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Paleomagnetic determination of paleolatitude and rotation of Bering Island (Komandorsky Islands) Russia: comparison with rotations in the Aleutian Islands and Kamchatka

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Abstract. A paleomagnetic study was carried out on Paleogene sedimentary rocks from Bering Island, Komandorsky islands, located at the far western end of the Aleutian Island Arc. The age of these sediments has been debated at length, but the combination of magnetostratigraphy with the fossil record indicates that the base of the section is of early Eocene (approximately 55 Ma) and the top latest Eocene age. Paleomagnetic data were obtained from 260 samples from 60 individual bedding units. The combined data show a clockwise rotation R=26.3°±8.5°, F=8.1°±2.5° with respect to the North American Plate and R=38°±8.8°, F=8.7°±2.7° with respect to the Eurasian Plate. They also show a shallowing of the inclination which yields a paleolatitude of 53°, 12° south of its expected latitude. The shallowing may have a component due to compaction, but the wide variation in sampled lithologies, combined with internal consistency of the data set, would argue against the shallowing being significant. To compare these data with other Aleutian Arc data we compiled a comprehensive survey of all available data sets. Out of these we selected four islands for which the data passed basic reliability criteria, namely Umnak, Amlia, Amchitka and Medny islands. All four showed significant clockwise rotation with respect to both North American and Eurasian polar wander paths. Several mechanisms can generate the observed rotation, ranging from block rotation driven by oblique relative motion of the Pacific plate, through lateral transport along the curve of the arc, to whole-arc rotation about its eastern end. The distribution and age spread of the rotation data are insufficient to discriminate between mechanisms, but it seems likely that different mechanism may have operated at different times and in different locations.

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1 Introduction

Bering Island and Medny Islands are located in the Komandorski Islands on the western end of the Aleutian Arc (Figs. 1 and 2). Tectonically they are located on the subduction-zone boundary between the northwest Pacific and the Bering Sea. Present-day motion of the Pacific plate relative to the North American plate changes along the length of the Aleutian Arc from normal convergence in the east to transform motion in the west. Conventional tectonic models show three major tectonic plates in the region, the North American, Eurasian, and Pacific plates (e.g. Chapman and Solomon, 1976; DeMets, 1992). Recent models also include Okhotsk (Savostin et al., 1983; Cook et al., 1986; Seno et al., 1996) and Bering plates (Lander et al., 1994; Mackey et al., 1997). In addition, GPS data from the Komandorsky Islands (Gordeev et al., 2001), geomorphologic features off Cape Kamchatka (McElfresh et al., 2002), plus the earthquake and stress regime for the region (Geist et al., 1994) suggest existence of a Komandorsky block.

The initiation of the Aleutian Arc is widely believed to have taken place in early Tertiary time, although the precise date has come under considerable debate. It had been generally assumed that the Aleutian Arc initiated 55–50 Ma ago (Scholl et al., 1987). New $^{40}Ar/^{39}Ar$ age determinations and existing K-Ar ages suggest that Aleutian Arc volcanism began during the middle Eocene, at about 46 Ma, not at 55 Ma, possibly starting after the major change in the Pacific plate motion at 47 Ma (Sharp and Clague, 2002; Jicha et al., 2006). Basaltic lavas from the Finger Bay volcanics, the oldest exposed rocks in the central Aleutian Arc (Adak Island) have an isochron age of 37.4±0.6 Ma (Jicha et al., 2006) which is about 15 Ma younger than the dates reported earlier for the Finger Bay volcanics. In the far-western part of the arc, very recent $^{40}Ar/^{39}Ar$ ages (Layer et al., 2007) include one age of 46.2±1.5 Ma from an exposure of primitive arc basalt from Medny Island. This, and the other ages quoted above contrast

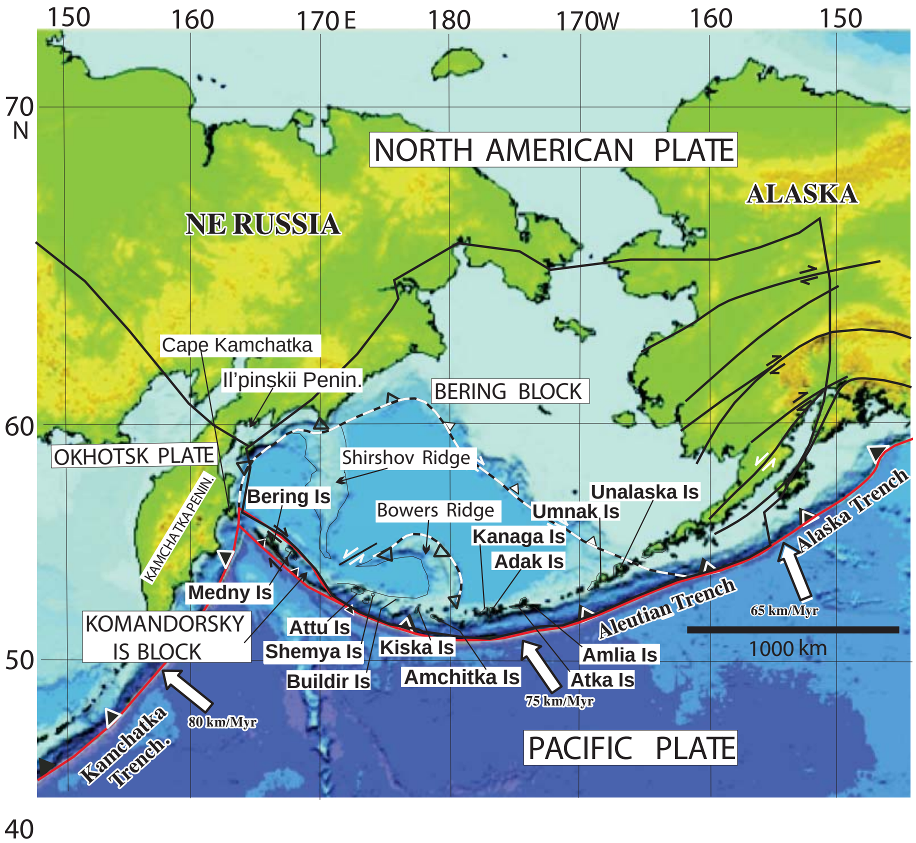

Fig. 1. Location map modified from Scholl (2007). Solid lines show boundaries of the: North American Plate; Pacific Plate; Okhotsk Plate; Bering Block; Komandorsky Islands Block derived from Scholl (2007), Chapman and Solomon (1976), Mackey et al. (1997), and Pedoja et al. (2006). The dashed lines show the earlier subduction zones along the Bering Sea margin and Bowers Ridge. Shirshov Ridge may also have been a subduction zone. Rates and direction of subduction along the Alaska, Aleutian and Kamchatka trenches are also shown.

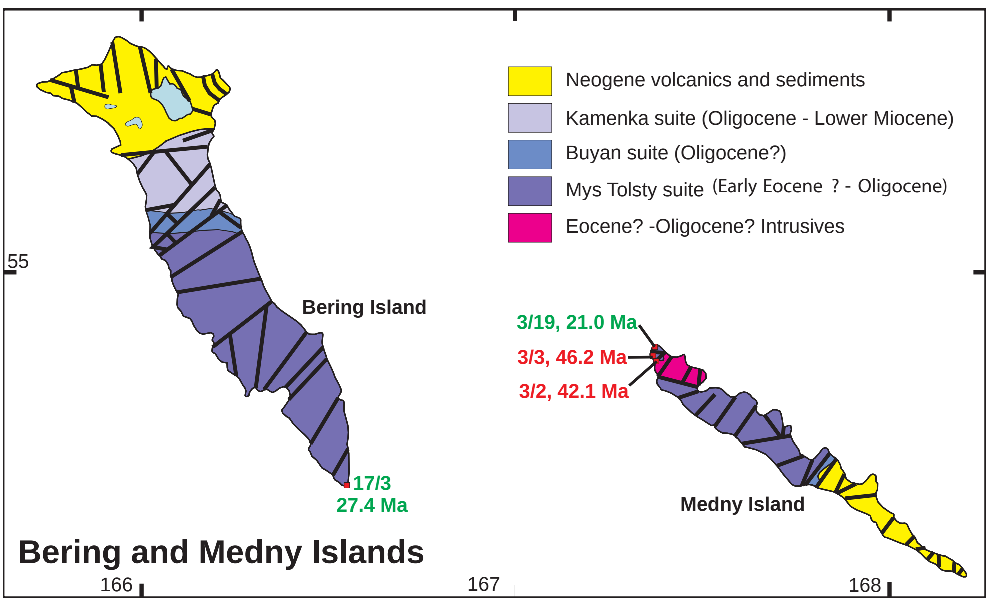

Fig. 2. Geologic map of Bering and Medny islands, Komandorsky Islands based on Shmidt (1978) with the new $^{40}Ar/^{39}Ar$ ages from Layer et al. (2007). The heavy lines are mapped faults.

with the magnetostratigraphy and fossil record from Bering Island presented here that suggest the forearc sediments were being deposited in earliest Eocene time.

The structural evolution of the Aleutian Arc is poorly understood because it is difficult to determine the rates and geometry of slip with time, because extensive deformation and erosion have obscured much of its geologic history, and because of a lack both of subaerial exposure and data from the submarine environment. The arc is structurally segmented into several blocks that have undergone clockwise rotation accompanied by arc-parallel extension (Geist et al., 1988; Shillington et. al., 2004). This motion has created submarine canyons along roughly arc-perpendicular boundaries of blocks and has formed basins on their northern margins, all indicative of block rotation. This analysis of the present-day morphology of the arc and the relative motion of the Pacific plate suggests that the rotated blocks are moving along the arc towards Kamchatka and that block rotations are ongoing (Gaedicke et al., 2000; Gordeev et al., 2001; Avé Lallemant, 1996; Avé Lallemant and Oldow, 2000; Park et al., 2002). The initiation of regional subsidence and extensional deformation of the Aleutian platform as well as an acceleration in block-style deformation of the Aleutian forearc have been attributed to a change in Pacific plate motion in the late Cenozoic at $\sim$5 Ma (e.g., Harbert et al., 1986). The paleomagnetic data presented in this paper support this model, but the paucity of such data makes it difficult to constrain the overall kinematics.

An important aspect of the tectonic evolution of the Aleutian Arc, particularly in the context of models involving rotating blocks, is rotation about a vertical axis. This can be investigated using paleomagnetic data. Previous attempts to constrain the kinematic history with paleomagnetic data have been largely unsuccessful because of difficult access, poor exposure and thermal and metamorphic overprinting of the rocks sampled from the Aleutian Arc complex. In this paper we present new data from Bering Island in the Komandorski islands, and re-evaluated data from the Aleutian islands that show clear clockwise rotations and some relative latitude changes.

2 Bering Island: geological setting and sampling

Bering Island together with Medny Island form part of the Komandorsky Islands and are located at the western end of the Aleutian Island Arc (Figs. 1 and 2). Bering Island is about 90 km long, with an average width of about 20 km. Cenozoic sedimentary and volcanic rocks are widespread on the island and form the Komandorskyi series (Zhegalov, 1961, 1964). The lower part of this series, from oldest to youngest, consists of the Mys Tolsty, Buyan and Kamenka suites of Paleogene age. The upper part consists of Neogene volcanic and sedimentary rocks that are exposed on the north-western part of the island. Some authors divide the Mys Tolsty suite (from bottom to top) into the: Gavanskaya, Gavrilovskaya, Poludenskaya and Nikitinskaya suites (Ivaschenko et al., 1984; Rostovtseva and Shapiro, 1998). The main tectonic structure of the island is a synclinal fold that has a roughly E-W strike (Figs. 2 and 3). The Kamenka suite forms the central part of this fold. The scale of folding is about 15–20 km. The Mys Tolstyi and Buyan suites form the southern limb of the fold, where bedding dip rarely exceeds 10°.

The interpretation of the ages of the stratigraphic units on Bering Island has evolved with time. Yu. A. Zhegalov assigned the Komandorsky series to the Oligocene-Lower Miocene (Zhegalov, 1961, 1964). On the basis of diatoms the Kamenka suite was determined to be Lower Miocene (Dolmatova, 1974) and later as Oligocene (Fedorchuk et al., 1987; Tsvetkov et al., 1989, 1990). Mollusks from the Kamenka suite gave Oligocene-Lower Miocene ages (Gladenkov, 1984). Rocks deposited at the base of the Komandorsky series on Medny Island contain planktonic foraminifera *Subbotina* cf. *nana*, *S*. cf. *velascoensis*, *S*. cf. *turgida*, S. cf. *linaperta* of Late Paleocene age (Shmidt et al., 1973; Shmidt, 1978). Age analogs of these rocks may exist on south Bering Island (Ivaschenko et al., 1984; Rostovtseva and Shapiro, 1998). In the lower part of Kamenka suite nannoplankton are found, namely *Coccolithus pelagicus*, *Dictyococcites bisectus*, *Cyclicargolithus floridanus*, *Gribrocentrum reticulatum*, *Reticulofenestra* cf. *dicfyoda*, *R. umbilicus*, *Discoaster binodosus*, indicating a Middle Eocene (Bartonian) and possibly Late Eocene age for the suite (Gladenkov and Shcherbina, 1991; Shcherbina, 1997).

The age of the upper part of the Mys Tolsty suite is no older than Middle Eocene. Nanoplankton *Coccolithus pelagicus*,*Dictyococcites bisectus* and some forms of *Dictyococcites* were found here (Gladenkov and Scherbina, 1991; Shcherbina, 1997). On recent official stratigraphic charts of Bering Island the age of the Mys Tolsty suite is Middle-Upper Eocene, and the age of the Kamenka suite is Upper Eocene-Oligocene (Gladenkov et al., 1998). The results of this study indicate that the base of the Mys Tolsty suite is probably of mid Early Eocene age.

We collected paleomagnetic samples from sedimentary rocks of the Mys Tolstyi and Buyan suites. Field-oriented hand samples were collected from the south-eastern part of the island on the Pacific and Bering Sea sides (Fig. 3). The thickness of the section was calculated graphically using measured azimuth of the shore line and bedding dip.

2.1 Pacific side section

The oldest rocks of the Mys Tolsty suite are exposed on the Pacific side of the island. Sampling was conducted from the south cape of the island to the Bobrovaya river and then across the island (Fig. 4). Here the Mys Tolsty suite is divided into 28 units. The thickness of the whole section 2390–2400 m (Fig. 5). The lower section (units 1–20) is

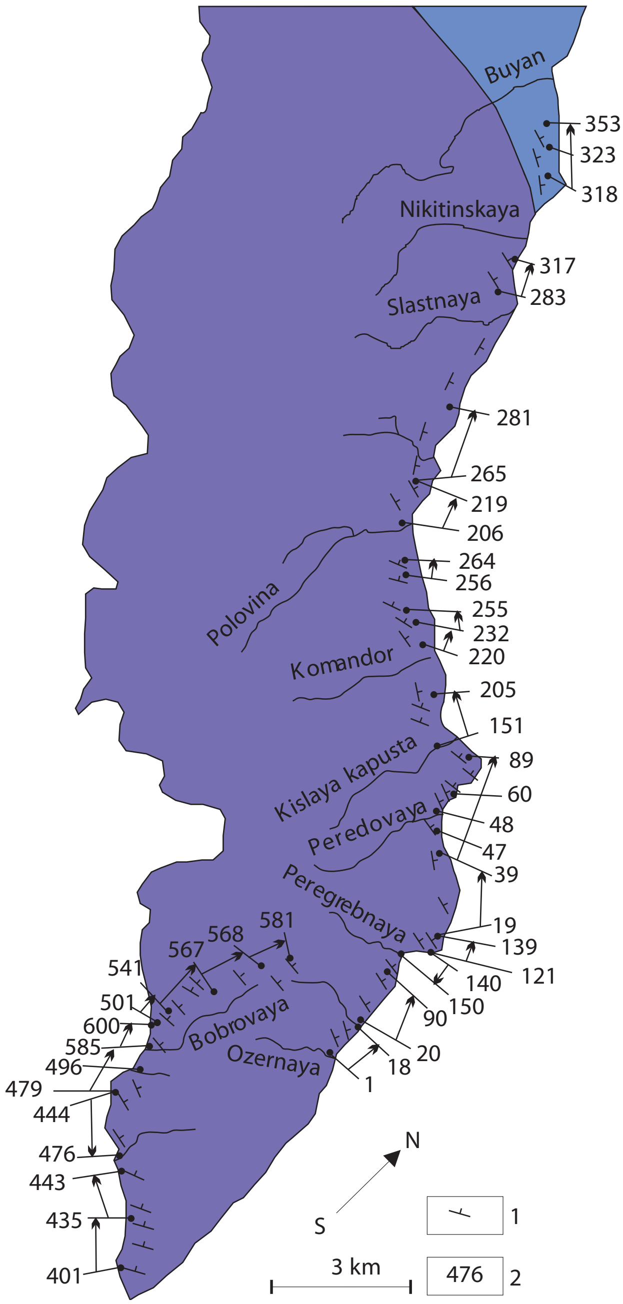

Fig. 3. Sampling sites on the southeastern end of Bering Island. Sample numbers are shown with arrows indicating whether they were collected up or down section. The direction of dip, which seldom exceeds 10°, is also shown.

dominated by coarse-to-fine-grained tuff-sandstone interbedded with siltstone and mudstone layers. The sandstone includes pebbles of different composition – granite, basalt, red and green jasper and sedimentary rocks. The middle part of section (units 21–27) is dominated by interbedded siltstone, mudstone, and diatomite. The upper part of the section is commonly made up of thin-layered interbeds of mudstone and siliceous rocks. Calcareous-sandstone concretions are present in deposits that are most often in the upper part of the section and often include the mollusk *Variamussium* sp.

2.2 Bering Sea side section

Based on the stratigraphy on the Bering side, the section sampled contains the younger part of the Mys Tolsty and Buyan suites (Fig. 2). The Mys Tolsty suite is divided into 32 units (Fig. 5) with a total thickness of 2890–2900 m. The lower part (units 1–9) consists of interbeded siltstone and mudstone. In the middle part (units 10–26) exposures contain sandstone with coarser lithology and with rare layers of siltstone and mudstone. Mudstone, siliceous and diatomaceous rocks are common in the upper part (units 27–32). Calcareous-sandstone concretions are typical for this suite. Mollusks present in concretions and other units include: *Variamussium* sp., *Neilenella poronaica* Yok., *Yoldia* sp., *Y. chehalisensis* Arn., *Y. watasei* Kaneh., *Polinices* sp., *Ancistrolopis* sp., *Nuculana* sp., *N. hannibali* Clark, *Acila decisa* Conr., *Solemya* sp., *Delectopecten* sp., *Dentalium* sp., *Fusinus* sp., *Neptunea* sp., *Malletia* sp., *Eucrassatella lincolnensis* Weav., *Lucinoma acutilineneata* Conr. (Minyuk, 2004).

The Buyan suite is divided into 7 units that are dominantly sandstone, and conglomerate of different texture and compositions, with rare layers of diatomaceous rocks, siltstone and mudstone including calcareous-sandstone concretions. Some of the units showed cross bedding. The thickness of the Buyan suite is 380 m.

3 Laboratory methods and results

Typically three to five oriented 2 cm×2 cm×2 cm cubes were cut from each hand sample. The intensity of the natural remanent magnetization (NRM) was measured on a JR-4 spinner magnetometer (AGICO, Czech Republic), and magnetic susceptibility was measured on a KLY-2 kappabridge (AGICO, Czech Republic). Stepwise (up to 10 steps) thermal demagnetization was applied to all samples. Susceptibility was monitored during thermal demagnetization in order to recognize mineralogical changes.

3.1 Magnetic properties

Magnetic properties, magnetic susceptibility and NRM intensity, show strong variations in both sections and are commonly dependant on the type of rock (see Figs. 4 and 5, Table 1). As a rule the coarser lithological units (sandstone) have high values of NRM intensity and susceptibility. In the Bering Sea section high values of susceptibility and intensity are found in units 12–14 of the Mys Tolsty suite. On the Pacific side, high values of NRM intensity and magnetic susceptibility are typical for the lower part of the Mys Tolsty

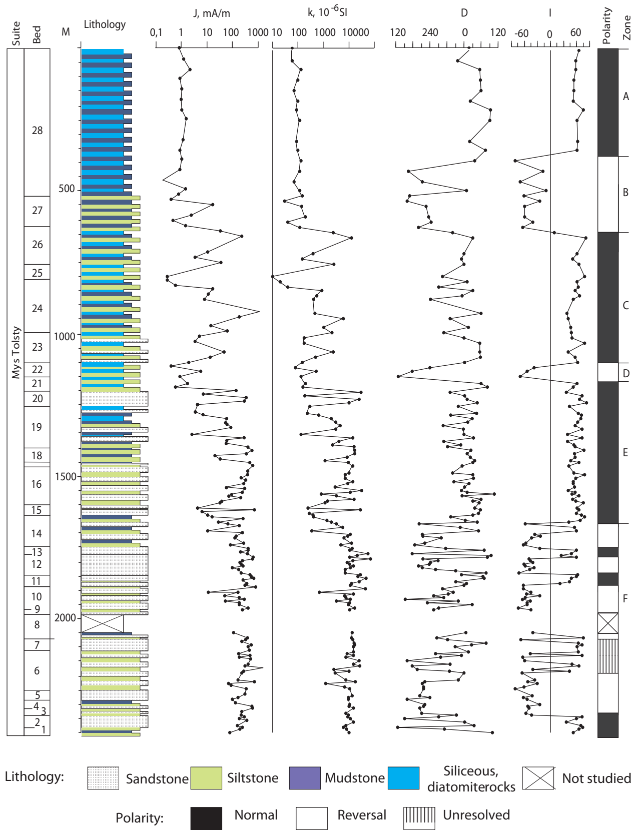

Fig. 4. Magnetostratigraphic data of Pacific side section with NRM intensity (J), magnetic susceptibility (k), declination (D) and inclination (I) plotted against stratigraphic level. The polarity of the observed paleomagnetic field is also shown.

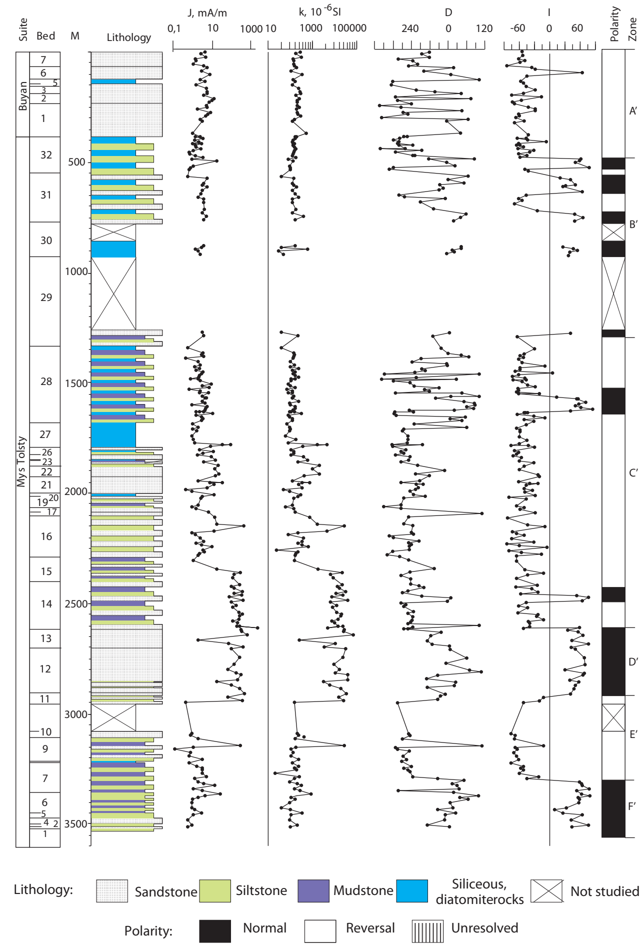

Fig. 5. Magnetostratigraphic data of Bering Sea section. See Fig. 4 for explanation.

suite (unit 1–20). Rocks of the Buyan suite show low intensity and susceptibility although they consist of very coarse-grained material, including conglomerates. This may be due to a change of source area during accumulation of the Buyan deposits.

3.2 Thermal demagnetization

The specimens yielded few components of magnetization upon thermal demagnetization. A present-day field component is removed at temperatures between 100–150°C and is characterized by a rapid decrease of intensity. A characteristic component of remanent magnetization is usually removed at demagnetization temperatures above 200°C (Figs. 6, 7, and 8). Some samples show a stable secondary magnetization which is difficult to separate from the characteristic magnetization. Not all samples were heated above 450°C, because of strong increases in magnetic susceptibility during heating.

Magnetic susceptibility of some samples increases by factors of ten (Fig. 9). This property is more common for fine-grained rocks – siltstone, mudstone, diatomite and common also for Cenozoic sediments from other parts of the Kamchatka region – Ilpinsky peninsula (Paleogene sediment), Karaginsky Island (Neogene sediments) (Minyuk, 2004). We relate this behavior of magnetic susceptibility to the presence of siderite ($FeCO_3$). There are many calcareous deposits and we infer that invisible siderite is dispersed among them. Siderite is unstable during heating and transforms to magnetite (Ellwood et al., 1986, 1989; Pan et al., 2002) even at relatively low temperatures, that complicates interpretations of demagnetization results.

3.3 Magnetostratigraphy

Figures 4 and 5 show the magnetostratigraphic data. Normal polarity dominates in the Pacific section, reversed polarity in the Bering Sea section. In each section 6 magnetozones were identified and labeled A through F for the Bering side and A' through F' for the Pacific side. We consider that the Pacific section is a downward continuation of the Bering Sea section and correlate magnetozone A' in the Pacific section with

Table 1. General magnetic properties of the sampled sections.

Section	Suite	Unit	J, mA/m from–to (mean)	k, 10^{-6} SI from–to (mean)
Bering Sea	Buyan	1–7	1.0–11.8 (4.3)	138–438 (250)
	Mys Tolsty	15–32	0.4–89.9 (4.8)	25–5575 (375)
		12–14	1.7–2430.0 (268.4)	313–84 850 (22 263)
		1–11	0.1–25.6 (2.7)	25–1088 (225)
Pacific	Mys Tolsty	28	0.2–17.0 (1.9)	38–250 (125)
		21–27	0.3–1135.0 (70.5)	12–15 800 (1663)
		1–20	2.8–1615.0 (255.0)	163–86 338 (14 488)

J – gives the range and mean of NRM intensity; k – the magnetic susceptibility per volume.

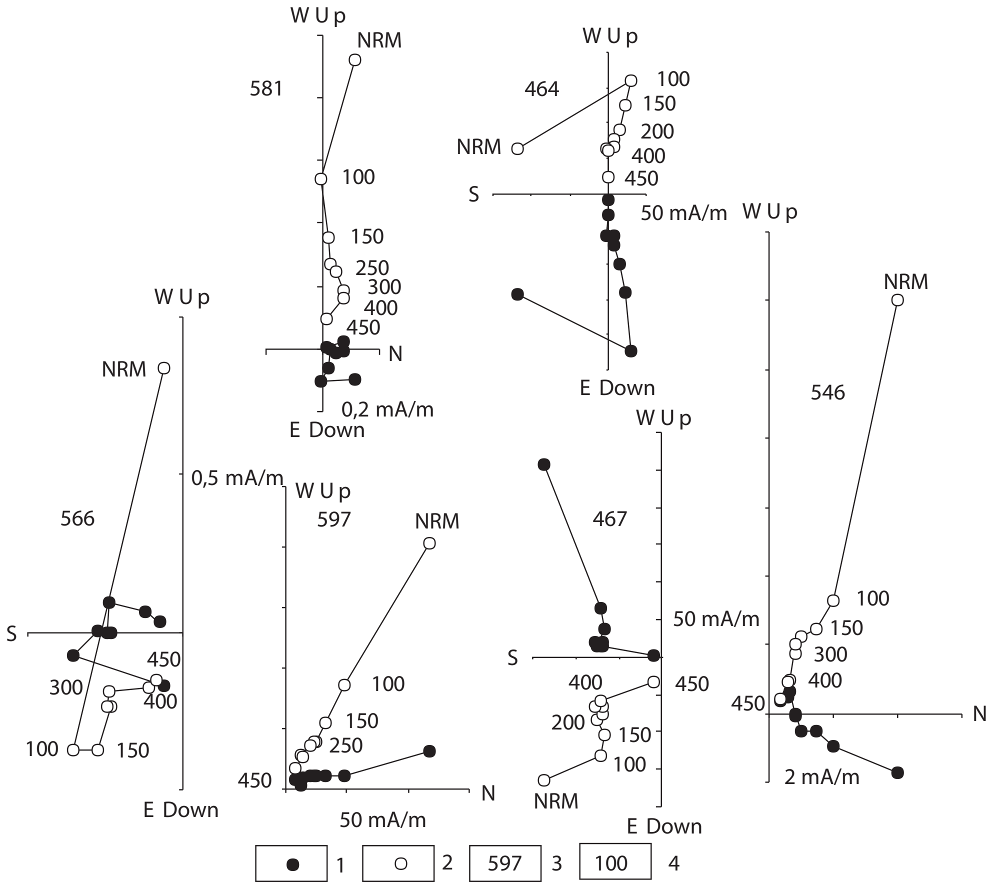

Fig. 6. Examples of thermal demagnetization orthogonal vector diagrams of samples from Mys Tolsty suite on Pacific section. 1 (2) – projected on to the horizontal (vertical) plane, 3 – sample number, 4 – temperature in °C.

magnetozone F in the Bering Sea section. For this correlation we took into account polarity magnetozones, bedding of rocks, lithology and the magnetic properties. Magnetozones A and F' have similar low magnetic properties. In contrast, the thickness of the remaining units with high NRM intensity and high magnetic susceptibility are different in the two sections as are the polarities. This lack of correlation suggests that there is little duplication of section.

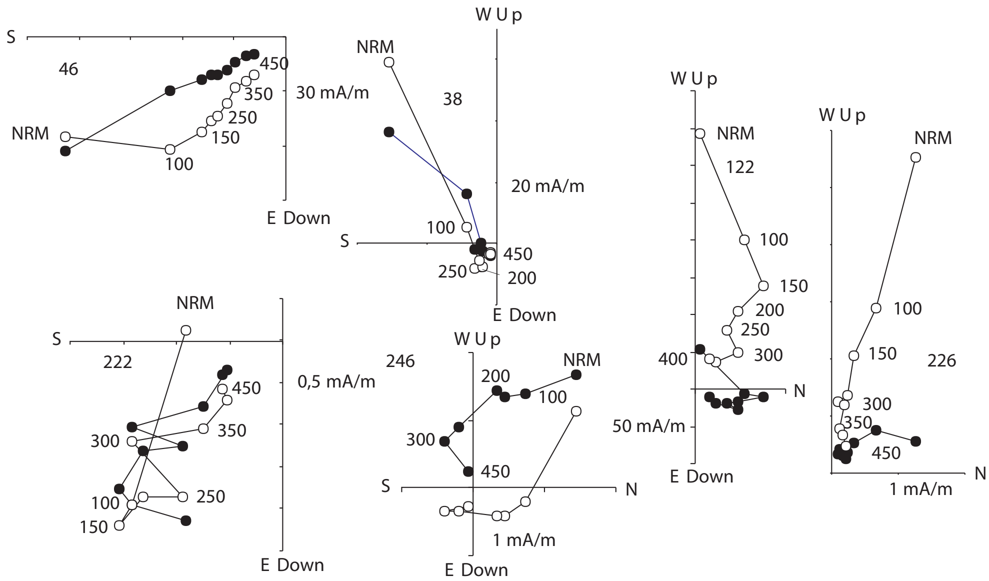

Fig. 7. Examples of thermal demagnetization orthogonal vector diagrams of samples from suite of Mys Tolsty on Bering Sea section. For explanations see Fig. 6.

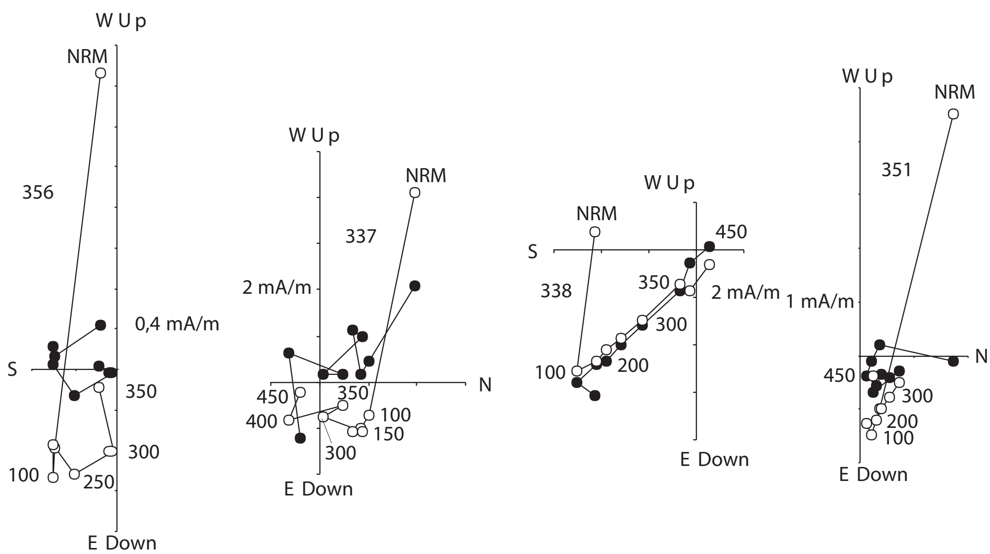

Fig. 8. Examples of thermal demagnetization orthogonal vector diagrams of samples from Buyan suite. For explanations see Fig. 6.

The lack of biostratigraphic data from the studied sections makes it hard to correlate the observed magnetozones with the geomagnetic polarity time scale. Nevertheless nannoplankton from the upper part of the Mys Tolsty suite, as well as nannoplankton from the Kamenka suite that conformably overlies the Buyan suite, belong to zones CP14–CP15 (Shcherbina, 1997). In recent stratigraphic scales these zones correspond to chrons 13r–20n (about 34 to 44 Ma) of Late and Middle Eocene age (Berggren et al., 1995). The Kamenka suite overlying the Buyan suite has Late Eocene-Oligocene ages (Gladenkov et al., 1998). If we presume that the upper part of the Mys Tolsty suite corresponds to Middle Eocene, it is possible to correlate the observed polarities with 17r–20n chrons (Fig. 10). The reversed magnetozone of the Buyan suite then correlates with chron 17r. The Buyan suite consists of sandstone and conglomerate and overlies an unconformity. The existence of an unconformity at the level of chron 17r in the Kamchatka Paleogene reference section on Ilpinsky Peninsula (Fig. 1) provides some support for this age call (Minyuk, 2004). The fossil record from the Il'pinsky

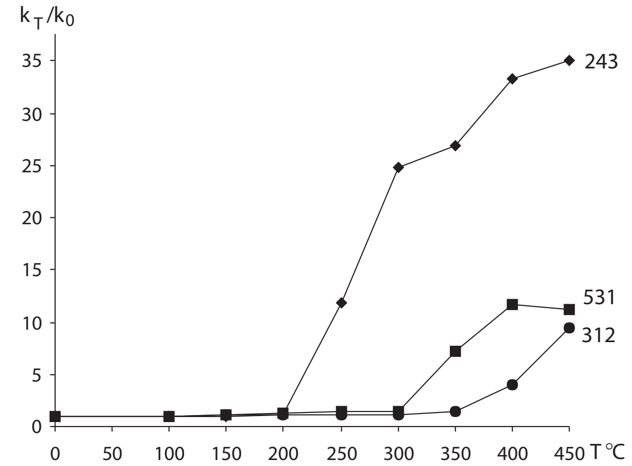

Fig. 9. Magnetic susceptibility ratios versus temperature. k_0/k_T – magnetic susceptibility before and after heating.

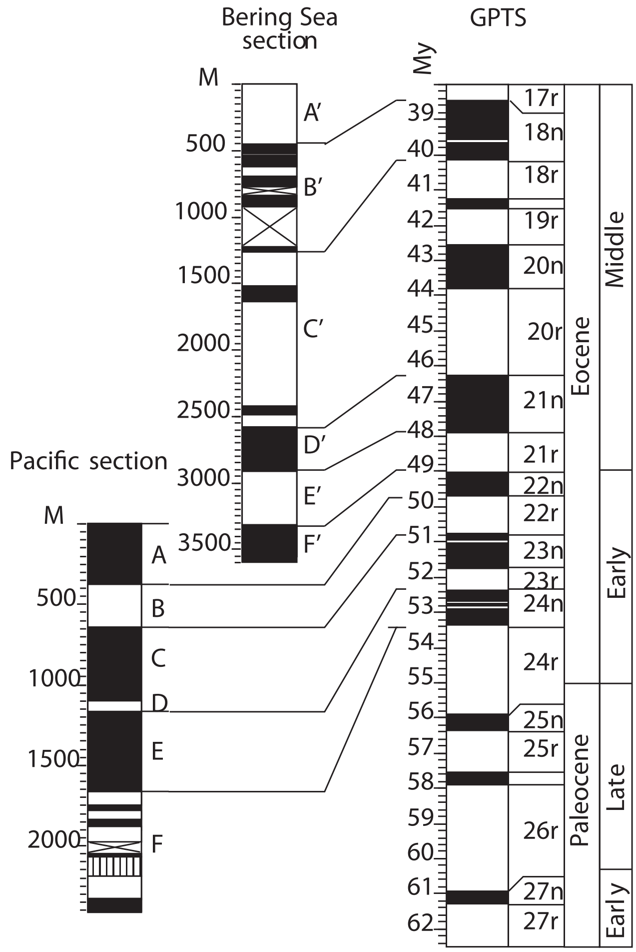

Fig. 10. Correlation of Paleogene sections of Bering Island with Geomagnetic Polarity Time Scale (Cande and Kent, 1992, 1995).

peninsula also provides well matched analogs for the fossils from the Gubbio and Contessa sections in Italy, thus providing control over the magnetostratigraphy of the section. With chron 17r as a tie point, the magnetozones of the Mys Tolsty suite correlate reasonably well with chrons 18n–24r. In this case the lowest part of the Mys Tolsty suite would have an Early Eocene age, the same age as the lower part of the Paleogene section on Medny Island based on planktonic foraminifera data (Shmidt et al., 1973; Shmidt, 1978). In contrast, tholeiitic basalt underlying sediments presumed to be part of the Mys Tolsty suite on the northern end of Medny Island (Fig. 2) give a ^{40}Ar/^{39}Ar age of 46.2±1.5 Ma (Layer et al., 2007) placing the Mys Tolsty suite in the Middle Eocene. The age of the basalt is identical to the oldest dated samples from the Aleutian Arc (Jicha et al., 2006) which have been interpreted as representing arc basement. If the Middle to Late Eocene age range for the nanoplankton assemblages (Shcherbina, 1997; Minyuk and Gladenkov, 2004) apply to the whole Buyan/Mys Tolstiy suite, and the correlation of Buyan unconformity with that seen in the Il'pinsky section, and the other correlations of magnetic properties are fortuitous, then it is possible for the Buyan suite to be Late Oligocene, and the lower Mys Tolsty suite Middle Eocene in age. Our preferred interpretation, shown in Fig. 10, is the match with the Il'pinsky section.

3.4 Paleomagnetic directions and paleopoles

To estimate the significance of the characteristic magnetization (ChRM) directions determined for the Bering Island sections, the reversal test (McFadden and McElhinny, 1990) and fold test (McElhinny, 1964) were used. For the reversal test we compare the directions of neighboring polarity magnetozones. For all pairs of zones the reversal test is positive except for B− to C+ in the Pacific section which is indeterminate (Table 2). The fold test is also positive for the two sections, indicating a pre-folding origin of the ChRM (Table 3).

Mean ChRM directions and paleopoles were calculated for each magnetozones in both sections and separately for all sections shown in Table 4. The observed directions and paleopoles were compared with reference data for the North-American and Eurasian plates (Besse and Courtillot, 2003). Observed data show a clockwise rotation R=26.3°±8.5°, and a shallowing or flattening of the inclination F=8.1°±2.5° with respect to the expected value if the sites had remained fixed with respect to the North American Plate. If fixed with respect to the Eurasian Plate, R=38°±8.8°, F=8.7°±2.7°. Rotations were calculated following Demarest (1983) using the 40 Ma reference pole of Besse and Couritllot (2003) representing the youngest part of the sections.

4 Comparison with other paleomagnetic data from the Aleutian Island Arc

Early paleomagnetic studies from the Aleutian Arc were very limited in both distribution and quality. In general, these earlier paleomagnetic data indicated little or no latitudinal displacement with respect to North America (Stone, 1975). Subsequent paleomagnetic data from the islands suggest significant clockwise rotation for many of the pre-Quaternary rocks, but the measurements were made in the 1960s and 1970s with limited, if any, demagnetization techniques applied (Table 5). More recent studies have yielded clockwise rotations in Eocene and Lower Oligocene sedimentary rocks on Umnak and Amlia islands (Harbert, 1987), and similar rotations from Miocene volcanic rocks from Amchitka island (Krutikov et al., 2008). These three reliable studies of pre-Quaternary rocks are described first, with a summary of Quaternary sites in Sect. 4, and all of the known remaining paleomagnetic data for the whole Aleutian island arc in Sect. 5.

4.1 Amchitka Island

Amchitka Island lies south of the present-day volcanic arc, just west of the 180° meridian (Fig. 1). Three formations have been mapped the oldest of which, the Amchitka Formation, consists mainly of pillow lavas and breccias, which are older than 35 My (Carr et al., 1970). It is overlain by the Banjo Point formation which is dominated by basaltic breccias and minor pillow basalt and sedimentary rocks (Bath et al., 1972). This is overlain by the youngest of the extrusive rocks, the Chitka Point Formation, which is dominated by lava flows and breccias with subsidiary sedimentary beds. Three K-Ar measurements give a best-guess age of 14.1±1.1 Ma (Carr et al., 1970) which is consistent with the mid-Miocene age estimate based on pollen and spores from a coal sample (Carr et al., 1970) and is backed up by a new ^{40}Ar/^{39}Ar age of 13.8±0.2 (Layer, pers. comm. 2006). Samples from each of these formations were collected and measured in the late 1960s (Stone, 1972). The results from the Amchitka and Banjo Point Formations are listed in Table 6, with an explanation in Sect. 5.3. Based on the original results, the only data set that looked promising for re-measuring were from the Chitka Point Formation. The data from the re-measuring study failed both the fold test and the reversal test, but it was determined that the fold test was probably false because a high likelihood exists that the flows had primary dips, whereas over large distances they all appear to be horizontal. For this reason the final result is based on samples uncorrected for apparent (primary) tilt. The formal McFadden and McElhinny (1990) reversal test failed because only three reversed samples versus 16 normal were available. In practice the means of both polarities overlap within their 95% confidence limits.

The final magnetic vectors were used to calculate the equivalent Virtual Paleomagnetic Pole (VGP) positions.

Table 2. Reversal test for Paleogene rocks of Bering Island.

Magnetozone	Ds	Is	N	R	γ_o	γ_c	Test
Pacific section							
A+	43	67	9	8.6688	8.5	16.5	+
B−	209	−61	5	4.8765			
B−	209	−61	5	4.8765	14.9	**21.5**	–
C+	7	65	19	17.3153			
C−	209	−61	5	4.8765	12.1	17.6	+
C+E	14	66	62	57.6548			
F+	52	72	23	20.7639	7.0	12.6	+
F−	230	−65	23	21.6226			
Bering Sea section							
A’	202	−65	18	17.4689	7.6	12.9	+
B’	14	65	11	10.1438			
B’	14	65	11	10.1438	7.1	14.9	+
C’	197	−72	76	68.5124			
C’	197	−72	76	68.5124	1.0	17.9	+
D’	16	71	7	6.6631			
D’	16	71	7	6.6631	12.2	13.6	+
E’	225	−65	13	12.6606			
E’	225	−65	13	12.6606	10.5	13.2	+
F’	20	69	13	12.1076			

Ds, Is – Declination, Inclination in stratigraphic coordinates, N – number of samples; R – unit vector sum, $\gamma_o(\gamma_c)$ – observed (calculated) angle between pairs of reversed and normal directions following McFadden and McElhinny (1990). If $\gamma_c>\gamma_o$ the test is positive for $\gamma_c<20$. For $\gamma_c>20$ (bold) the test is indeterminate.

These data show no significant latitudinal motion of the island after deposition of the Chitka Point Formation, but show a significant clockwise rotation with respect to the North American plate of R=54°±8.1°, F=4.4°±3.1° (Table 5).

4.2 Umnak Island

Late Eocene–Early Oligocene sedimentary rocks were studied in Umnak Island (191.17° E, 52.92° N) (Fig. 1) (Harbert, 1987). These rocks consist of laminated and gently folded siltstone, mudstone and sandstone. They show normal and reversal polarities (Harbert, 1987) and pass the reversal test (McFadden and McElhinny, 1990). The mean vectors show no significant latitudinal motion and a clockwise rotation of R=36.7°±11.2°, F=0.8°±3.5° (Table 5).

In addition to the study by Harbert (1987), two pilot studies were made. One was collected by Hugh McLean of the USGS and the other by D. B. Stone. Both sets were measured at the University of Alaska. The results are included in Table 5, however the more extensive data set of Harbert (1987) was used to determine the rotation and flattening.

Table 3. Fold test for Paleogene rocks of Bering Island.

Section	N	Dg	Ig	kg	α_{95}	Ds	Is	ks	α_{95}	ks/kg	F	Test
Pacific	122	4	27	4.6	6.7	32	68	12.4	3.8	2.69	1.24	+
Bering Sea	138	2	24	5.0	6.0	31	69	12.7	3.5	2.54	1.22	+

N – number of units selected from Table 7 (see Supplement: http://www.stephan-mueller-spec-publ-ser.net/4/329/2009/smsps-4-329-2009-supplement.pdf); Dg, Ig, (Ds, Is) – mean declination and Inclination in geographic (stratigraphic) coordinates; kg, α_{95} (ks, α_{95}) – Fisher (1953) dispersion and α_{95} circle of confidence; ks/kg – ratio of dispersion after unfolding from geographic to stratigraphic reference frames; Fold test (McElhinny, 1964); Pass or fail of fold test.

Table 4. Paleogene paleopoles for Bering Island.

Magneto-zone	Ds	Is	N	k	Paleo-latitude	α_{95}	dp	dm	Lat	Long
					Pacific section					
A	43	67	9	24.2	49.7	10.7	17.7	14.7	63.6	249.6
B	209	−61	5	32.4	−42.0	13.6	20.8	16.0	67.1	278.3
C	7	65	19	10.7	47.0	10.8	17.4	14.1	80.9	314.4
E	16	66	43	16.0	48.3	5.6	9.2	7.5	78.1	283.5
F+	52	72	23	9.8	57.0	10.2	18.0	15.9	61.6	230.4
F−	230	−65	23	16.0	−47.0	7.8	12.6	10.2	58.3	249.4
F	58	69	46	11.7	52.5	6.4	10.9	9.2	56.6	237.7
A–F	32	68	122	12.4	51.1	3.8	6.4	5.3	70.5	254.4
					Bering Sea section					
A’	202	−65	18	32.0	47	6.2	10.0	8.1	74.1	277.1
B’	14	65	11	11.7	47	13.9	22.4	18.1	78.1	292.6
C’	197	−72	76	10.0	57	5.4	9.5	8.4	80.3	237.2
D’	16	71	7	17.8	55.4	14.7	25.6	22.3	80.9	246.6
E’	225	−65	13	35.4	47	7.1	11.5	9.2	61.1	253.1
F’	20	69	13	13.4	52.5	11.7	19.9	16.9	78.0	259.79
A’–F’	31	69	138	12.7	52	3.5	5.9	5.1	77.4	258.8
					Pacific section + Bering Sea section					
Total	210	−69	260	12.4	53	2.6	4.4	3.8	72.6	252.0

Ds, Is – Mean Declination, Inclination in stratigraphic coordinates, N – number of samples, k – Fisher (1953) precision parameter of the mean paleomagnetic directions, Paleolatitude, α_{95}, radius of the 95% confidence circle of the virtual paleomagnetic pole; dp/dm – semi-axes of the confidence circle of paleomagnetic pole, Lat, Long – Latitude, Longitude of geomagnetic pole.

4.3 Amlia Island

On Amlia Island (186.08° E, 52.10° N) (Fig. 1) 9 samples from Middle Eocene–Early Oligocene volcanoclastic sedimentary rocks were studied. One sample shows reversal polarity but not antiparallel to normal directions. Fisher precision parameter k increases after tilt correction. Characteristic magnetization of these rocks indicates no significant latitude motion, but a significant clockwise rotation with respect to North American Plate of $R=70°\pm23°$, $F=-4°\pm5°$ (Table 5) (Harbert, 1987).

4.4 Medny Island

Medny Island (Figs. 1 and 2), in the Komandorsky Islands group, was sampled by Bazhenov et al. (1992) and measurements made using modern paleomagnetic protocols. The sediment sampled are of Oligocene/Eocene age and show a significant clockwise rotation: $R=70°\pm14°$, $F=15°\pm5°$ with respect to the North American Plate (Bazhenov et al., 1992).

Table 5. Comprehensive compilation of paleomagnetic data from the Aleutian Island Arc.

Island	Locality Lat, Long	Rock Type	Age	Dating Method	N	D	I	k	α_{95}	F	dF	R	dR	demag type	Reference
Unalaska	53.97 N, 193.27 E	Driftwood Bay, volcanic flows DFB	400–800 ka	Ar/Ar	11	1.4	68.4	95.8	3.9	−1.5	5.1	+1.6	8.5	AF+T	Stone and Layer (2006)
Umnak	53.53 N, 193.27 E	Ashishik volcanic flows ASH	1.9 Ma	Ar/Ar	6	196.3	−81.3	14.5	18.2	21.9	4.3	+21.8	16.1	AF+T	Stone and Layer (2006)
	53.53 N, 191.92 E	New Jersey Creek volcanic flows NJC	1.9 Ma	Ar/Ar	10	342.5	66.9	247.0	3.1	1.4	4.0	−6.1	6.9	AF+T	Stone and Layer (2006)
	53.47 N, 191.92 E	Crater Creek volcanic flows CCR	50 (?) ka	Ar/Ar	11	356.2	68.7	71.5	5.4	1.1	7.0	−3.3	12.0	AF+T	Stone and Layer (2006)
	52.92 N, 191.97 E	Starr Pt, Driftwood Bay sediments	∼35 Ma	microfossils	29	35.4	72.3	42.2	4.0	0.3	5.4	+32.8	12.0	AF+T	Harbert (1987)
	52.92 N, 191.97 E	dikes	15 ka	indirect K-Ar	4	15.7	70.6	43.0	10.7	−3.5	55.7	+20.5	–	AF+T	Harbert (1987)
	52.9 N, 191.05 E	Nikolski sediments 1	∼35 Ma	microfossils	9	67.0	64.0	23.0	11.0	−16.9	12.9	+67.8	19.3	AF+T	Stone et al. (1983)
	52.9 N, 191.06 E	Nikolski sediments 2	∼35 Ma	microfossils	11	39.7	74.7	19.9	10.5	−14.5	8.7	+41.1	13.7	AF	Stone (unpublished)
Amlia	52.10 N, 186.08 E	sediments	∼35 Ma	microfossils K-Ar	9	37.7	74.3	60.5	6.0	2.7	12.3	+49.5	28.9	AF+T	Harbert (1987)
	52.10 N, 186.08 E	sediments	∼35 Ma	microfossils K-Ar	7	–	54.0	27.0	12.0	–	–	–	–	AF+T	Stone et al. (1983)
	52.10 N, 186.08 E	dikes	15 Ma	indirect K-Ar	1	10.9	68.0	25.0	8.9	−6.6	11.1	+14.7	18.0	AF+T	Harbert (1987)
Atka	52.25 N, 185.9 E	lava flow	0.2±0.3 Ma	K-Ar	12	342.8	64.5	17.1	10.8	−5.9	12.6	−17.2	18.5	NRM	Bingham (1971)
Adak	51.96 N, 183.43 E	Adagdak volcanics	<500 ka	K-Ar	38	345.8	69.0	42.5	3.6	−0.6	4.5	−14.5	7.2	AF	Cameron (1970), Cameron and Stone (1970)
	51.96 N, 183.38 E	Andrew volcanics	<500 ka	Geo-morpho-logy and setting	23	3.6	70.4	23.2	6.4	2.3	8.4	+3.1	14.6	AF	Cameron (1970), Cameron and Stone (1970)
	51.96 N, 183.4 E	Adagdak and Andrew volca-nics combined	<500 ka	K-Ar, Geo-morphology and setting	61	352.2	69.7	31.6	3.3	1.6	4.9	±7.8	8.2	AF	Cameron (1970), Cameron and Stone (1970)
	51.95 N, 183.4 E	Adagdak volcanics ADK	<500 ka	K-Ar	11	10.0	71.3	95.2	4.7	3.2	6.2	−10.7	10.9	AF+T	Krutikov et al. (2008)
	51.89 N, 183.4 E	Andesite domes	5 Ma	K-Ar	37	332.8	70.5	3.8	25.5	−26.6	20.1	−35.2	23.9		Cameron (1970), Cameron and Stone (1970), Stone (1975)
	51.9 N, 183.4 E	Finger Bay volcanics, Andrew Lake fm., sites	40 Ma	Microfossils from Andrew Lake Fm. (Hein and McLean, 1980; Jicha et al., 2006)	5	318.0	53.0	14.0	21.0	−30.2	20.2	−40.2	25.1	AF	Cameron (1970), Cameron and Stone (1970), Stone (1975)
	51.9 N, 183.4 E	As above, smpls	40 Ma	as above	77	326.0	55.7	4.1	9.2	−19.5	9.2	−32.3	11.5	AF	Cameron (1970), Cameron and Stone (1970), Stone 1975)
	51.9 N, 183.4 E	As above, time units	40 Ma	as above	16	274.0	70.2	5.9	16.6	−1.6	21.3	−84.9	40.1	AF+T	Krutikov et al. (2008)
Kanaga	51.9 N, 182.95 E	Round Head volcanics RDH	120 ka	Ar/Ar	8	7.5	71.7	379.8	2.9	3.0	3.7	+7.9	6.4	AF+T	Bingham and Stone (1972), Stone and Layer (2006)
	51.9 N, 182.9 E	Mt Kanaton volcanics KAN	200 ka	Ar/Ar	5	355.5	65.7	298.9	4.4	−3.5	5.7	−4.6	8.7	AF+T	Bingham and Stone (1972), Stone and Layer (2006)
Amatig-nak	51.25 N, 180.85 E	sediments	∼35 Ma	extrapolation to other islands	6	53.0	57.0	22.0	15.0	−25.5	13.9	−53.5	18.2	AF+T	Stone et al. (1983)
Amchitka	51.4 N, 179.4 E	East Cape Pluton	16 Ma	K-Ar (Carr et al., 1970)	8	173.3	65.5	8.4	20.2	−104.8	23.9	+4.1	38.0	none	Bath et al. (1972)
	51.6 N, 178.4 E	East Cape Pluton	16 Ma	K-A (Carr et al., 1970)	3	188.1	−49.7	55.7	16.7	−26.7	14.9	+10.7	17.7	AF @. 200 Oe	Bath et al. (1972)
	51.6 N, 179.3 E	Amchitka Fm.	>36 Ma	underlies Banjo Pt Fm.	31	too scattered for meaningful interpretation								AF	Stone (1972)

Table 5. Continued.

Island	Locality Lat, Long	Rock Type	Age	Dating Method	N	D	I	k	α_{95}	F	dF	R	dR	demag type	Reference
	51.6 N, 179.3 E	Amchitka Fm.	>36 Ma	underlies Banjo Pt Fm.	31	too scattered for meaningful interpretation								AF	Stone (1972)
	51.6 N, 179.3 E	Amchitka Fm. Core A	>36 Ma	underlies Banjo Pt Fm.	16	–	26.4	4.4	19.9	–	–	–	–	none	Bath et al. (1972)
	51.6 N, 179.3 E	Amchitka Fm. Core B	>36 Ma	underlies Banjo Pt Fm.	17	–	67.7	7.7	13.8	–	–	–	–	none	Bath et al. (1972)
	51.6 N, 178.88 E	White House Cove intrusive	<14Ma	possible source of local alteration of Chitka Pt. Fm (Carr et al., 1970)	16	6.9	69.9	45.3	5.5	−3.5	7.3	+9.4	12.6	none	Bath et al. (1972)
	51.5 N, 179.2 E	Banjo Point volcanics	35 Ma	as below	8	23.0	49.0	8.0	17.0	−28.3	17.1	+29.7	20.8	AF	Stone (1972)
	51.5 N, 179.2 E	Banjo Point volcanics	35 Ma	Late Eocene, micro fossils and molluscs, underlies Chitka Pt. (Carr et al., 1970)	19	173.3	65.5	20.2	8.4	−12.1	24.0	−176.2	38.4	none	Bath et al. (1972)
	51.6 N, 178.75 E	Chitka Point volcanics	14 Ma	Forams, Spores and K-Ar (Carr et al., 1970)	19	39.7	59.3	17.8	8.2	−17.2	8.8	+42.2	11.9	AF @. 200 Oe	Stone (1972)
	51.6 N, 178.75 E	Chitka Point volcanics	14 Ma	Forams, Spores and K-Ar (Carr et al., 1970)	19	52.3	67.3	85.4	4.1	−7.0	4.9	+54.7	8.0	AF+T	Krutikov (2006)
Kiska	52.95 N, 177.5 E	Vega Bay sediments	∼30 Ma	K-Ar	7	327.0	52.0	11.8	15.4	−26.0	17.0	−30.6	20.8	AF	Panuska (1980)
Shemya	52.73 N, 174.13 E	intrusives, samples	12 Ma	K-Ar	56	13.1	80.6	39.8	3.1	13.0	5.2	+14.4	15.6	AF	Cameron and Stone (1970); Stone (1975)
	52.73 N, 174.13 E	intrusives, sites	12 Ma	K-Ar	7	11.2	78.8	147	5.0	10.2	7.6	+12.9	21.0	AF	Cameron and Stone (1970); Stone (1975)
Medny	57.2 N, 167.52 E	Komandorsky	38–54 Ma	Forams, Molluscs and Flora	10	73.0	66.0	12.0	12.9	−20.7	7.5	+65.1	11.7	AF+T	Bazhenov et al. (1992)
	57.2 N, 167.52 E	Medny Fm basalts	34(?) Ma	K-Ar		76.0	52.0	15.0	5.7	−22.0	6.8	+73.1	10.6	AF+T	Bazhenov et al. (1992)
Bering	57.2 N, 166.56 E	sediments	38–54 Ma	fossils and magneto-stratigraphy	260	30.0	69.0	12.4	2.6	−11.7	3.3	+26.3	8.5	T	this study

N – number of sites or samples; D, I – declination and inclination of the magnetization vector; k, α_{95} – Fisher dispersion parameter and radius of the 95% circle of confidence (Fisher, 1953); F – flattening or paleolatitude displacement with respect to the North American plate and error dF; R – rotation with respect to North America with error dR – semi intervals of confidence.

4.5 Quaternary volcanics

The active volcanoes of the arc are commonly geographically confined to the northernmost edge of the arc topography, the main exception is from Atka Island eastwards where the Aleutian ridge widens as it approaches Umnak Plateau and the Bering Sea shelf. The volcanoes sampled for paleomagnetism are all younger than about 2 Ma, and have been extensively studied to investigate secular variations in the Earth's magnetic field (Stone and Layer, 2006). The data from each of the studies in Sect. 4 are given in Table 5, and combined show no rotation or flattening.

4.6 Adak Island

Adak Island (∼177° W) is located in the center of the Aleutian Island arc. The north end of the Island is dominated by three young (<500 kA) volcanic centers, namely Mt Moffett, Mt Adagdak and a subsidiary vent complex known as Mt Andrew. Samples from Mts Adagdak and Andrew were collected and measured in the 1960's (Cameron and Stone, 1970), and selected samples from Mt Adagdak re-measured in 2006 (Krutikov et al., 2008).

4.7 Unalaska Island

The only known data for this island are from Driftwood Bay on the flanks of Makushin volcano and were collected in the 1960's for a paleosecular variation study (Bingham and Stone, 1972). Duplicate samples were re-measured in the 1990's using a stricter protocol combining initial AF demagnetization followed by multi-step thermal demagnetization. These results as listed in Table 5 show no rotation or translation since the extrusion of the flows between about 400 and 800 ka (Stone and Layer, 2006). The Unalaska study was part of a larger project involving volcanic flow sequences on Umnak and Kanaga islands.

4.8 Umnak Island

The east end of Umnak is dominated by Okmok caldera and surrounding volcanic units. These were sampled as part of

Table 6. Paleomagnetic data from Banjo Pt Fm., Amchitka Island.

Locality	Smpl #	Site lat ° N	Site long ° E	Site Demag Am^{-1}	J mAm^{-1}	Ds	Is
Banjo Pt	811	51.50	179.20	15.3	83.2	52.7	50.6
Banjo Pt	812	51.50	179.20	15.3	97.7	344.7	−11.3
Banjo Pt	813	51.50	179.20	15.3	103.6	41.4	52.1
Banjo Pt	814	51.50	179.20	15.3	185.6	8.0	53.9
Banjo Pt	815	51.50	179.20	15.3	202.6	11.0	29.1
Banjo Pt	816	51.50	179.20	15.3	255.8	5.2	35.9
Banjo Pt	817	51.50	179.20	30.6	34.7	75.9	70.6
Banjo Pt	818	51.50	179.20	15.3	193.8	342.3	28.5
Banjo Pt	819	51.50	179.20	15.3	73.5	75.5	66.9
Rifle Rg	806	51.40	179.20	15.3	67.0	238.9	−78.1
Rifle Rg	807	51.40	179.20	15.3	67.0	201.2	−79.3
Rifle Rg	810	51.40	179.20	15.3	25.2	119.8	51.8
Rifle Rg	18	51.40	179.30	30.6	36.2	139.9	−32.6
Rifle Rg	19	51.40	179.30	30.6	29.8	152.7	−53.3
Rifle Rg	20	51.40	179.30	30.6	35.8	137.7	23.4
Rifle Rg	23	51.40	179.30	30.6	14.5	152.4	71.7
Means	Ds	Is	N	R	k	α_{95}	
Banjo Pt	31.3	58.2	9	7.03	4.07	29.20	
Rifle Rg	76.4	82.4	7	5.48	3.95	34.80	
Combined	38.3	69.6	16	12.18	3.92	21.50	
	VGP lat	VGP lon	dm	dp			
Combined	66.8	249.79	36.6	31.3			

Original paleomagnetic data (Stone, 1972), showing sample number; site location; AF – demagnetization level; J – magnetization intensity; Ds, Is – Declination and Inclination of the mean vector in stratigraphic coordinates.

the same paleosecular variation study described under Unalaska Island. The results for the three sets of flows sampled on Umnak Island (Crater Creek, New Jersey Creek and Ashishik) give similar results to those described for Unalaska. They show no significant translation or rotation with the exception of the Ashishik flows, which appear to have recorded a field disturbed by a polarity transition.

4.9 Atka Island

Twelve oriented cores were taken from a single massive flow from the cliffs near the Atka dock (Bingham and Stone, 1972). Since the cooling time of a flow is short compared with the secular variation of the geomagnetic field, this measurement represents a spot reading of the field, and its deviation from a dipole is well within the expected secular variation changes in field direction.

4.10 Kanaga Island

Two sections of young volcanic flows (Mt Kanaton, 200 ka and Round Head, 120 ka) were sampled for paleoscular variation studies (Bingham and Stone, 1972; Stone and Layer, 2006) and show no rotation or translation.

5 Other Paleomagnetic data

These data sets come from various islands and represent data obtained for various reasons ranging from standard paleomagnetic determinations of the ancient geomagnetic field to interpreting aeromagnetic surveys on Amchitka Island. They are listed here for completeness and because of the difficulty in finding many of them in the literature. To the best of our knowledge this comprises the sum total of all paleomagnetic measurements made in the Aleutian Island arc to date.

5.1 Adak Island

Most of the island is mapped as "Finger Bay Volcanics" (Coats, 1956) which are part of the Eocene Lower Series seen throughout the arc (e.g., Vallier et al., 1994). A precise age of 37.4±0.6 Ma for the Finger Bay volcanics on the southern end of the island was recently obtained using $^{40}Ar/^{39}Ar$ dating (Jicha et al., 2006). The Andrew Lake Formation, which immediately overlies the Finger Bay volcanics, was sampled from the north end of the island for paleomagnetic studies in 1967 and 1968. The section studied was largely sedimentary with few volcanic rocks exposed. Selected samples were re-measured in 2006 (Krutikov et al.,2008)

Re-measurement of the Andrew Lake Formation samples clearly show that the characteristic magnetization is an overprint. The data fail the reversal test in both stratigraphic and geographic coordinates, and also fail the fold test ($k_{\mathrm{geog}}/k_{\mathrm{strat}}$=1.53), which means that charateristic magnetization was acquired subsequent to deformation. Since the Andrew Lake Formation samples were collected from outcrops near to two young volcanic centers, Moffett and Adagdak volcanoes, they are prone to both thermal and chemical remagnetization processes. In geographic coordinates, the mean direction is steep and directed southward, which can be interpreted as a result of post-magnetization tilting.

A little south of the volcanic centers are exposures of five andesite domes with K-Ar ages of about 5 Ma. Four of these domes were sampled for paleomagnetic studies. The paleomagnetic signatures of these domes are all different from expected directions and from each other (Cameron and Stone, 1970; Stone, 1975). Individually the domes appear to have a stable magnetization with respect to alternating field demagnetization, and three of the four show reversed polarity (Table 5). No conclusions concerning rotations or translations can be drawn from these data.

5.2 Amatignak Island

The original data sets for this island were not found, only the final results of a 1970's study which are given in Table 5.

5.3 Amchitka Island

Three major subdivisions have been made for the rocks exposed on Amchitka Island, the Amchitka, Banjo Point and Chitka Point formations. The results for the Chitka Point Formation have been discussed in Sect. 3.1, and this section is devoted to the remaining studies.

Amchitka formation

This is the oldest formation (>36 Ma) and is dominated by volcanic breccia flows (Carr et al., 1970). Paleomagnetic data for this formation come from deep drill core sections that give inclination and an arbitrary declination and from fully oriented samples from surface outcrops. The measurements made on the drill cores were in support of interpretations of aeromagnetic anomalies, so were not demagnetized. The fully oriented surface samples gave essentially random directions of magnetization. In some examples the magnetization changed polarity within one sample. These data are most easily interpreted in terms of the breccias cooling below their magnetic blocking temperature while they were still in motion.

Banjo point formation

This formation, exposed on the south-east end of the island, overlies and is generally conformable with the Amchitka Formation. It has an estimated age of 35 Ma based on fossil assemblages (Eocene/Oligocene) (Carr et al., 1970). Two sets of paleomagnetic measurements have been made on samples from surface outcrops, one in support of aeromagnetic surveys that were not demagnetized (Bath et al., 1972) and the other that was given blanket alternating field demagnetization (Stone, 1972). Duplicates of these latter samples have not yet been re-measured, and the original data are too scattered to make a meaningful interpretation. Table 6 gives the data quoted by Stone (1972) and repeated here since the reference is a report to the Atomic Energy Commission that may be impossible to access today.

East cape Pluton

Located at the eastern end of Amchitka this pluton is dioritic in composition with a single K-Ar age of 15.8±0.7 Ma, and was sampled for magnetic properties (Bath et al., 1972). Paleomagnetic data were collected from eight samples, three of which were demagnetized using alternating magnetic fields. These data are given in Table 5 and show that the polarity changes with demagnetization levels as low as 100 Oe (126 Am^{-1}).

White House Cove intrusive

The locality sampled is a small outcrop of what appears to be a much larger intrusive, based on a magnetic anomaly that coincides with the White House Cove location and with two other smaller exposures across the bay. The relationship of the pluton to the Chitka Point Formation is unclear, but it seems likely that it was responsible for some of the alteration seen in the surrounding flow units. On this basis it must be younger than the Chitka Point flows and is thus <14 Ma. Carr et al. (1970) measured the magnetization of sixteen samples, but did no demagnetization experiments. No direct measure of ancient horizontal exists, but because the intruded lavas are effectively horizontal, it is reasonable to assume that no significant post-intrusion tilting has occurred.

5.4 Kiska Island

This island was sampled in the late 1970s as an add-on project to a sedimentologic study (Panuska, 1980). Only nine samples from the Vega Bay Formation were collected, two were rejected and remaining seven gave the results shown in Table 5. The Vega Bay Formation is older than 29 Ma based on a K-Ar age from a basalt fragment in the sediment.

5.5 Shemya Island

Shemya is a small island, roughly 3 km by 6 km, which has been home to the US Air Force since World War II. In contrast to many of the other Aleutian islands, exposure is aided by quarries and road cuts as well as by the usual sea cliffs. The west half of the island has the least exposed units, being underlain by sediment of the Lower Marine series (Eocene) that do not form sea cliffs or provide building material. Only one locality was sampled in this half of the island, and with blanket AF demagnetization did not produce easily interpretable results. However, demagnetization did produce large changes in the groupings of the magnetic directions, that indicate that the samples may respond to detailed thermal demagnetization techniques (Cameron, 1970; Cameron and Stone, 1970). The remainder of the island is made up of interbedded pyroclastic rocks and associated basaltic vents together with hornblende dacite and hornblende andesite porphyrys. These are mid-Miocene in age based on a tholeiitic basalt K-Ar age of 12.3±1.5 Ma and a hornblende dacite age of 15±3 Ma. The results of paleomagnetic studies on these igneous rocks, again using blanket AF demagnetization, give internally consistent results with both normal and reversed polarities but with the overall mean direction being steeper than expected, and showing a few degrees of clockwise rotation (Table 5). These results are with respect to a geographic reference frame and the North American plate. A lack of tilting was inferred, at least for the north side of the island, because the sediment intruded by the basaltic plugs appeared to be flat lying; however, the sediments are largely conglomerate, so the assumption that they are flat lying may well be in error.

5.6 Attu Island

Attu is the westernmost of the American Aleutian Islands. It has been sampled for paleomagnetic studies on two occasions, once by Stone and the University of Alaska group, and once by Rubenstone in association with Harbert at the University of Pittsburgh. Separately these samples gave data that were hard to interpret, but may be easier to unravel when combined; however the data are currently lost in archives.

6 Kamchatka rotations

Many paleotectonic reconstructions of the Aleutian Arc and Kamchatka terranes have been presented (e.g. Kononov, 1989; Bazhenov et al., 1992; Seliverstov, 1998; Levashova et al., 2000a, b; Kovalenko, 2000, 2001; Park et al., 2002; Konstantinovskaya, 2003; et al.). Detailed discussion of these scenarios is beyond the scope of this paper; however they all consider the terranes to be moving, but with many differences in directions, velocities, and associations of related arcs or plates. Significant differences in the proposed times of accretion have been suggested. Few models use paleomagnetic data to discuss rotations associated with the moving terranes and eventual collisions, an exception being Kovalenko (2000, 2001).

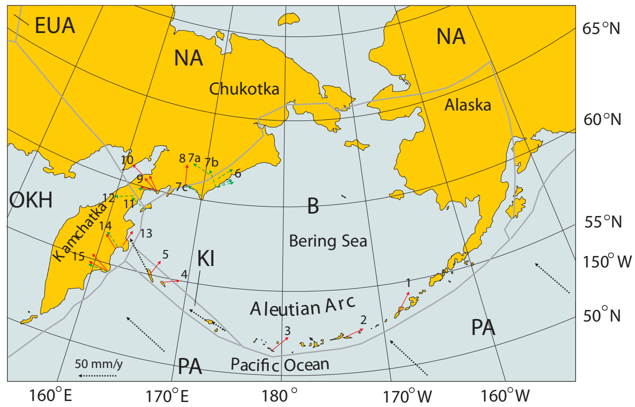

Fig. 11. Rotations and GPS data from Aleutian Arc and Kamchatka. Dashed green arrow – rotation of Upper Cretaceous units, solid red arrow – rotation of Paleogene rocks; dotted black arrow – direction and velocity movement of Pacific Plate and Komandorsky and Aleutian Islands with respect to N. America.
1 – Umnak Island (Harbert, 1987); 2 – Amlia Island (Harbert, 1987); 3 – Amchitka Island (Krutikov et al., 2006); 4 – Medny Island (Bazhenov et al., 1992); 5 – Bering Island (Minyuk, 2004, this paper); 6 – Olyutorsky range (Kovalenko, 1996, 2001; Kovalenko et al., 1998); 7 – Olutorsky terrane (Heiphetz et al., 1994): 7a – Apuka River, 7b – Machevna Bay, 7c – Javevyn Bay; 8 – Malinovsky Range (Kovalenko and Remizova, 1997); 9 – Ilpinsky Peninsula (Kovalenko, 1992, 2001; Minyuk, 2004); 10 – Chemurnaut Bay (Minyuk, 2004) 11 – Karaginsky Island (Kovalenko et al., 1999; Kovalenko and Kravchenko-Berezhnoy, 1999); 12 – Srediny Range (Levashova et al., 1998); 13 – Kamchatsky Cape (Bazhenov et al., 1992; Pechersky and Shapiro, 1996; Pechersky et al., 1997); 14 – Kumroch Range (Levashova et al., 1997, 1998); 15 – Kronotskii Cape (Bazhenov et al., 1992; Levashova et al., 2000a, 2000b), GPS data (Avé Lallemant and Oldow, 2000; Gordeev et al., 2001; Bürgmann et al., 2005; Cross, 2007).

We show the available published paleomagnetic data for rotations in Fig. 11. The red arrows are for locations of Paleogene age and green arrows for Cretaceous ages. Two groups of directions have been identified. The first is located in Kamchatka and Koryakiya and shows counterclockwise rotation, and the second in the Aleutian sector that shows clockwise rotation. It appears that all of Kamchatka was rotated after collision of the Cretaceous and Cenozoic terranes. In contrast to most of the other Kamchatka terranes, Kamchatsky Cape is rotated clockwise. Such a rotation might be expected if Kamchatsky Cape was initially part of the Aleutian Arc (Geist et al., 1994) and was thus rotated along with the Aleutian Islands before the collision and perhaps with Kamchatka since accretion. The argument against the Cape

Kamchatka – Aleutian Arc connection is that Cape Kamchatka has Cretaceous basement, whereas no rocks older than Eocene, or possibly latest Paleocene have been recognized in the Aleutian Arc.

7 GPS Data

The relative motion of the Aleutian Islands today is instructive in unraveling their past motions. Over the last decade GPS measurements for the Aleutian and Komandorski Islands and for Kamchatka locations have increased dramatically. As can be seen from Fig. 11, the Komandorsky Block is moving rapidly westward along the Arc heading for Kamchatka (Avé Lallemant and Oldow, 2000; Gordeev et al., 2001; Bürgmann et al., 2005; Cross, 2007). Extrapolating back through time allows Bering Island to be located at about the longitude of the central Aleutian Arc in Paleogene time. A similar travel path was also suggested by Rostovtseva and Shapiro (1998) based on the composition of the sedimentary rocks on Bering Island. The composition requires that the source of the sediment was an active volcanic area that included metamorphic and ultramafic complexes. They related this to Shirshov-Bowers ridge the south end of which is now adjacent to the central Aleutians. If the Komandorsky Islands followed a path from the central Aleutians to their present location, this could account for both the observed rotation and latitude changes observed in the Komandorsky Islands.

8 Discussion

All five of the most reliable Aleutian Arc sites show clockwise rotations of the islands. Within the 95% error limits the islands have similar, but not necessarily overlapping rotations. For the three western islands, Amchitka, Medny and Bering, these data generally support idea of block structures within the Aleutian Arc rotating in response to the oblique convergence of the Pacific plate (Geist et al., 1988). This leaves open the question as to how and why the easternmost islands, Amlia and Umnak, rotated since there is little or no postulated oblique subduction there. It is also of interest to note that none of the Pleistocene volcanoes show rotation, however they are located on the northern edge of the arc, and thus largely isolated from the block rotations. The oldest known rotated parts of the Aleutian Arc are Bering and Medny islands located at the far western end. These islands are of Eocene, possibly Paleocene age. The youngest rotation is of Middle Miocene age from Amchitka Island, but there is no information on when any of the rotations took place.

Taking into account motion of the Pacific and Kula plates relative to the North American plate, it would appear that the convergence in the vicinity of Umnak Island from Late Eocene to present has been roughly perpendicular to the arc. This would preclude block rotations as the cause of the observed clockwise motion. The Umnak data also indicate little or no latitudinal motion with respect to North America indicating that it must have been more or less in-place. Further west, near Amlia Island, some oblique plate convergence is possible, and the presence of Amlia basin north of the island is evidence for block rotation of about 10°–20° leaving a balance of the observed rotation approximately the same as that observed for Umnak Island. The paleolatitude determination for Amlia Island also shows no relative northward translation, but with significant error bars (±12°). Further west, Amchitka Island exhibits evidence of block rotation in both the morphology of its surroundings and in the paleomagnetic data. It is also moving westwards today along the curve of the Aleutian Arc which introduces further rotation (Cross, 2007). The paleomagnetic data from Amchitka indicate a few degrees of northward translation. In the far west, the Komandorsky islands show clockwise rotations and significant northward motion with respect to North America. The rotation and northward translation of Medny Island are both roughly twice as large as those recorded for Bering Island. Both rotations and latitude changes for the Komandorki islands and Amchitka Island can be accounted for by block rotations while being driven westwards along the curved arc, but similar models cannot be applied to Umnak and Amlia islands.

A possible model that can account for both block rotations as proposed by Geist et al. (1988) for the western part of the arc as well as rotations observed in the eastern part of the arc, where they would not be expected, is shown in Fig. 12. This model is based on a model by Scholl (2007) but with the propagation of the ancestral Aleutian Arc from the Alaskan mainland into the Pacific taking a more southerly trend (Fig. 12a). Following the initiation of the Aleutian Arc the Komandorski islands were part of the forearc located east-southeast of their current locations with respect to North America. Following the capture of Bowers ridges by the migrating Aleutian Arc, the Komandorsky islands started to move westwards and northwards. The Umnak and Amlia island sediments were deposited before the central part of the arc itself began to uncurl northwards (Fig. 12b). The volcanic rocks on Amchitka Island were erupted when the arc was roughly the shape it is today and were moved westwards by the oblique subduction and underwent local block rotation as proposed by Geist et al. (1988) (Fig. 12c).

9 Conclusions

Recent paleomagnetic data from Paleogene rocks on Bering Island show good paleomagnetic stability through two sections. The reversal stratigraphy of these sections when compared to the global magnetostratigraphic record indicate that Buyan and Mys Tolsty suites are of Early-Middle Eocene age and correlate with chrons 17r to 24r. This would make them the oldest rocks found in the Aleutian Arc. The data set passes reversal tests between different polarity zones in each section, and a paleomagnetic fold test. Because the dip of these sediments is very small and sampled sections are basically monoclinal, all the samples from the two sections were used for the fold test. After removal of data from polarity transitions and inconsistent behavior on heating, 260 sites remained. These data were used to determine the rotation and inclination changes for Bering Island. These data show that Bering Island rotated in a clockwise direction by 26.3°±8.8° with respect to the North American Plate. During deposition of the sediments studied the Island was located at a more southerly paleolatitude of 53° (expected 65°). The rocks studied consist of sandstone, siltstone, mudstone and diatomite, so it is possible that there was some post depositional shallowing of the inclination by compaction. However, the several different lithologies involved and the internal consistency of the data set allows some confidence in the resulting paleolatitude. Bering Island thus moved northward 12° post deposition. Medny Island shows a greater amount of clockwise rotation than Bering Island. Here, Paleogene rocks rotated clockwise by 70°±14° and had a paleolatitude of 48° (expected 65°) with respect to the North American Plate (Bazhenov et al., 1992). Medny Island thus moved northward 17° post deposition. Thus, the far western part of the Aleutian Arc (the Komandorski Island block) has rotated in a clockwise direction and was located at more southern latitudes.

Excluding the quaternary volcanic rocks, the only other data available for the west and central Aleutians are from Amchitka Island (Krutikov et al., 2008). The Middle Miocene Chitka Point Formation shows normal and reversed magnetization with almost anti-parallel directions, but because there are only three reversed samples the data do not pass reversal test of McFadden and McElhinny (1990). The closeness of the reversed and normal data plus the good distribution of magnetic directions are interpreted as showing that there was no significant latitudinal motion of Island later than Middle Miocene time, but there is a clear clockwise rotation of 55°±8° with respect to the North American Plate and a paleolatitude of 50° (expected 57°).

On east end of the Aleutian Arc there are data from Upper Eocene-Lower Oligocene rocks of Umnak Island and Amlia Island (Harbert, 1987). The data from Umnak Island pass a reversal test following McFadden and McElhinny (1990) while Amlia Island data show that the Fisher precision parameter k increases after tilt correction. These data suggest a rotation for Umnak Island of 36.7°±11.2° and 70°±23° for Amlia Island R=70°±23°, F=−4°±5°. Neither data set shows significant latitude movements.

The model presented to explain these rotations and latitude changes involves an initial Aleutian Arc bowed to the south. This greater curvature prior to the deposition of the sediments on Umnak and Amlia islands can explain their paleomagnetic data, the remainder of the rotations and paleolatitude changes can be explained by local block rotations and translation along the curvature of the arc.

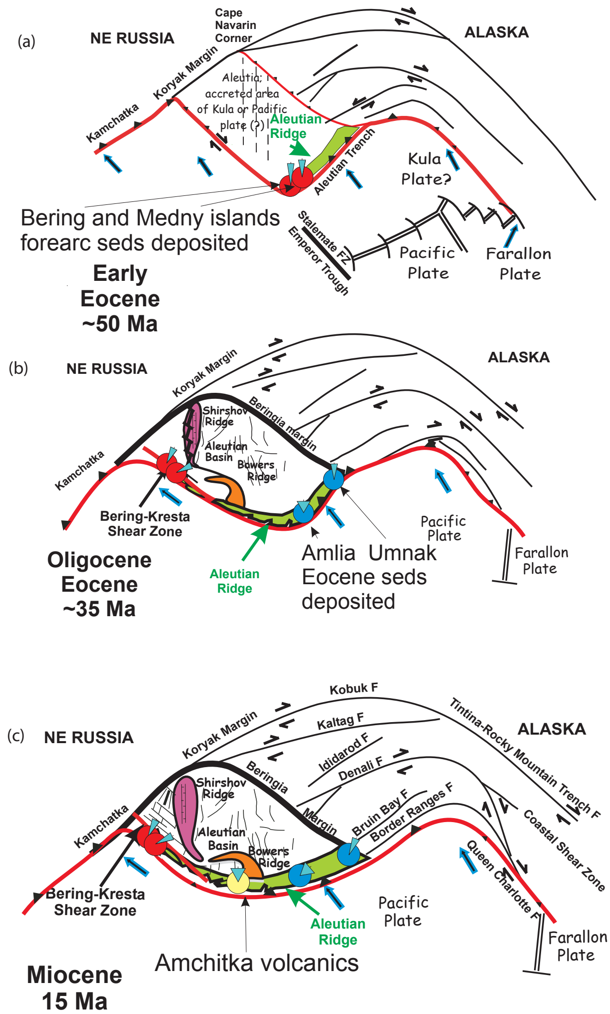

Fig. 12. **(a)** Schematic map of the Gulf of Alaska region in Early Eocene time loosely based on Scholl (2007). Interior and southern Alaska lie between the ancestral faults shown and labeled in Fig. 12c. The Aleutian arc is propagating southwestwards across the Pacific progressively shutting down the Bering Sea shelf and Koryak subduction zone. The fore-arc sediment that now resides in the Komandorsky Islands was being deposited at this time and is shown with the observed paleomagnetic directions aligned with magnetic north. As the Komandorsky Islands moved west, they passed both Bowers and Shirshov ridges which are the presumed source of the cobbles of granite and metamorphic rocks in the fore-arc sediments. **(b)** By Oligocene-Eocene time the Aleutian arc has cut off all of the Bering sea and trapped the Bowers-Shirshov subduction zone. The Komandorsky Islands have been transported along the arc by oblique subduction of the Pacific plate, and probably rotated about vertical axes. The sediment deposited at Amlia and Umnak islands recorded magnetic north for this time. **(c)** Between Oligocene and Miocene times the Bering/Koryak subduction zones were reactivated and the Aleutian arc uncurled before the Amchitka volcanics were erupted. After they were erupted oblique subduction moved blocks of the fore-arc westwards and imparted a significant clockwise rotation to Amchitka.

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