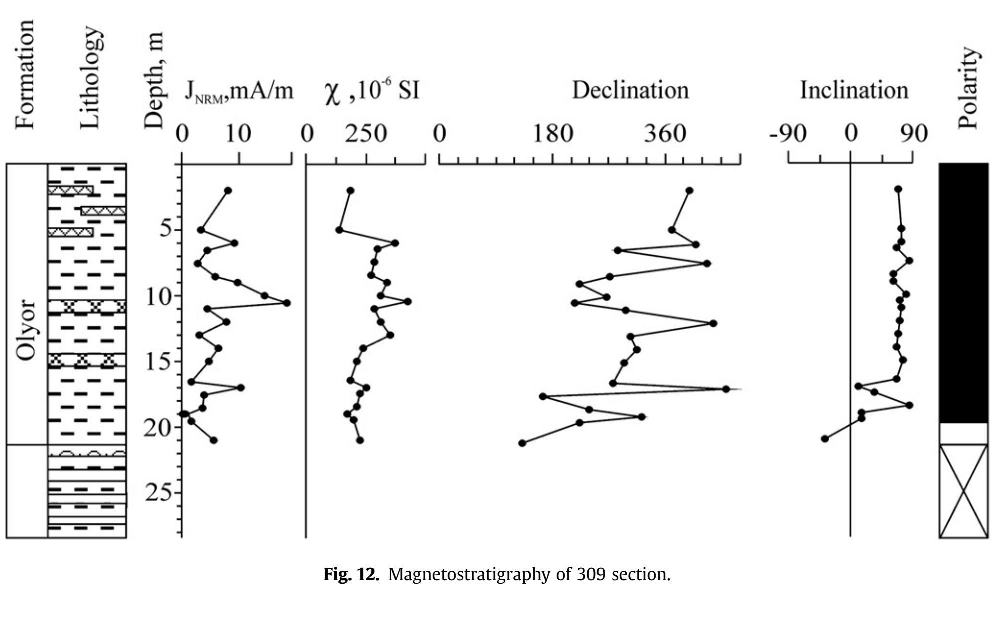

Fig. 12. Magnetostratigraphy of 309 section.

Table 1
Paleomagnetic data from Adycha sediments.

Sections	N[a]	J_{NRM}[b], mA/m	χ[c], 10^{-6} SI	D_c[d]	I_c[e]	K[f]	α_{95}[g]
2	4	1.0–7.7 (2.4)	75–112 (84)	27	76	39	14.8
3	20	0.4–6.1 (2.9)	62–132 (112)	30	74	74	3.8
4	13	1.2–7.2 (3.2)	112–132 (112)	23	69	78	4.7
7	4	3.0–10.5 (7.4)	132	32	72	241	5.9

[a] N = number samples.
[b] I_{NRM} = Intensity of natural remanent magnetization, in bracket is mean value.
[c] χ = magnetic susceptibility, in bracket is mean value.
[d] D_c = Magnetic declination of characteristic remanent magnetization, mean value.
[e] I_c = Magnetic inclination of characteristic remanent magnetization, mean value.
[f] K = Fisher precision parameter.
[g] α_{95} = Circle of 95% confidence.

1988). The Elhkakvun sediments reveal mainly normal polarity in the upper part of the formation from 8 to 18.5 m depth. The lower part of the formation (depth 18.5–20.0 m) has reversed polarity (Minyuk, 2004). This change in polarity apparently corresponds to the Brunhes-Matuyama boundary (Figs. 14, 15).

Early Pleistocene deposits were also studied in borehole section 10 (depth 15.0–37.5 m), drilled in the lower reaches of the Paltitka River (Fig. 1). These sediments overlay the Pliocene Bezymyany Creek Formation. At the base of the section, the deposits consist of gray sand with gravel and pebbles, which are replaced by gray to dark gray sandy silt, often with peat. The pollen assemblage from these deposits is characterized by dominant angiosperm pollen (56.9–81.2%) with lesser numbers of spores (13.5–42.4%) and gymnosperm pollen (0.6–5.3%). Trace amounts of tree *Betula* (0.2–1.9%) and *Alnus* (up to 0.6%) pollen are present. Percentages of shrub pollen of these taxa are also low. Herb pollen percentages are significant (Poaceae – up to 42.5%, Cyperaceae, Ranunculaceae, etc.). The most abundant gymnosperm taxon is *Pinus* subgen. *Haploxylon* (0.3–5.2%), with lesser quantities of *Pinus* subgen. *Diploxylon*, *Picea* sect. *Eupicea*, *Tsuga* sp., and *Larix* sp. *Bryales* (up to 39.9%) are the most abundant spore type. According to Belaya (1988), this assemblage indicates an Early Pleistocene vegetation of graminoid marshes, shrub tundra with scattered stands of *Larix*, and coniferous woodland. Sediments of borehole 12 have reversed polarity and correlate with the Matuyama chron (Fig. 15).

4.3.2. Valkaray depression

Sediments demarcating the Early and Middle Pleistocene boundary in the Valkaray depression are assigned to the Enmakay Formation that was first studied by V.L. Sukhoroslov (Biske, 1982). The formation is found near the mouth of the Ryveem River (Fig. 1). As a rule, Enmakay deposits are buried and located at absolute elevations of 0 to −25 m. They consist of fine-grained sands and silts with a bluish-gray color. The thickness of the formation is 10–15 m. The Enmakay Formation overlays pebbles of the Ryveem Formation of Miocene age or Paleozoic rocks. Several outcrops of Enmakay deposits are exposed on Enmakay Cape.

A diverse foraminifera complex, including warm-water boreal and southern boreal species, was identified from sediments in this formation. The assemblage includes extinct taxa, *Elphidiella quasioregonensis*, *Elphidiella hannai*, *Elphidiella nitida*, *Elphidiella alaskensis*, *Elphidiella rolfi*, *Elphidiella umbonata*, *Sigmomorphina sawanensis*, and *Ozawaia* sp. This foraminifera complex has no analogues in sediments of northern Russia, but it has similarities to the Anvil layers of Alaska (Gubina et al., 1984). The Enmakay sediments have yielded abundant diatoms (more than 200 taxa), including marine, brackish-water, and freshwater forms (Polyakova, 1997). A more ancient complex of diatoms with equal representation of modern and extinct species is characteristic of the lower layers of the formation. This material was found in bore holes near the modern shoreline. This complex is comparable with faunal zones *Neodenticula koizumii* – *Neodenticula kamtschatica* and *N. koizumii* of the North Pacific timescale. The second set of diatoms is correlated with zones of *Actinocyclus aculatus* and *Simonseniella curvirostris*. It contains important biostratigraphic markers, such as *Simonseniella barboi*, *Simonseniella curvirostris*, and *Simonseniella matuyamae*, which are prevalent in the age range of 1.6–0.3 Ma (Polyakova, 1997).

The mollusk fauna from the Enmakay Formation includes marine arctoboreal and boreal taxa: *Astarte borealis borealis* (Schum.), *A. borealis placenta* Morch., *A. elliptica* (Brown), *A. montagui striata* Leach, *A. montagui fabula* (Reeve), *Macoma incongrua* (Mart.), *Macoma calcarea* (Gmelin), *Macoma moesta* (Deshayes), *Hiatella arctica* (Linne), *Cyclocardia ventricosa ovata* (Rjabinina), *Ciliatocardium* cf. *ciliatum* (Fabr.), *Mya truncata truncata* Linne, *Mya Pseudoarenaris* Schlesch., *Spisula voyi* (Gabb.), *Serripes groenlandicus* Chemn., *Nucula pernula* (Miller), *Liocyma fluctuosa* (Gould), *Yoldiella intermedia* (Sars), *Axinopsida orbiculata* (Sars), *Neptunea lyrata* (Gmelin), *Buccinum glaciale* Linne, and *Boreotrophon clathratus* (Linne) (Sukhoroslov and Minyuk, 1982; Shilo, 1987).

The pollen assemblage includes shrub *Betula*, *Alnaster*, Poaceae, *Bryales*, tree *Betula*, *Alnus* sp., Cyperaceae, *Sphagnum*, *Pinus* subgen

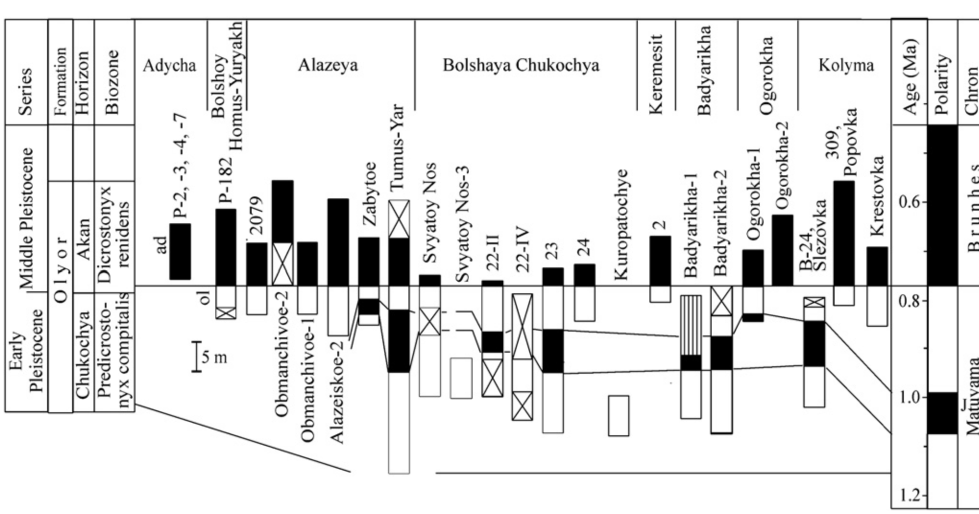

Fig. 13. Correlation of boundary Lower-Middle Pleistocene sediment of Northern Yakutia. J – Jaramillo, ol – Olyor Formation, ad – Adycha beds. Vertical bars for Badyarikha-1 section represent anomalous directions caused by permafrost.

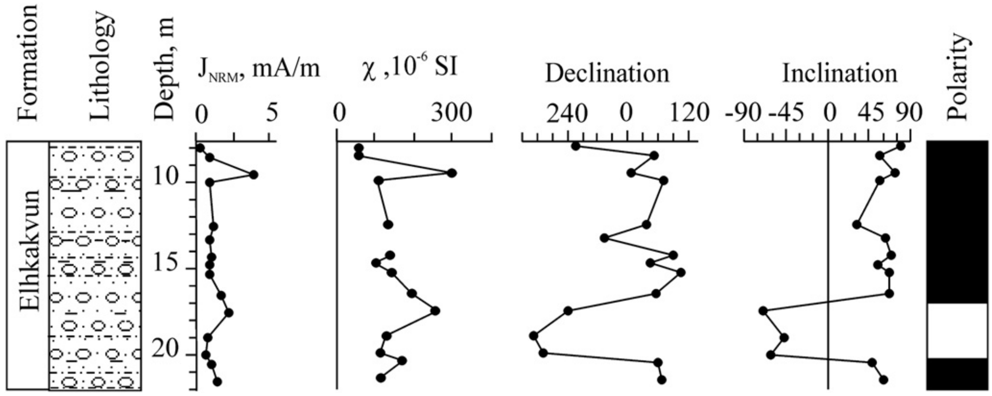

Fig. 14. Magnetostratigraphy of mine 172 section.

Haploxylon, *Picea* sect. *Eupicea* sect *Omorica*, and *Larix*. The data suggest the presence of forest–tundra (Shilo, 1987).

Paleomagnetic study of the Enmakay deposits was done on the coastal site 267 (1.5 km to the west of Enmakay Cape) and in mines 206, 151, 255 and quarry 15. The deposits have homogeneous magnetic characteristics. Sites 15, 255 and 267 display normal magnetization in their upper stratigraphic layers and reversed polarity in the bottom (Fig. 13). Polarity changes in these sections are identified with the Brunhes-Matuyama boundary. Reversed magnetization characterizes most deposits exposed in mine 151 and 206. A zone of normal polarity, which is associated with the Jaramillo subchron, occurs in the middle part of the section (Fig. 15).

4.4. Magadan region

Boundary sediments between the Lower and Middle Pleistocene were studied in the upper reaches of the Kolyma River in the valleys of the Berelekh, Malyk-Sien, and Burkandya rivers and their tributaries (Figs. 1, 16). These deposits belong to the Belichan layers (horizon) (Shilo, 1987), whose type section is located at the bottom of the Quaternary sequence in mine 40. Paleomagnetic studies of Quaternary sediments were conducted on 11 sections from the upper Kolyma River (Minyuk, 2004).

4.4.1. Mine 40, 30-m terrace of Berelekh River

Mine 40 is located in the Berelekh valley between Poludennyi and Belichan Creeks. Sediments of interest are from a buried 30-m alluvial terrace consisting of gray sand, loam, and sandy loam with pebbles and gravel. The thickness of the alluvial deposits is 13.5 m.

Pollen spectra from the Belichan layer contain *Betula* sect. *Albae*, *B. middendorffii*, *Pinus* sect. *Cembrae*, *P.* cf. *pumila*, *Larix*, *Alnus*, *Picea* sect. *Eupicea*, *Quercus*, *Ulmus*, *Tilia*, *Picea* sect. *Omorica*, *Abies*, *Sphagnum*, *Bryales*, Polypodiaceae, *Selaginella sibirica*, *Selaginella sanguinolenta*, *Cryptogramma stellerii*, Cyperaceae, Poaceae, *Ericales*, *Rhododendron*, *Ephedra*, Chenopodiaceae, and *Artemisia* (Shilo, 1987). Spectra indicate the establishment of mixed forests of birch with larch or alder forest with birch and occasional lime, oak, elm, and hazel (Voskresensky et al., 1984).

The Quaternary section of mine 40 was sampled from three horizons. Samples were labelled as 71, 311 and 312. Samples 311 and 312 were taken from the bottom layers of the Belichan horizon. Magnetic properties are shown in Table 2. Samples taken from the bottom of section 71, 311, and 312 have reversed magnetization. In the uppermost part of section 71 (height of 8 m from the base of the alluvium) one sample has normal polarity (Table 2). It is possible that this change in polarity corresponds to the Brunhes-Matuyama boundary (Fig. 15).

4.4.2. Section 313, 30–35-m terrace of Berelekh River

The section, consisting of alluvium of the 30–35 m terrace, is located in the Berelekh basin between Kuranah and Sosed Creeks. The upper part of the alluvial deposits was sampled for paleomagnetic studies. The sediments consist of sand, clay–sand, and silt. The magnetostratigraphy of this section is very similar to that

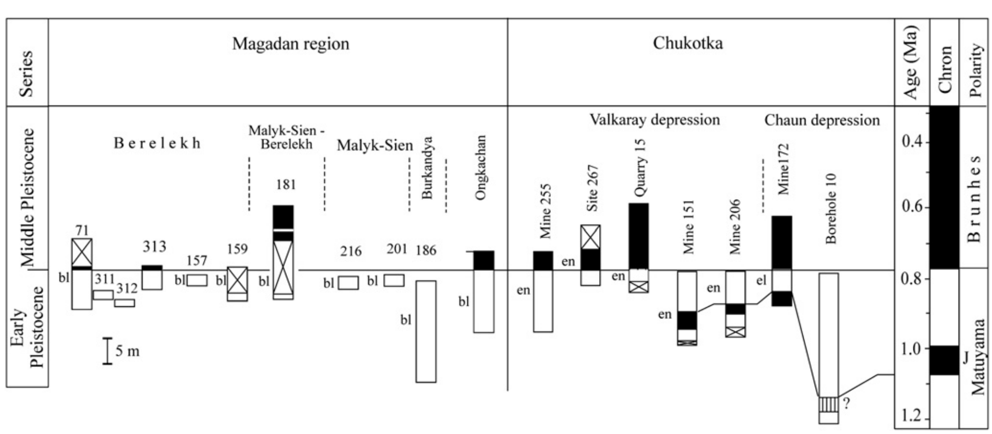

Fig. 15. Correlation of Lower-Middle Pleistocene sediments of Chukotka and the Magadan region. J – Jaramillo; bl – sediment of Belichan horizon; en – Enmakay Formation; el – Elhkakvun Formation.

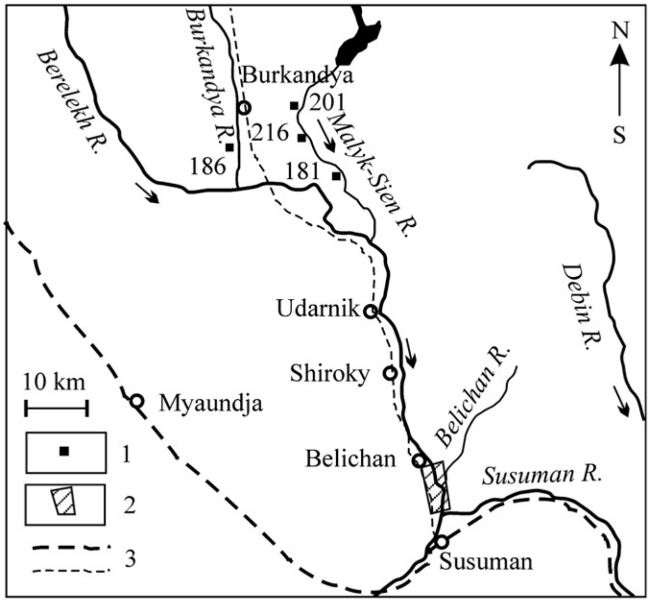

Fig. 16. Map showing the locations of studied sections in Magadan region: (1) = mines; (2) = sections 71, 311, 312, 313, 157, 159;(3) = roads.

of Mine 40. All samples except one top sample show reversed polarity (Table 3).

4.4.3. Section 157, 25–30-m terrace of Berelekh River

This section is located in the Berelekh valley near the mouth of Poludennyi Creek and is composed of alluvium, which forms the 25–30-m terrace. Only the upper part of the section, including sand and clay–sand, was sampled for paleomagnetics. The magnetic property of these samples does not differ from those described above for Section 313. After demagnetization, all samples show reversed polarity (Table 3) and correlate to the Matuyama chron (Fig. 15).

4.4.4. Section 159, 35–40-m terrace of Berelekh River

This section is also in the Berelekh valley, 0.8 km downstream from Poludennyi Creek. The sediments are predominantly alluvial sand with thin layers of silt and silty sand. Magnetic characteristics of the collected samples from this section are similar to ones from section 157. They were formed during reversed polarity in the magnetic field (Table 3).

Table 2
Paleomagnetic data of sediments from the 30-m terrace, Berelekh River, mine 40.

Sample	Height, m	χ[a], 10^{-6} SI	J_{NRM}[b], mA/m	D_{NRM}[c]	I_{NRM}[d]	D_c[e]	I_c[f]
71-6	8.0	75	0.7	245	73	210	80
71-8	3.5	62	2.7	149	−63	137	−74
71-9	1.0	175	24.0	142	−72	120	−82
71-10	0.3	137	16.7	172	−62	135	−86
311-1	2.1	87	2.1	333	−82	90	−85
311-2	1.9	50	0.4	131	−43	161	−59
311-3	1.7	50	0.7	205	−56	219	−67
311-4	1.5	37	0.1	304	−66	197	−64
311-5	1.3	37	0.2	135	−86	161	−36
312-1	0.9	1362	442.4	217	−65	214	−68
312-2	0.7	188	15.8	225	−74	212	−71
312-3	0.5	212	13.9	191	−53	210	−51
312-4	0.3	463	94.7	303	−47	302	−61

[a] χ = Magnetic susceptibility.
[b] J_{NRM} = Intensity of natural remanent magnetization.
[c] D_{NRM} = Declination of natural remanent magnetization.
[d] I_{NRM} = Inclination of natural remanent magnetization.
[e] D_c = Magnetic declination of characteristic remanent magnetization.
[f] I_c = Magnetic inclination of characteristic remanent magnetization.

4.4.5. Mine 181

Mine 181 is located between the Malyk-Sien and Berelekh rivers in the middle part of Valunny Creek. The stratigraphic sequence from bottom to top is: 1) bedrock; 2) alluvium with boulders, gravel, and sand with layers and lenses of loam, silt and sand (thickness 9.4 m); 3) glacio-lacustrine facies composed of clays and fine-grained sands (thickness 4.7 m); 4) glacio-fluvio gravel (thickness 10.7 m); and 5) lacustrine-swamp, and slope facies composed of clay, sandy loam, loam, silt, and peat (thickness 9.3 m).

According to the data of T.P. Prokhorova (pers. comm.), the pollen assemblage from the alluvium is dominated by trees and shrubs (up to 59%), including *Pinus* subgen *Haploxylon*, *P.* subgen *Diploxilon*, *P.* cf. *silvestris*, *Picea* sect. *Eupicea*, *Larix*, *Betula* sect *Albae*, *B.* sect. *Costatae*, *B.* sect. *Nanae*, *Alnus*, *Alnaster*, *Salix*, and *Myrica*. Cyperaceae is the most common herb (18.8–36.3%). Spores (15.2–28.0%) consist of *Sphagnum*, *S. sanguinolenta*, *Polypodium vulgaris* etc. Larch forests with birch, alder, spruce, and pine were present during the accumulation of the alluvium. The pollen spectra represent a warm stage at the beginning of the Middle Pleistocene or the end of the Early Pleistocene. The pollen complex from the overlying sediments indicates cold-climate vegetation.

After demagnetization, the samples from the alluvial deposits (samples 181-1/) show reversed polarity, whereas glacio-lacustrine sediments (sample 181) have normal polarity (Table 3). Polarity changes may correspond to the Brunhes-Matuyama boundary.

4.4.6. Mine 216

Mine 216 is located on Poteryany Creek in the valley of Malyk-Sien River where buried alluvium forms the 15–17-m terrace. These deposits consist of gravel-pebble sediments with layers and lenses of sand, gravel, sandy loam, loam, and silt. The thickness of the alluvium is 2.3 m. It is overlain by slope deposits with boulders and layers of sand and clay, with a thickness of 40 m. According to T.P. Prokhorova (pers. comm.), this alluvium accumulated during a warm epoch at the beginning of the Middle Pleistocene or the end of the Early Pleistocene. The vegetation was light-coniferous, larch and birch forests with the presence of hazel, *Myrica*, waxmyrtle, diploid pines and spruces. Alluvial deposits within the mine have been sampled from two horizons. All samples show reversed polarity (Table 3) and correlate to the Matuyama chron (Fig. 15).

4.4.7. Mine 201

Mine 201 is located in the valley of the Malyk-Sien River. Here overlying basement rocks is a buried 6–8-m terrace with a thin (2 m) layer of alluvial deposits that consist of gravel and boulders with lenses of gray silty sand. Glacio-fluvio sandy loam with pebbles, boulders and detritus are found above the alluvium. Their thickness is ~60 m. The alluvial palynological complexes according to T.P. Prokhorova (pers. comm.) are identical to those of mine sections 216 and 181. Paleomagnetic investigations sampled only the alluvial deposits. All samples display reversed polarity (Matuyama chron) (Table 3).

4.4.8. Mine 186

The mine is located on the right bank of the Burkandya River near the mouth of Sagyl-Kurun Creek. Alluvial sediments (thickness 42 m) are composed of sand, clay, loam silt with pebbles and boulders which overlay Mesozoic-age rocks. The samples for paleomagnetic analysis were taken from 5 levels within the section and show reversed polarity.

Table 3
Paleomagnetic data of sediments, upper Kolyma region.

Sample	Depth, m	χ[a], 10^{-6} SI	J_{NRM}[b], mA/m	D_{NRM}[c]	I_{NRM}[d]	D_c[e]	I_c[f]
Section 313, 30–35-m terrace of Berelekh							
313-1	0.4	50	0.4	344	72	5	70
313-2	0.9	25	0.2	45	78	171	−34
313-3	1.3	38	0.3	360	28	201	−43
313-4	1.5	38	0.2	294	−24	206	−80
313-5	1.7	50	0.4	337	72	214	−70
313-6	1.9	75	1.7	24	1	238	−6
313-7	2.1	50	0.3	233	−34	196	−56
313-8	2.7	50	0.5	127	−72	163	−58
313-9	2.9	5	0.7	351	−56	328	−72
313-10	3.1	75	0.3	356	15	342	−60
313-11	3.3	75	0.6	70	−54	127	−75
313-12	3.5	88	0.5	1	−69	206	−84
313-13	3.7	50	0.2	21	20	2	−12
Section 157, 25–30-m terrace of Berelekh							
157-1	0.1	50	0.6	204	−70	160	−60
157-2	0.4	100	2.5	347	47	80	−51
157-3	1.6	50	0.7	58	−58	248	−84
157-4	1.9	50	0.7	225	−81	214	−68
Section 159, 35–40-m terrace of Berelekh							
159-6	5.1	50	0.3	248	−74	201	−76
159-5	5.4	50	0.5	68	−20	246	−56
159-4	5.7	50	0.9	62	−13	90	−56
159-3	6.0	63	1.2	71	3	130	−67
159-2	6.3	50	1.8	62	−3	107	−45
Mine 181							
181-6	20.7	88	2.4	77	60	73	55
181-5	22.5	125	1.8	219	74	322	85
181-4	24.0	213	11.6	142	38	124	40
181-3	25.0	238	9.7	112	−44	108	−42
181-2	25.8	212	7.3	360	76	6	77
181-1/4	37.4	112	0.7	168	−58	168	−58
181-1/3	37.3	112	0.3	222	−64	222	−64
181-1/2	37.2	100	0.5	231	−65	180	−51
181-1/1	37.1	88	0.3	242	−75	188	−60
Mine 216							
216-2в	43.5	112	0.4	152	−46	149	−63
216-2e	42.0	100	0.5	166	−65	188	−79
216-2/1	43.2	138	0.9	276	−64	277	−72
Mine 201							
201-1/1	68.0	5425	301	48	−56	69	−53
201-1/2	68.2	3775	204	56	−43	313	−58
201-2	68.5	1250	115	57	−45	59	−50
201-3	69.0	5400	163	341	−38	342	−70
201-4	69.5	412	306	89	−84	2	−84
201-5	70.0	5150	244	184	−64	205	−56
Mine 186							
186-56	19.0	100	0.3	332	−9	315	−11
186-55	28.0	125	0.5	146	−70	220	−72
186-54	37.2	150	2.2	262	−70	266	−71
186-53	37.4	750	0.5	260	−75	290	−71
186-52	37.6	100	0.9	178	−52	167	−58

[a] χ = Magnetic susceptibility.
[b] J_{NRM} = Intensity of natural remanent magnetization.
[c] D_{NRM} = Declination of natural remanent magnetization.
[d] I_{NRM} = Inclination of natural remanent magnetization.
[e] D_c = Magnetic declination of characteristic remanent magnetization.
[f] I_c = Magnetic inclination of characteristic remanent magnetization.

4.4.9. Ongkachan section

This section is located on the Ongkachan River (156°52.0′E, 69°27.3′N), a right tributary to the Hinike River (Khvorostova et al., 1968). The stratigraphic sequence from top to bottom is: 1) gray silty clay, loam (3.6 m); 2) brown gravel, pebble (24 m); 3) gray loam (0.9 m); 4) yellowish-brown gravels, pebbles (9 m); 5) conglomerates (10 m); and 6) compacted clay and sand (4.9 m).

The pollen assemblages in the lower part of the section (bed 6) are dominated by trees and shrubs (>60%). Herb pollen is 4–22.3%, and spores are 24.4–35.2%. Climate during this period was warmer than today (Khvorostova et al., 1968). These sediments correlated with the Belichan horizon (Voskresensky et al., 1984). Palynological spectra from beds 3–5 are dominated by herbs and spores, with 18.2–35.5% arboreal pollen. The Brunhes-Matuyama boundary was found in unit 5 (Fig. 17).

5. Discussion and summary

Data on the stratigraphic placement of the Brunhes-Matuyama boundary are important for the correlation of sediments from disparate sites and for the reconstruction of latitudinal climatic zones during the Early-Middle Pleistocene. Modern Western Beringia encompasses a variety of vegetation zones (Kolosova, 1980). In central Yakutia, in the lower part of the Aldan River basin, deciduous forest grows with an understory of grass and shrubs and with isolated stands of pine forests. Grasslands, shrubs and forest typify the floodplains. The central Kolyma region is characterized by a mosaic of light-deciduous forest, shrub tundra, moss-lichen tundra, and alpine tundra. The northern coast of Chukotka is dominated by *Eriphorum vaginatum* tussock tundra. Arctic graminoid-shrub-moss, shrub-lichen tundra and northern shrub tundra with *Dryas punctata* and *Cassiope tetragona* typify the coastal areas of Eastern Yakutia.

In contrast to today, Pliocene Western Beringia supported forests of pines, larches, firs, hemlock, fir, birch, and alder (Fradkina, 1983; Giterman, 1985; Grinenko et al., 2005). Vegetation of the Early Pleistocene also differed from modern with a predominance of tundra landscapes (Biske and Baranova, 1976; Giterman, 1985; Shilo, 1987).

The Ozheleznenye Galechniki beds of Central Yakutia belong to the Talagay horizon of the Early-Middle Pleistocene (Krasnov, 1983). These layers include the classic Aldan mammal fauna (Vangengeim, 1961, 1977). During the time that these sediments were accumulating, forest dominated by spruce and birch covered much of Central Yakutia.

In Eastern Yakutia sediments of Early-Middle Pleistocene belong to the Akan horizon, and the Early Pleistocene sediments are from the Chukochya horizon (Shilo, 1987). These units belong to the Olyor Formation and its age-equivalents are found in many river basins of the coastal lowlands. This formation, is characterized by the Olyor faunal complex, includes the fauna of both large and small mammals (Sher, 1971). The early faunal assemblages in this complex (biozone *P. compitalis*) are comparable to the Tamanian fauna of Eastern Europe. The late fauna, belonging to the biozone typified by *Dicrostonyx renidens*, correlate with the Eastern European Tiraspolian fauna (Sher, 1984). Changes in faunal composition occur near the Brunhes-Matuyama boundary. Larch-birch forest-tundra and tundra established during the late Early Pleistocene–early-Middle Pleistocene in Eastern Yakutia (Krasnov, 1983; Shilo, 1987). In some sections, such as in the basins of B. Chukochya, Keremesit, Alazeya rivers, vegetation change approximately coincides with the Matuyama-Brunhes boundary (Grinenko and Zharikova, 1982; Bashlavin et al., 1986; Lvova, 1989; Grichuk, 1995).

In the upper reaches of the Kolyma River, the Brunhes-Matuyama boundary occurs in sediments of the Middle Pleistocene Belichan horizon. During the accumulation of the Belichan layers birch forests were very diverse and included mixtures of broadleaf and conifer species, alder (Shilo, 1987; Voskresensky et al., 1984). The occurrence of numerous birch taxa is also characteristic of Olyor floras (Grichuk, 1995). Major restructuring of the vegetation in this area took place before the Brunhes-Matuyama inversion. Dark-coniferous forest dominated by spruce and cedar pine (*Pinus sibirica*), with larch and pine forests once again became established at the end of the Matuyama epoch (Davidovich, 1985).

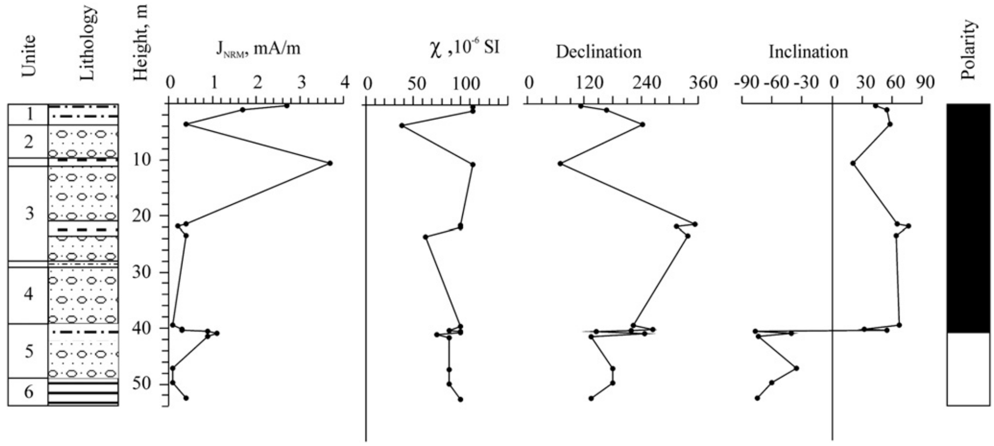

Fig. 17. Magnetostratigraphy of Ongkachan section.

The Brunhes-Matuyama boundary is a characteristic event horizon in the Elhkakvun and Enmakay formations of Chukotka. The latter deposits typically contain marine facies, which in the upper part include a diatom assemblage that correlates with diatom zones of *A. aculatus* and *S. curvirostris* (Polyakova, 1997). In the diatom zonal time scales of the northern Pacific, the Brunhes-Matuyama reversal takes place at the base of the *S. curvirostris* zone (Gladenkov, 2001). Palynological data from Enmakay sediments indicate the presence of forest-tundra woodlands (Shilo, 1987), whereas the vegetation inferred for the Elhkakvun Formation was graminoid marshes, shrub tundra with scattered stands of larch and coniferous woodlands (Belaya, 1988).

In Kamchatka, the Brunhes-Matuyama boundary is evident in volcanic sequences (Shantser, 1982a,b; Braitseva et al., 1984; Minyuk, 2004). In the eastern part of the peninsula, this boundary is located in the Tumrok or Iult volcanic complex and in Central Kamchatka in the Kreruk volcanic complex.

Thus, the Brunhes-Matuyama boundary is a powerful instrument for correlating different facies from diverse paleogeographic regions, for defining the boundary between the Lower and Middle Pleistocene, and for estimating times of change in faunal evolution, particularly as relates to the mammoth fauna (Lister et al., 2005). In terms of lithology, the best sections for detailed study of the Matuyama-Brunhes transition are located in Northern Yakutiya.

Acknowledgements

We thank Patricia Anderson for help with the English and with Anatoly Lozhkin for helpful discussions.

References

Alekseev, M.N., Giterman, R.E., Grinenko, O.V., Kamaletdinov, V.A., Katasonov, E.M., Kolpakov, V.V., Liskun, I.G., Minyuk, P.S., Sokolovskaya, V.T., Fradkina, A.F., Shofman, I.L., 1982. XI Congress INQUA, 1982. Guidebook for Excursion A-14. Middle Lena River, Yakutsk Vicinity. VINITI Press, Moscow.

Alekseev, M.N., Grinenko, O.V., Kamaletdinov, V.A., Fradkina, A.F., 1984. Cenozoic deposits of the Lena and Aldan rivers. In: Trofimuk, A.A., Alekseev, M.N., Bilanenko, V.A., Dagys, A.S., Moralev, V.M., Khomentovsky, V.V., Shherbov, B.L. (Eds.), Guidebook for Excursions on the Siberian Platform. Excursions 052, 053, 054, 055. 27th International Geological Congress, USSR, Moscow, 1984. Institute Geology and Geophysics Press, Novosibirsk, pp. 152–173.

Baksi, A., Hsu, V., McWilliams, M., Farrar, E., 1992. $^{40}Ar/^{39}Ar$ dating of the Brunhes-Matuyama geomagnetic field reversal. Science 256, 356–357.

Bashlavin, D.K., Zhigultseva, S.N., Ovander, M.G., 1986. Pliocene–Pleistocene sediments in the eastern part of the Yana-Indigirka lowland. Izvestiya Akademii Nauk SSSR. Seriya Geologicheskaya (Proceedings of the USSR Academy of Sciences ser Geol.) 10, 130–135 (in Russian).

Belaya, B.V., 1988. Neogene of the Chaun depression on palynological data. In: Volobueva, V.I. (Ed.), Neogene and Paleogene Continental Sediments of North-East of the USSR. V. 3. Chukotka. NEISRI FEB RAS Press, Magadan, pp. 40–57 (in Russian).

Biske, F.S., 1978. Quaternary Sediments of the Far North-East. Nauka Press, Novosibirsk (in Russian).

Biske, S.F., 1982. Enmakay formation. In: Vereschagin, V.N., Rostovtsev, K.O., Zhamoida, A.I., Kovalevsky, O.P., Kotlyar, G.V., Mironova, L.V., Prozorovskaya, E.L., Latysheva, E.V. (Eds.), Stratigraphic Dictionary of the USSR, Paleogene, Neogene, Quaternary. Nedra Press, Leningrad, p. 497 (in Russian).

Biske, S.F., Baranova, Yu. P., 1976. Main paleogeographic features of Beringia in the pre-Quaternary Cenozoic. In: Kontrimavichus, V.L. (Ed.), Beringia in Cenozoic. DVNTS AN SSSR Press, Vladivostok, pp. 121–128 (in Russian).

Borisov, B.A., 2007. Further improvement of the general stratigraphic scale. In: Lavrushin, Yu.A., Khoreva, I.M., Chistyakova, I.A. (Eds.), Basic Problem of Quaternary: Results and Future Studies. Proceeding of All-Russian Quaternary Meeting, Moscow, 7–9, November, 2007. Geos Press, Moscow, pp. 49–51 (in Russian).

Braitseva, O.A., Ganeshin, G.S., Shantser, A.E., 1984. Kamchatka. In: Krasnov, I.I. (Ed.), Stratigraphy of USSA, Quaternary System, V. 2. Nedra Press, Moscow, pp. 437–447 (in Russian).

Carlut, J., Quidelleur, X., Courtillot, V., Boudon, G., 2000. Paleomagnetic directions and K/Ar dating of 0 to 1 Ma lava flows from La Guadeloupe Island (French West Indies): implications for time-averaged field models. Journal of Geophysical Research 105, 835–849.

Channell, J.E.T., Curtis, J.H., Flower, B.P., 2004. The Matuyama-Brunhes boundary interval (500–900 ka) in North Atlantic drift sediments. Geophysical Journal International 158, 489–505.

Coe, R.S., Singer, B.S., Pringle, M.S., Zhao, X., 2004. Matuyama-Brunhes reversal and Kamikatsura event on Maui: paleomagnetic directions and $^{40}Ar/^{39}Ar$ ages. Earth and Planetary Science Letters 222, 667–684.

Davidovich, T.B., 1985. Vegetation and climate of the Upper Kolyma region during the Pliocene. PhD thesis, Novosibirsk (in Russian).

Elias, S.A., Crocker, B., 2008. The Bering Land Bridge: a moisture barrier to the dispersal of steppe–tundra biota? Quaternary Science Reviews 27, 2473–2483.

Fradkina, A.F., 1983. The Neogene Palynofloras of the North East Asia. Nauka Press, Moscow (in Russian).

Gibbard, P.L., Head, M.J., 2009. IUGS ratification of the Quaternary system/period and the Pleistocene series/Epoch with a base at 2.58 Ma. Quaternaire 20, 271–272.

Gibbard, P., Van Kolfschoten, T., 2004. The Pleistocene and Holocene epochs. In: Gradstein, F., Ogg, J., Smith, A. (Eds.), A Geological Time Scale 2004. Cambridge University Press, Cambridge, pp. 441–452.

Giterman, R.E., 1985. The History of the Vegetation of the USSR North-East in Pliocene and Pleistocene. Nauka Press, Moscow (in Russian).

Gladenkov, A. Yu., 2001. North Pacific marine Neogene diatom zonation: origination, modern state, and prospects of detail. In: Gladenkov, Yu.B., Kuznetsova, K.I. (Eds.), Toward Detailed Stratigraphic Schemes and Paleogeographic Reconstructions. GEOS Press, Moscow, pp. 85–108 (in Russian).

Grichuk, M.P., 1995. Paleobotanic evidences from Upper Cenozoic sequences of the Bolshaya Chukochya River, north-eastern Russia. In: Bychkov, Yu.M., Lozhkin, A.V. (Eds.), History of Climate and Vegetation in Beringia during the Late Cenozoic. NEISRI FEB RAS Press, Magadan, pp. 78–140 (in Russian).

Grinenko, O.V., Zharikova, A.P., 1982. Palynological complexes from Upper Cenozoic sediments of the Kolyma lowland. In: Biske, S.F. (Ed.), Quaternary Sediments of the East USSR. NEISRI FEB RAS Press, Magadan, pp. 18–19 (in Russian).

Grinenko, O.V., Kamaletdinov, V.A., Ivanenko, G.V., Sergeenko, A.I., Fradkina, A.F., Patyk-Kara, A.G., 2005. The Regional Stratigraphic Scheme Charts of the Paleogene and Neogene sediments of East of the Siberian Platform. Explanation Notes. Yakutsky Nauchny Tsentr Press, Yakutsk (in Russian).

Gubina, V.I., Lashtabeg, V.A., Levchuk, L.K., Polovova, T.P., Sukhoroslov, V.L., 1984. Pliocene–Pleistocene Boundary in the North of Chukotka. Institute of Geology and Geophysics Press, Novosibirsk (in Russian).
Horng, C.S., Lee, M.Y., Pälike, H., Wei, K.Y., Liang, W.T., Iizuka, Y., Torii, M., 2002. Astronomically calibrated ages for the geomagnetic reversals with the Matuyama chron. Earth Planets Space 54, 679–690.
Kamaletdinov, V.A., 1982. Basement relief and Quaternary cover structure in Lena-Amga interfluve. In: Grinenko, O.V., Gusev, G.S., Mikhailov, G.P., Spektor, V.B., Fradkina, A.F., Tskhurbayev, F.I. (Eds.), Geology of the Cenozoic of Yakutia. Yakutskii filial Press, Yakutsk, pp. 94–103 (in Russian).
Kaplina, T.N., Lahtina, O.V., Rybakova, N.O., 1981. Cenozoic sediments of the middle part of Alazeya river basin (Kolyma lowland). Izvestiya Akademii Nauk SSSR. Seriya Geologicheskaya (Proceedings of the USSR Academy of Sciences ser Geol.) 8, 51–63 (in Russian).
Kaplina, T.N., Kartashova, G.G., Nikitin, V.P., Shilova, G.N., 1983. New data on sand unite of Tuostakh depression. Bulleten Komissii po izucheniyu.chetvertichnogo perioda (Quaternary Commission Bulletin) 52, 107–122 (in Russian).
Khvorostova, Z.M., Smirnova, A.N., Nikitin, V.P., 1968. Quaternary sediment from Ongchag section in the upperstream of Kolyma River. Geologiya i Geophizika (Geology and Geophysics) 1, 49–57 (in Russian).
Kolosova, L.N. (Ed.), 1980. The Geographic Atlas, fourth ed. Main Administration of Geodesy and Cartography of Soviet Ministry of USSR Press, Moscow (in Russian).
Krasnov, V.I. (Ed.), 1983. Resolutions of All-Union Stratigraphic Conference on the Precambrian, Paleozoic and Quaternary of the Middle Siberia (Novosibirsk, 1979). Part 3. Quaternary. Explanation Notes to Stratigraphic Charts of Quaternary. SNIIGGMS Press, Leningrad (in Russian).
Kyshtymov, A.I., Krutous, V.I., Belaya, B.V., Sadykov, A.P., 1988. Paleogene and Neogene sediments of the Arctic and Pacific onshore of Chukotka. In: Volobueva, V.I. (Ed.), Neogene and Paleogene continental sediments of North-East of the USSR.V.1. Arctic and Pacific onshore of Chukotka, Kolyma basin. NEISRI FEB RAS Press, Magadan, pp. 4–18 (in Russian).
Lister, A.M., Sher, A.V., van Essen, H., Wei, G., 2005. The pattern and process of mammoth evolution in Eurasia. Quaternary International 126–128, 49–64.
Liu, Q., Roberts, A.P., Rohling, E.J., Zhu, R., Sun, Y., 2008. Post-depositional remanent magnetization lock-in and the location of the Matuyama-Brunhes geomagnetic reversal boundary in marine and Chinese loess sequences. Earth and Planetary Science Letters 275, 102–110.
Lvova, E.M., 1989. The results of spore-pollen analyze of upper Cenozoic sediment from middle part of Alazeya river (Yakutiya). In: Zykina, V.S. (Ed.), The Cenozoic of Siberia and North East of the USSR. Nauka Press, Novosibirsk, pp. 120–124 (in Russian).
Minyuk, P.S., 1989. Magnetostratigraphy of the Pliocene and Pleistocene of Northern Yakutiya. In: Linkova, T.I., Krasny, L.L. (Eds.), Geophysical Investigations in the Solution of Geological Problems. NEISRI FEB RAS Press, Magadan, pp. 120–139 (in Russian).
Minyuk, P.S., 2004. Magnetostratigraphy of Cenozoic of the North-East Russia. NEISRI FEB RAS Press, Magadan (in Russian).
Patyk-Kara, N.G., Gapon, O.I., Grinenko, O.V., 1982. Structural–geomorphological character of the Kolyma lowland. In: Grinenko, O.V., Gusrev, G.S., Mikhailov, G.P., Spektor, V.B., Fradkina, A.F., Tskhurbaev, F.I. (Eds.), Geology of the Cenozoic of Yakutia. Yakutskii filial Press, Yakutsk, pp. 70–77 (in Russian).
Polyakova, E.I., 1997. Arctic Seas of Eurasia in the Late Cenozoic. Nauchny Mir Press, Moscow, 146 p. (in Russian).
Rusanov, B.S., 1968. Biostratigraphy of Cenozoic of Southern Yakutia. Nauka Press, Moscow (in Russian).
Shackleton, N.J., Berger, A., Peltier, W.R., 1990. An alternative astronomical calibration of the Lower Pleistocene timescale based on ODP site 677. Transactions of the Royal Society of Edinburgh 81, 251–261.
Shantser, E.V. (Ed.), 1982a. Stratigraphy of USSR. Quaternary System. V. 1. Nedra Press, Moscow (in Russian).
Shantser, A.E., 1982b. The division and correlation of continental volcanic formations of the Late Cenozoic of Kamchatka. In: Biske, S.F. (Ed.), Quaternary Sediments of the Far USSR, vol. 3. NEISRI FEB RAS Press, Magadan, pp. 31–33 (in Russian).
Sher, A.V., 1971. Mammals and Stratigraphy of the Pleistocene of the Extreme Northeast of the USSR and North America. Nauka Press, Moscow (in Russian).
Sher, A.V., 1981. On the foundation of the sediment age of the Middle part of Alazeya river (Kolyma lowland). Doklady Akademii Nauk SSSR (Reports AS USSR) 258 (1), 179–182 (in Russian).
Sher, A.V., 1984. Age of Quaternary sediment of the Yana-Kolyma lowland and its mountain rim. Doklady Akademii Nauk SSSR (Reports AS USSR) 278 (3), 708–713 (in Russian).
Sher, A.V., Virina, E.I., Zazhigin, V.S., 1977. Stratigraphy, paleomagnetism, and mammal fauna of the Pliocene–Pleistocene sediments of the Lower Kolyma River. Doklady Akademii Nauk SSSR (Reports AS USSR) 234 (5), 1171–1175 (in Russian).
Shilo, N.A. (Ed.), 1987. Resolutions of Interdepartmental Stratigraphic Conference on the Quaternary of the Eastern USSR, Magadan, 1982. NEISRI Press, Magadan (in Russian).
Singer, B.S., Hoffman, K.A., Coe, R.S., Brown, L.L., Jicha, B.R., Pringle, M.S., Chauvin, A., 2005. Structural and temporal requirements for geomagnetic field reversal deduced from lava flows. Nature 434, 633–636.
Singer, B.S., Pringle, M.S., 1996. Age and duration of the Matuyama-Brunhes geomagnetic polarity reversal from $^{40}Ar/^{39}Ar$ incremental heating analyses of lavas. Earth and Planetary Science Letters 139, 47–61.
Sukhoroslov, V.L., Minyuk, P.S., 1982. Biostratigraphy and paleomagnetic data of marine Emnakay sediments. In: Biske, S. (Ed.), Quaternary Sediments of the Far USSR. V. 1. NEISRI Press, Magadan, pp. 27–29 (in Russian).
Tauxe, L., Herbert, T., Shackleton, N.J., Kok, Y.S., 1996. Astronomical calibration of the Matuyama-Brunhes boundary: consequences for magnetic remanence acquisition in marine carbonates and the Asian loess sequences. Earth and Planetary Science Letters 140, 133–146.
Vangengeim, E.A., 1961. Paleontological Foundation of the Anthropogene Stratigraphy of the North of Eastern Siberia. Academy Science of USSR Press, Moscow (in Russian).
Vangengeim, E.A., 1977. Paleontological Foundation of the Anthropogene Stratigraphy of the Northern Asia (on Mammals). Nauka Press, Moscow (in Russian).
Vangengeim, E.A., Zazhigin, V.S., 1982. Review of faunal complexes and fauna of the USSR territory. In: Shantser, E.V. (Ed.), Stratigraphy of USSR. Quaternary System. V. 1. Nedra Press, Moscow, pp. 267–279 (in Russian).
Virina, E.I., Zazhigin, V.S., Sher, A.V., 1984. Paleomagnetic characteristic of the type sites of Olyor faunistic complex. Izvestiya Akademii Nauk SSSR. Seriya Geologicheskaya (Proceedings of AS USSR ser. Geol.) 11, 61–72 (in Russian).
Voskresensky, S.S., Grichuk, M.P., Karevskaya, I.A., et al., 1984. Stratigraphy of Quaternary Sediments of Idigirka-Kolyma Mountain. MGU Press, Moscow (in Russian).