島弧の移動と合体のダイナミクス：北西太平洋縁辺における構造論的事例

言語: en
出版者: InTech
公開日: 2019-07-29
キーワード (Ja): 島弧ー海溝系, 収束境界, 地球科学, 地化学, 地質学, 地球物理学, 太平洋, 古地理復元, 古地磁気学, 岩石学, プレート運動, 岩石磁気学, 堆積盆, 層序学, 応力ー歪, テクトニクス
キーワード (En): arc-trench system, convergent margin, earth science, geochemistry, geology, geophysics, Pacific, paleogeographic reconstruction, paleomagnetism, petrology, plate motion, rock magnetism, sedimentary basin, stratigraphy, stress-strain, tectonics, forearc basin, unconformity event, basin-filling stratigraphy, northwestern Pacific margin, plate tectonics, allochthonous block, lateral migration, Cretaceous, central Hokkaido, Jurassic, Sorachi group, Kumaneshiri group, Asian continental margin, Hokkaido, paleostress, anisotropy of magnetic susceptibility, fracture, marginal sea, northwestern Pacific, Philippine Sea Plate
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Chapter 2

Cretaceous Research: Paleolatitudes and Northward Migration of Crustal Fragments in the NW Pacific Inferred from Paleomagnetic Studies

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/67359

Abstract

Lateral migration of the Oshima and Sorachi-Yezo Belts within south central Hokkaido was quantitatively evaluated by means of paleomagnetic analyses in order to identify allochthonous blocks on the northwestern Pacific margin. The remanence stability of the Late Jurassic to Early Cretaceous voluminous igneous succession of the Kumaneshiri and Sorachi Groups and the overlying forearc sediments of the Cretaceous Yezo Group was evaluated through rock magnetic experiments. Twelve of the sites yielded characteristic primary components residing in mixtures of titanomagnetite and hematite having various mixing ratios. After an appropriate correction of inclinations' shallowing of the post-depositional detrital remanent magnetization (pDRM) based on anisotropic acquisition experiments of the isothermal remanent magnetization (IRM), we confirmed significantly shallow inclinations even for the flattening-corrected data set, implying northward transportation after the emplacement. Based on comparisons to expected paleomagnetic directions calculated from contemporaneous reference poles, we conclude that the allochthonous blocks, including south central Hokkaido, migrated northerly during the Early Cretaceous. Previous investigations of paleomagnetism and numerical modeling of burial processes of sedimentary basins indicate that some crustal blocks in Hokkaido and NE Japan experienced delayed transportation and eventually amalgamated with the mother continent by the end of the Paleogene.

Keywords: paleomagnetism, allochthonous block, lateral migration, Cretaceous, central Hokkaido

1. Introduction

The main part of the longitudinal mountainous range of Hokkaido is called the Sorachi-Yezo Belt (**Figure 1**). It is characterized by the occurrence of a Jurassic ophiolite (the Lower Sorachi Ophiolite) and a Cretaceous forearc basin sequence (the Nitarachi–Yezo Sequence). This ophiolite-forearc basin sequence is underlain tectonostratigraphically by Cretaceous accretionary complexes, whose eastern margin is defined as the Idonnappu Zone. Well-preserved accretion constituents have long been targets of geological surveys aiming to elucidate the evolutionary process of a longstanding arc-trench system (e.g., [1–3]). An implicit assumption in these studies was that the east-verging accretion had occurred somewhere along the northeastern Asian convergent margin and had a close genetic relationship with the autochthonous Cretaceous volcanic arc in the Sikhote Alin, Russia.

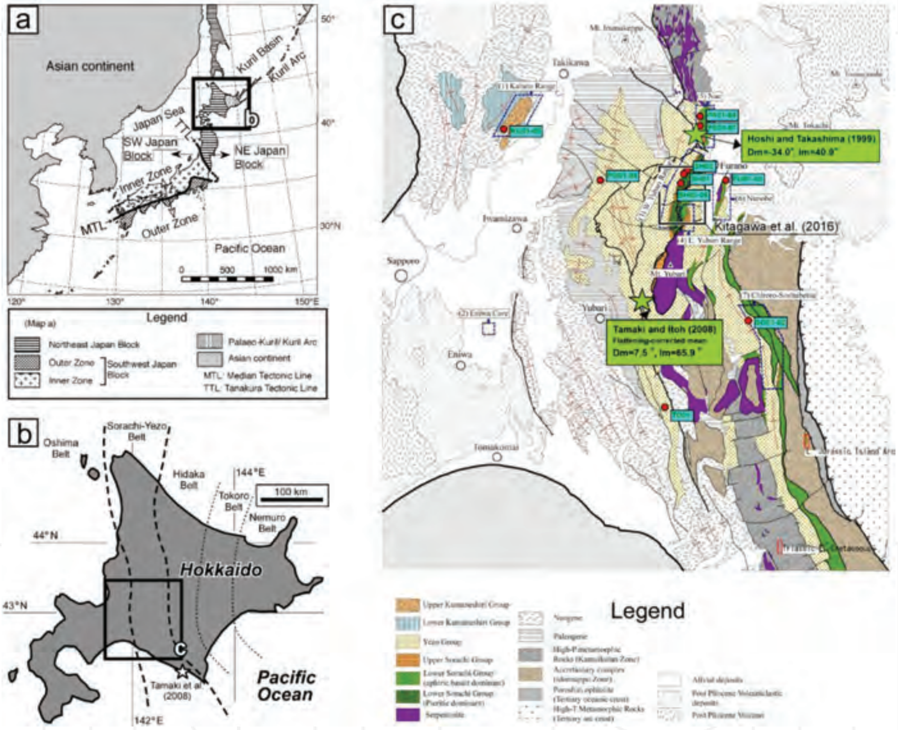

Figure 1. Index maps of study area. (a) Regional configuration and constituents of the Japanese Islands. (b) Pre-Cenozoic tectonic divisions in Hokkaido. (c) Geologic units around the sampling areas. Paleomagnetic sampling points are shown by dots. Stars and an enclosure indicate areas of previous paleomagnetic studies [4, 7, 10, 11].

However, recent paleomagnetic studies have cast doubt on part of the Mesozoic arc constituents having originated from a remote area. Tamaki et al. [4] found that the Upper Yezo Group (Campanian: [5]), distributed in the Urakawa area, preserves stable detrital remanent magnetization (DRM) characterized by a significantly shallow inclination. Compared to the expected

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geomagnetic directions in northeastern Asia, untilted and flattening-corrected paleomagnetic directions require northward transportation of the Urakawa area by as much as 3400 km since the Cretaceous. The DRM of the Middle Yezo Group in the Oyubari area in central Hokkaido (**Figure 1c**; Cenomanian/Turonian: [6]) shows fairly deep inclinations, suggestive of an autochthonous origin [7], and the presumed Cretaceous Yezo forearc basin in East Asia (e.g., [8]) may be divided into some blocks with quite different tectonic histories.

To unravel this paradox, we executed paleomagnetic analyses on the Kumaneshiri, Sorachi, and Yezo Groups around the southern part of central Hokkaido (**Figure 1c**) in the course of the present study. Comparing the flattening-corrected inclination values obtained from the volcanic arc components and forearc sediments, we verified the self-consistency of the migration hypothesis of the ancient arc-trench system. The authors submit a quantitative constraint on tectonic models of the East Asian convergent margin.

2. Geological setting and sampling

Voluminous Late Jurassic to Early Cretaceous igneous and volcaniclastic rocks associated with tuffaceous sedimentary rocks are distributed in the Oshima and Sorachi-Yezo Belts of Hokkaido (**Figure 1b**) and are called the Kumaneshiri and Sorachi Groups, respectively. They both originated from subaqueous volcanism and show a strong resemblance in stratigraphic succession. **Figure 2** presents composite columnar sections of the late Mesozoic strata for selected survey areas. Takashima et al. [9] confirmed gravels of oolitic limestone and trachyandesite suffering subaerial oxidation in the lower part of the Nunobe Formation and deemed that part of the igneous rocks of the Sorachi Group was derived from island arcs. The presence of the oolitic limestone also implies sedimentation under a considerably warm climate.

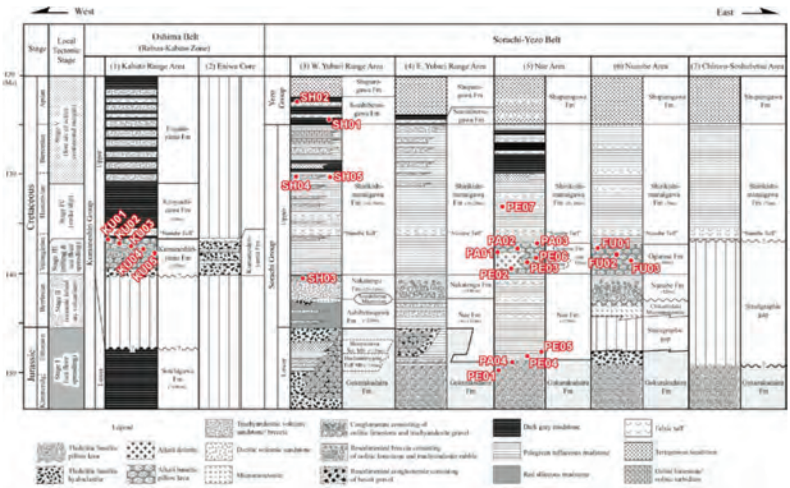

Figure 2. Composite columnar sections of the late Mesozoic strata for selected areas. See **Figure 1** for locations. Paleomagnetic sampling horizons are attached on the columns. The horizons of SO01, SO02, and TO01 are out of the range of the columns.

Because secondary magnetization caused by harsh alteration overprinted the magnetism, there are only a limited number of previous paleomagnetic works on the Sorachi Group. Hoshi and Takashima [10] measured remanent magnetization in dolerite and basalt (pillow lava) samples and obtained a shallow mean inclination implying northward transportation after emplacement. Large scatter in their data hindered precise discussion, but then Kitagawa et al. [11] analyzed limestone, volcaniclastic rock, and andesite with wider spatiotemporal coverage and reconfirmed significantly shallower inclinations than were expected for the coeval mother continent.

In this study, we obtained core samples to measure paleo- and rock magnetism at five sites from the Kumaneshiri Group (KU01–05), 17 sites from the Sorachi Group (FU01–03, PA01–04, PE01–07, SH03–05) and nine sites from the overlying Yezo Group (PO01–04, SH01–02, SO01–02, TO01) as shown in **Figures 1** and **2**. The lithofacies for all the sites are summarized in **Table 1**. Cores 25 mm in diameter were taken from each site using an engine drill, and the individual cores were oriented with a Brunton compass mounted on an aluminum orientation table. Along survey routes, sampling sites were selected to ensure that the structural attitudes needed for the tectonic tilt correction of paleomagnetic directions were clearly defined on outcrops. In the laboratory, cylindrical specimens 25 mm in diameter and 22 mm long were cut from each core sample.

Site	Lithology	Route
Yezo Group		
PO01	Silty tuff (weakly bioturbated)	Ponbetsu River (Nanashi Stream)
PO02	Medium sand-size tuff	Ponbetsu River (Nanashi Stream)
PO03	Medium – fine sand-size tuff	Ponbetsu River (Nanashi Stream)
PO04	Calcareous nodule	Ponbetsu River (Nanashi Stream)
SH01	Acidic tuff	Shirikishimanai River
SH02	Very fine sandstone	Shirikishimanai River
SO01	Tuffaceous mudstone	Soshubetsu River
SO02	Tuffaceous mudstone	Soshubetsu River
TO01	Acidic tuff	Hobetsu (Tomiuchi)
Kumaneshiri Group		
KU01	Pillow basalt	Kabato Range
KU02	Pillow basalt	Kabato Range
KU03	Basaltic volcaniclastic rock	Kabato Range
KU04	Basaltic volcaniclastic rock	Kabato Range
KU05	Basaltic volcaniclastic rock	Kabato Range
Sorachi Group		
FU01	Dolerite dike	Furano (Nunobe)
FU02	Pillow basalt	Furano (Nunobe)

Site	Lithology	Route
FU03	Pillow basalt	Furano (Nunobe)
PA01	Pillow basalt	Panketeshimanai River
PA02	Dolerite dike	Panketeshimanai River
PA03	Pillow basalt	Panketeshimanai River
PA04	Pillow basalt	Panketeshimanai River
PE01	Pillow basalt	Penketeshimanai River
PE02	Dolerite sill	Penketeshimanai River
PE03	Pillow basalt	Penketeshimanai River
PE04	Volcanic sandstone	Penketeshimanai River
PE05	Volcanic sandstone	Penketeshimanai River
PE06	Mudstone	Penketeshimanai River
PE07	Acidic tuff	Penketeshimanai River
SH03	Oolitic limestone (turbidite)	Shirikishimanai River
SH04	Volcanic fine sandstone containing mud patch	Shirikishimanai River
SH05	Volcanic mudstone	Shirikishimanai River

Table 1. Description of paleomagnetic samples.

3. Paleomagnetism

3.1. Basic methods

Bulk initial magnetic susceptibility was measured for all the specimens using a Bartington susceptibility meter (MS2). We conducted progressive thermal demagnetization (PThD) tests on selected pilot specimens from each site, except on samples that were too fragile for repeated heating, for which progressive alternating-field demagnetization (PAFD) testing was adopted. Natural remanent magnetization (NRM) was measured using a cryogenic magnetometer (760-R SRM, 2-G Enterprises) in a magnetically shielded room at Kyoto University and spinner magnetometers (SMM-85, Natsuhara-Giken; SSM-1A, Schonstedt Instrument) at Osaka Prefecture University. The PThD test was performed up to 680°C in air using a noninductively wound electric furnace with an internal residual magnetic field of less than 10 nT. The PAFD test was carried out stepwise up to 100 mT with a three-axis tumbler contained in μ-metal shield envelopes.

3.2. Demagnetization tests

Figure 3 depicts typical results of the PThD testing showing in situ coordinates. Focusing on the Pinneshiri area in the Kabato Range, for five sites in the Kumaneshiri Group (KU01–05), we found the stable components to have a converging trend on origin of the vector-demagnetization diagrams across a broad distribution of unblocking temperatures (T_{UB}) up to 600°C after the northerly component was demagnetized at around 300°C. In the eastern part of the sampling region (the Nokanan area), we successfully isolated similar high-T_{UB} components of remanent magnetization for five sites in the Sorachi Group (PE04, PE07, and SH03–05) and two sites in the lower Yezo Group (SH01–02). The directions of the characteristic remanent magnetization (ChRM) were calculated using a three-dimensional least squares analysis technique after [12].

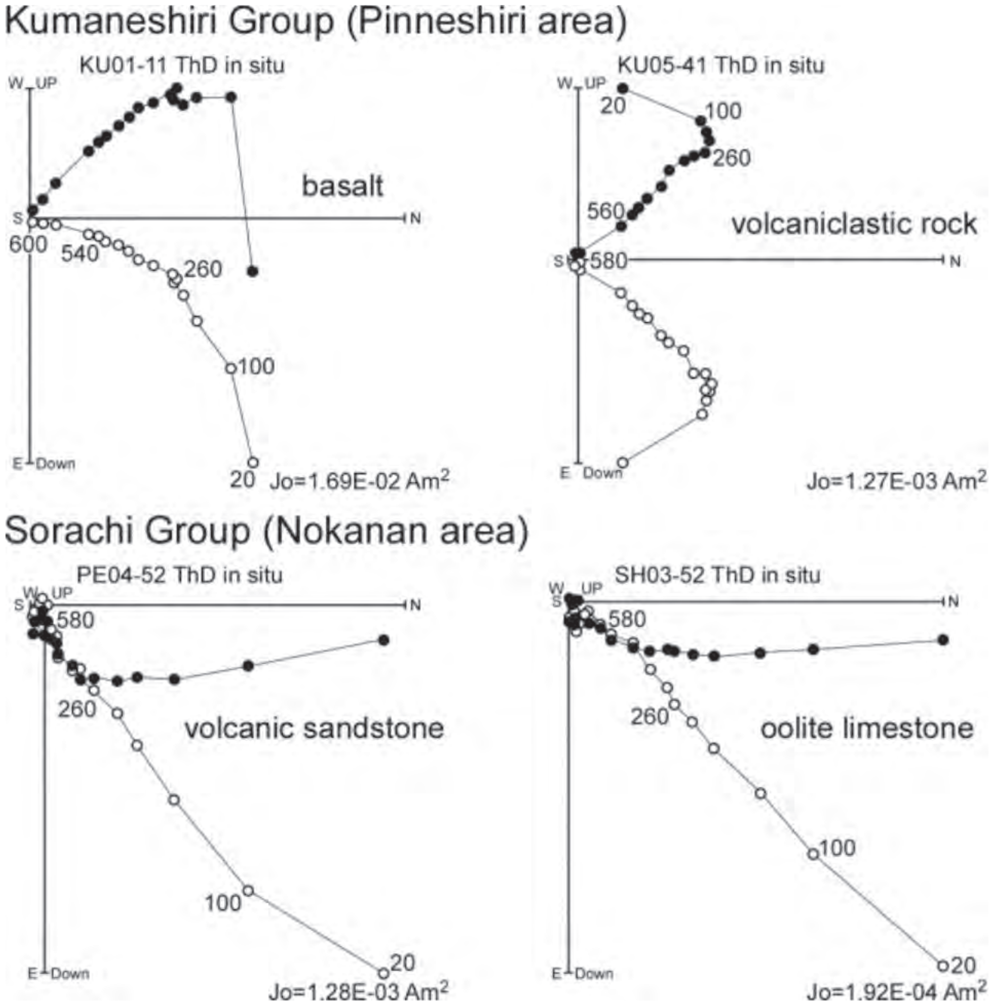

Figure 3. Typical results of progressive thermal demagnetization (PThD) in in situ coordinates. On the vector-demagnetization diagrams, solid (open) circles are projections of vector end-points on a horizontal (N-S vertical) plane. Numbers are demagnetization levels in °C.

Five site-mean ChRM directions obtained from the Kumaneshiri Group show normal polarity, and the precision parameter (κ) improves after tilt correction (**Figure 4**). Seven sites in the

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Sorachi and Yezo Groups in the Nokanan area are clustered into antipodal ChRM directions (**Figure 4**), which after polarity inversion, pass a positive reversal test at a 95% confidence level ($f = 1.04 < Fc$) after [13]. Although more rigorous verification may be desirable, we tentatively regard the two data sets as primary records of the earth's dipole field and utilize them for tectonic discussion.

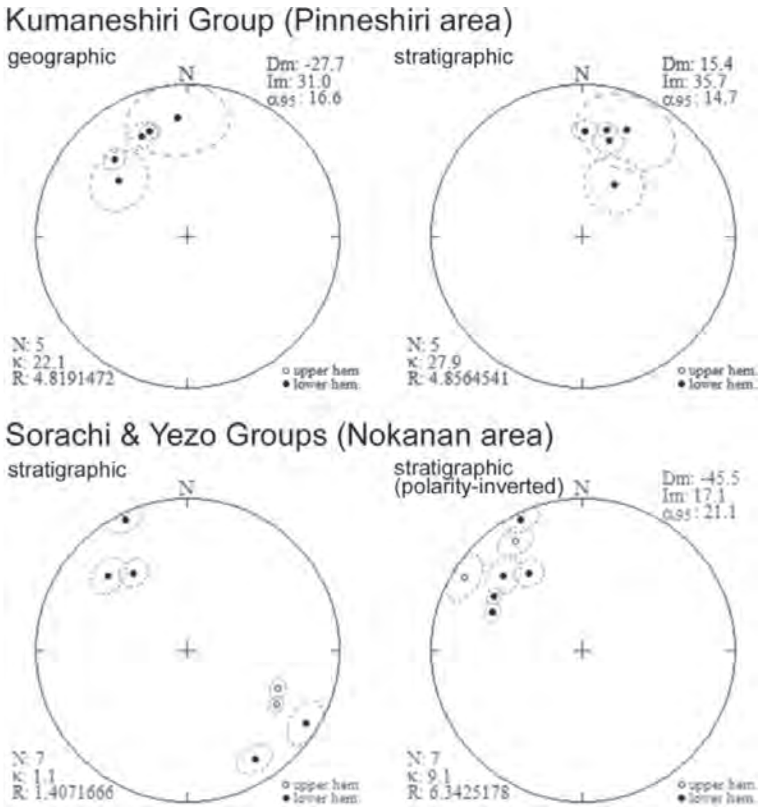

Figure 4. Site-mean directions of high T_{UB} components of the Kumaneshiri, Sorachi, and Yezo Groups in geographic and stratigraphic coordinates on equal-area projections. Solid (open) symbols are on the lower (upper) hemisphere of the equal-area projections. Dotted ovals are 95% confidence limits of site-means.

3.3. Identification of ferromagnetic minerals

3.3.1. Spectrum of coercive force (H_C)

In order to identify carriers of magnetic components in the samples, we undertook isothermal remanent magnetization (IRM) experiments. Stepwise IRM acquisition was performed according to an analytical technique developed by Kruiver et al. [14]. **Figure 5** shows the linear acquisition plot (LAP) and gradient of acquisition plot (GAP) of the IRM acquired in direct magnetic fields of up to around 3 T. As shown by these examples, the plots generated from a majority of the IRM data can be matched by single magnetic components with relatively low $B_{1/2}$ values (the field at which half the IRM saturation is reached), indicating the existence of low H_C ferromagnetic minerals. On the basis of the T_{UB} spectra mentioned before, we believe the remanent magnetization of the major samples resides in titanomagnetite.

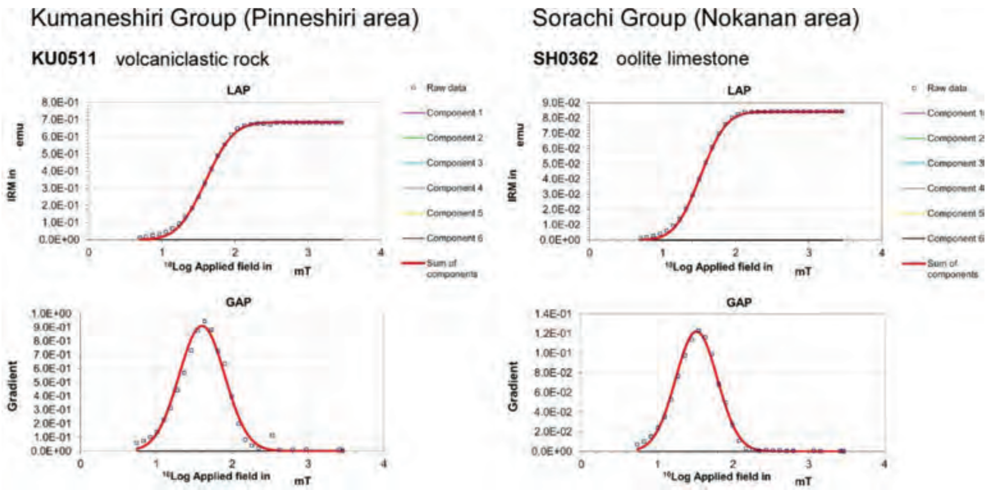

Figure 5. Linear acquisition plot (LAP) and gradient of acquisition plot (GAP) of the isothermal remanent magnetization (IRM) acquired in direct magnetic fields of up to around 3 T. Specimens were processed after alternating field demagnetization at 100 mT.

3.3.2. Thermal demagnetization of orthogonal IRMs

We performed PThD of composite IRMs on selected specimens. Based upon the procedure proposed by Lowrie [15], composite IRMs were imparted by applying direct magnetic fields of 3.0, 0.4 and then 0.12 T to the specimens in three orthogonal directions. As shown in **Figure 6**, the decay curve of the IRM components derived from PThD testing indicates that the dominant magnetic phase is generally the low H_C (<0.12 T) soft fraction with a broad spectrum of T_{UB} up to 580°C. In such a case, the major carrier of the high-T_{UB} component of the NRM is titanomagnetite. Smaller amounts of medium ($0.12 < H_C < 0.4$ T) and hard ($0.4 < H_C < 3.0$ T) fractions were identified. As for the basaltic rocks of the Kumaneshiri Group (KU0141, KU0231, and KU0511), a minor medium fraction is interpreted to be carried by fine (SD-size) grains of magnetite because they have T_{UB} spectra up to 580°C. A small amount of the hard fraction in volcanic samples (PE0421 in the Sorachi Group, SH0111 in the Yezo Group) is carried by hematite because they have T_{UB} spectra up to 680°C. These experiments clarified that the single-component NRMs preserved in samples of the Kumaneshiri, Sorachi and Yezo Groups are carried by a mixture of titanomagnetite and hematite mixed in various ratios.

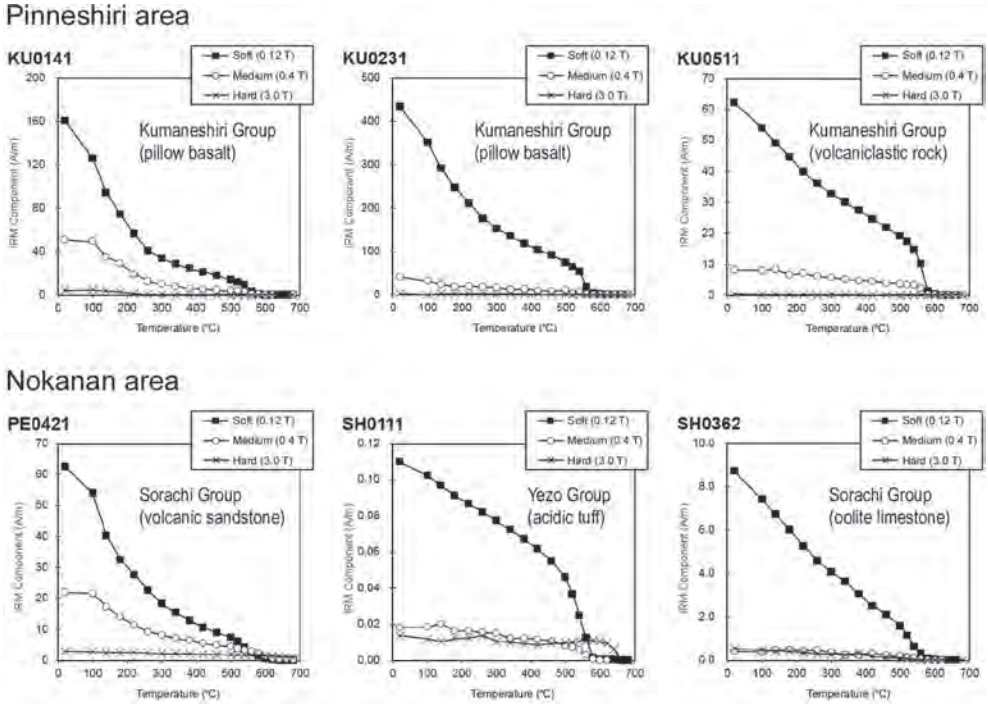

Figure 6. Thermal demagnetization curves of orthogonal IRMs for representative samples.

3.4. Magnetic fabric

3.4.1. Anisotropy of magnetic susceptibility

In order to describe the magnetic fabric of the samples, we determined each specimen's anisotropy of magnetic susceptibility (AMS). Measurement was done using a KappaBridge KLY-3S magnetic susceptibility meter (AGICO). All the results of AMS measurements are presented graphically in **Figure 7** except for site KU01, for which there were too little data to obtain statistical parameters. The tilt-corrected AMS fabric (principal susceptibility axes) presented on an equal-area projection for the volcanic and volcaniclastic rocks (e.g., FU01–03, KU02–05, PA01–04, PE01–03, SH01) seems to be irrelevant to the sedimentary surface (horizontal plane). On the other hand, a majority of the sedimentary rocks (e.g., PE04–06, PO01–04, SH02, SO01–02) exhibit arrangements of AMS axes bound to the bedding plane, namely, the minimum axis (K_3) is nearly perpendicular to the bedding in stratigraphic coordinates, which suggests that the samples preserve the original sedimentary structure without significant tectonic distortion, and the T parameter has positive values indicative of oblate fabric. Because the microfabrics being bound to the bedding plane may introduce shallowing of inclinations of the post-depositional detrital remanent magnetization (pDRM), we tested the degree of remanence anisotropy as described in the next section.

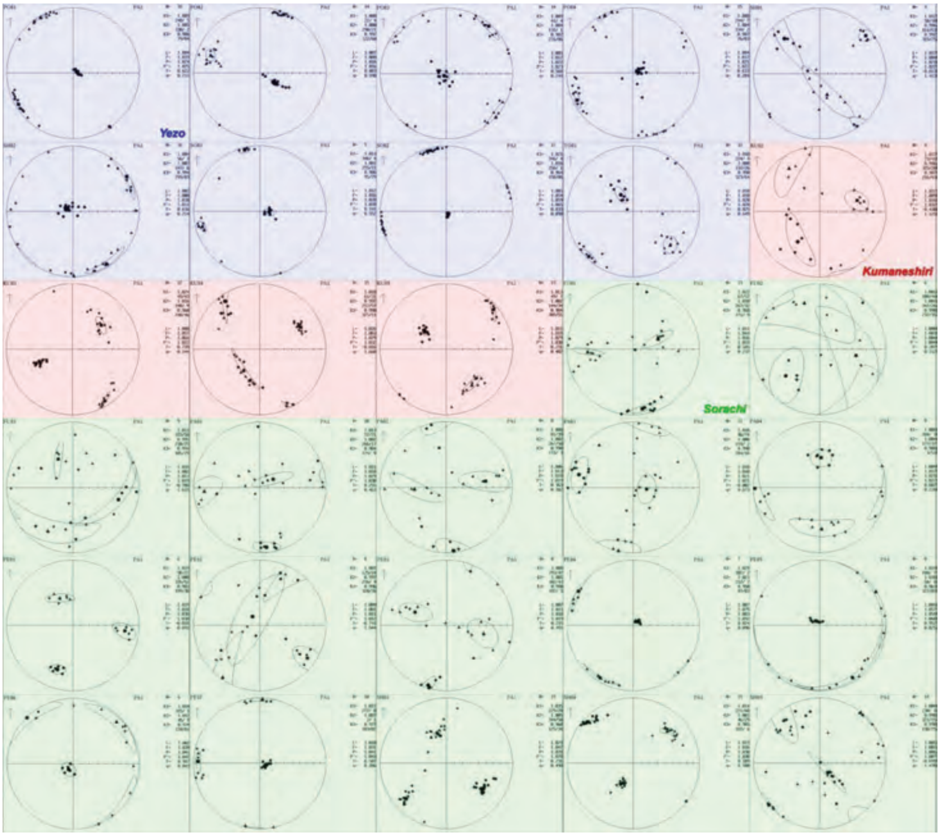

Figure 7. Anisotropy of magnetic susceptibility (AMS) fabric (principal susceptibility axes) for all specimens from each site of the Kumaneshiri, Sorachi and Yezo Groups plotted on the lower hemisphere of an equal-area projection. Data are shown in stratigraphic coordinates. Square, triangular and circular symbols represent orthogonal maximum (K_1), intermediate (K_2), and minimum (K_3) AMS principal axes, respectively, and larger symbols show their mean directions. Ovals surrounding the mean directions of the three axes are 95% confidence regions based upon Bingham statistics.

3.4.2. Anisotropy in IRM acquisition

We performed inclination shallowing testing based on the method of [16] using IRM anisotropy. On one specimen per site, from which we obtained the ChRM, we applied a direct magnetic field at 45° to the bedding plane to avoid any field impressed anisotropy [17]. We then measured the IRM, which was parallel (IRMx) and perpendicular (IRMz) to the bedding. **Figure 8** shows typical IRM acquisition curves for IRMz and IRMx. The value of IRMz is lower than IRMx for the entire range of acquisition (**Figure 8a**), suggesting that ferromagnetic minerals carrying NRM are anisotropic and follow a similar trend. The ratio IRMz/IRMx can be uniquely related to the amount of inclination shallowing ($\tan I/\tan I_F$ = IRMz/IRMx; I_F = inclination of the field in which remanence was acquired). The average IRMz/IRMx ratio for each sample was determined from the best-fit slope of IRMz against IRMx (**Figure 8b**).

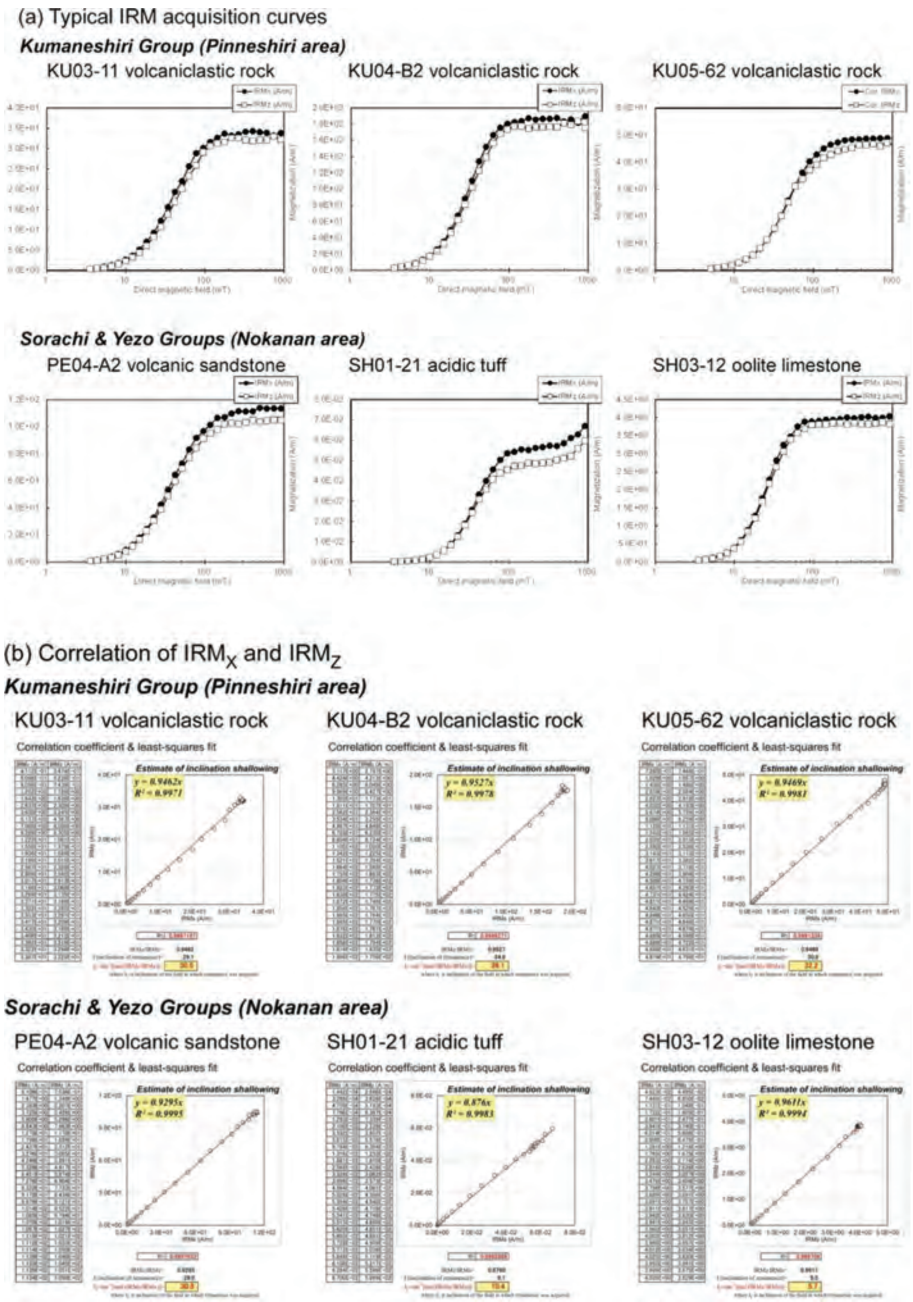

Figure 8. (a) Typical IRM acquisition curves for the bedding-normal (IRMz) and bedding-parallel components (IRMx) for selected samples. (b) Gradient of the best-fit correlation line of IRMz versus IRMx used to determine the IRMz/IRMx ratio, which gives an estimate of inclination shallowing in the sediments.

4. Discussion

4.1. Implications of shallowing correction

Inclination shallowing was found for most of the analyzed samples. As the shallowing occurred during postdepositional compaction prior to tectonic tilting, we applied the shallowing correction for the untilted data set in the study area. **Figure 9** presents the primary magnetic directions of the Kumaneshiri, Sorachi, and Yezo Groups before and after shallowing correction. As suggested by Jackson et al. [18], anisotropy of IRM or anhysteretic remanent magnetization (ARM) may decrease as a result of postdepositional processes such as electrostatic and coagulation effects, whereas the direction of the primarily acquired pDRM is immune from such secondary effects. In that case, our flattening estimation, based on IRM anisotropy, may underestimate the actual amount of inclination flattening. Our corrected data set (**Table 2**) would then provide a minimum estimate of the paleolatitude. Based on the assumption that the data sets are records of the earth's dipole magnetic field, the inclinations of formation-means for the Pinneshiri and Nokanan areas correspond to paleolatitudes of 20°N and 9°N, respectively.

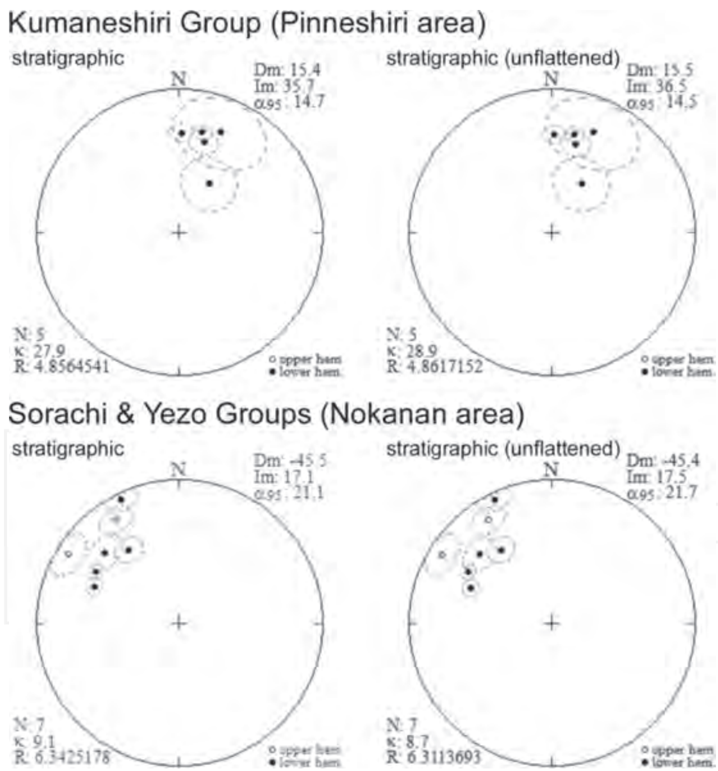

Figure 9. The primary magnetic directions of the Kumaneshiri, Sorachi and Yezo Groups before and after inclination shallowing correction in stratigraphic coordinates on equal-area projections. Solid (open) symbols are on the lower (upper) hemisphere of the equal-area projections. Dotted ovals are 95% confidence limits of site-means.

Site	N	D (°)	I (°)	D_C (°)	I_C (°)	I_F (°)	α_{95} (°)	κ
Yezo Group								
SH01	8	−174.7	−71.4	121.7	9.1	10.4	10.3	26.4
SH02	9	−116.9	−17.7	113.1	−35.6	−38.1	4.7	121.2
Kumaneshiri Group								
KU01	9	−4.8	22.5	22.3	25.0	25.0	23.2	5.9
KU02	7	−51.0	41.1	31.4	57.4	57.4	15.7	15.7
KU03	7	−19.7	27.6	12.9	29.1	30.5	4.8	158.5
KU04	7	−24.4	28.1	15.0	34.8	36.1	7.7	62.6
KU05	7	−43.4	30.5	1.0	30.8	32.2	5.9	106.6
Sorachi Group								
PE04	7	54.6	49.8	−46.7	29.0	30.8	9.3	43.5
PE07	7	−146.5	−57.9	121.5	−31.9	−31.9	4.2	158.7
SH03	11	40.6	39.9	−25.2	5.5	5.7	7.7	36.4
SH04	8	67.2	29.4	−34.7	37.7	37.7	7.6	53.4
SH05	8	−172.0	−49.3	148.3	16.5	16.7	8.4	34.7

N is number of specimens; D and I are in situ site-mean declination and inclination, respectively; D_C and I_C are untilted site-mean declination and inclination, respectively; I_F is inclination of the field in which remanence was acquired; α_{95} is the radius of 95% confidence circle; κ is Fisher's precision parameter.

Table 2. Mesozoic paleomagnetic directions.

4.2. Possible allochthonous blocks in central Hokkaido

The present study ratified the hypothetical transportation from low latitudes proposed by the authors in Refs. [10, 11]. The central part of Hokkaido, however, does not seem to have migrated en bloc because the Mesozoic paleomagnetic records in some areas are indicative of autochthonous origin. Our PThD examinations for the Yezo Group distributed along the Ponbetsu River (PO01–04) imply deep inclinations, although they were not magnetically stable enough to determine site-mean ChRM directions. As with the Oyubari area studied by Tamaki and Itoh [7] (see **Figure 1**), we posit that the western wing of the N-S trending anticline may be composed of in situ blocks, whereas we obtained significantly shallow inclinations from the core and eastern wing of the structure. An unsolved problem is that a clear geologic boundary between the blocks with mixed origins has never been detected.

Dismemberment of amalgamated blocks during the late Cenozoic collision between the Kurile and northeastern Japan arcs is also a knotty problem for reliable paleoreconstruction. Exploration drilling was executed in 1997 in central Hokkaido (42.9943°N, 142.0228°E; [19]). The vertically drilled borehole reached 4465 m depth and confirmed that the Cretaceous to Tertiary strata was repeatedly stacked by remarkable west-vergent thrusts. Actually, the western foothills of the backbone mountains consist of multiple-stacked thrust horses and the flat-lying horst-graben of the Paleogene and Cretaceous igneous basement [20]. Based on an interpretation of regional seismic profiles, Kazuka et al. [21] estimated the east-west crustal shortening across the Hidaka Mountains to be ~60 km. Thus, the origin of the allochthonous terranes should be clarified through further investigation of the three-dimensional structure of the island.

4.3. Estimate of N-S transportation

In order to determine the amount of tectonic movement of geologic units now distributed in south central Hokkaido, the expected direction should be calculated from the contemporaneous reference pole of the North China Block (NCB) after [22]. Because it formed a single entity with Siberia and Mongolia around the Early Cretaceous [23], the whole block can represent a coherent part of East Asia since the Cretaceous time. **Figure 10** presents a summary of Mesozoic to Cenozoic paleomagnetic information around the study area. Our results basically agree with the estimate of N-S transportation by the authors in Refs. [10, 11]. Based on temporal decreases in positive F values defined by Beck [24], allochthonous blocks migrated northerly during the Early Cretaceous. Paleomagnetic data reported from the Oyubari area in central Hokkaido [7] show an affinity to the NCB data. Considering a reconstructed subduction history by Ueda and Miyashita [25], simultaneous events of amalgamation on the continental margin may have occurred from 100 to 90 Ma.

Kimura et al. [26] regarded the Sorachi Group as a constituent of an enormous oceanic plateau that was driven to collide against the continent by rapid northward movement of the Izanagi Plate [27]. It seems, however, that their hypothesis clashes with the evidence of arc volcanism, as mentioned above. Takashima et al. [28] proposed an alternative idea that the geologic unit was transported by left-lateral slips on the margin between the Eurasian and Izanagi Plates. Although oblique subduction is a plausible cause of the large migration, lateral motion on the plate margin changed to a dextral direction after the demise of the Izanagi Plate [29]. In order to reconcile such controversial points, we present a comprehensive paleoreconstruction in the last chapter of this book.

Paleomagnetic analysis made it clear that some crustal blocks experienced delayed transportation. A composite mean of the Upper Yezo Group in the Urakawa area [4] gives a paleolatitude of 16.7°N. Using the NCB expected direction for comparison, northward transportation since the Late Cretaceous appears to be 3400 km. Based on geochemical modeling, Itoh et al. [29] suggested continued subsidence of the allochthonous 'forearc' region containing Urakawa area through the Paleogene. The considerable thickness of the missing unit is not attributed to eustatic sea-level changes but to tectonic subsidence of the forearc, which implies that a subduction erosion process [30] was active. It is noteworthy that an autochthonous block in central Hokkaido also suffered Paleogene subsidence. Tamaki et al. [31] executed 1D basin modeling on the basis of organic maturation data obtained from a deep borehole (MITI Yubari; [19]). Their burial history was better constrained because the data set contained maturity levels and the present thickness of the Eocene sedimentary units. They found accelerated accumulation rates during the Paleogene, which is an indicator of the emergence of a foreland basin setting (e.g., [32]). Simultaneous inversion of these areas implies that an amalgamation of migrated terranes occurred by the end of the Paleogene.

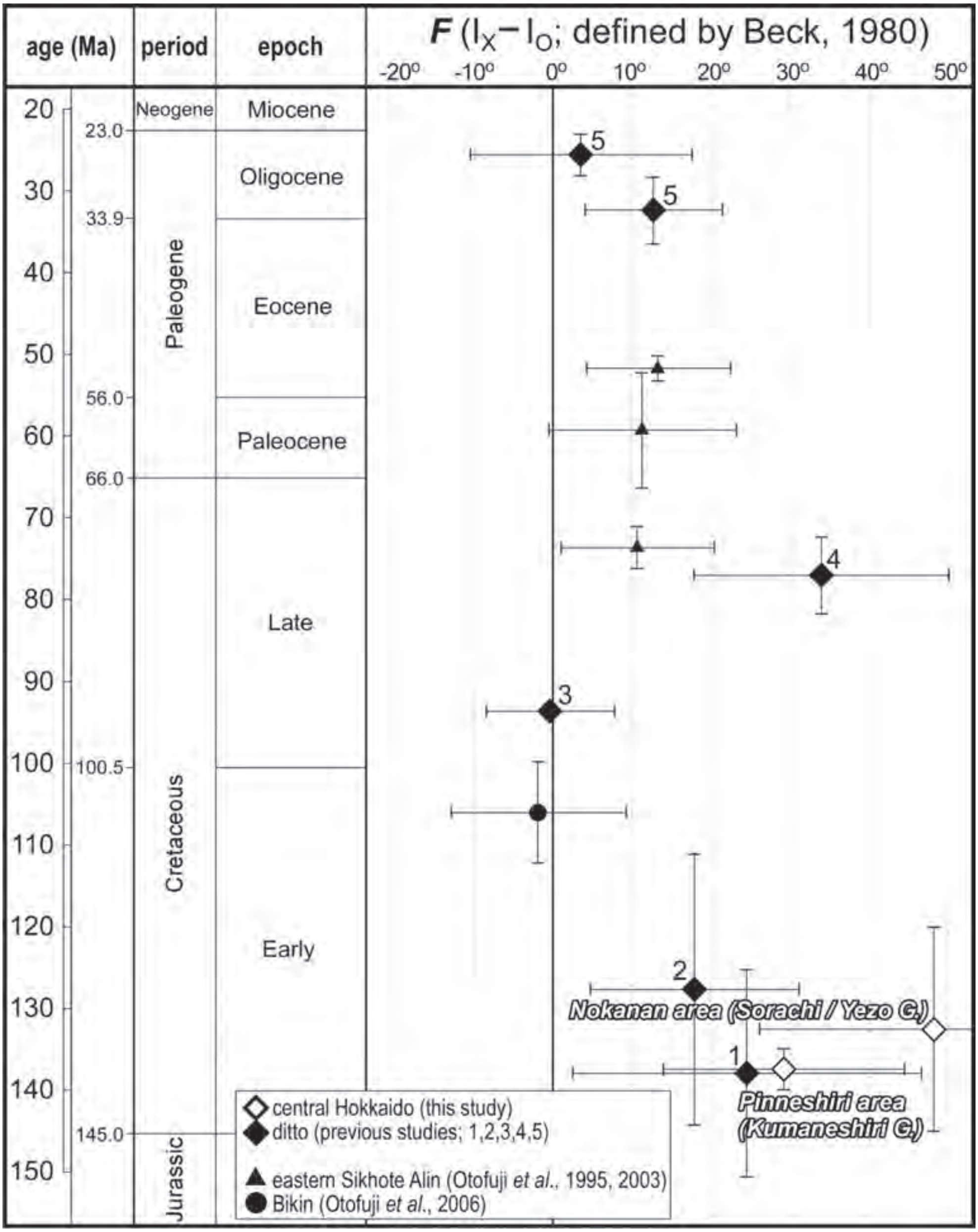

Figure 10. Plot of inclination flattening (F) (F = I [expected] – I [observed]; [24]) versus age for central Hokkaido (1 = [10]; 2 = [11]; 3 = [7]; 4 = [4]; 5 = [33]), eastern Sikhote Alin and Bikin. Stratigraphic positions of data in eastern Sikhote Alin and Bikin are after Otofuji et al. [34, 35] and Otofuji et al. [36], respectively. The age range of the Oyubari data (3: [7]) is shorter than the height of the median symbol.

5. Conclusions

Lateral migration of the Oshima and Sorachi-Yezo Belts within south central Hokkaido was quantitatively evaluated by means of paleomagnetic analyses. We tested the remanence stability of the Late Jurassic to Early Cretaceous voluminous igneous succession of the Kumaneshiri and Sorachi Groups and the overlying forearc sediments of the Cretaceous Yezo Group through rock magnetic experiments. Twelve of the sites yielded characteristic primary components residing in mixtures of titanomagnetite and hematite having various mixing ratios. Although anisotropic acquisition of the isothermal remanent magnetization suggested shallowing of inclinations of the post-depositional detrital remanent magnetization, we confirmed significantly shallow inclinations even for the flattening-corrected data, implying northward transportation after emplacement. Based on comparisons to expected paleomagnetic directions calculated from contemporaneous reference poles, we concluded that the allochthonous blocks, including central Hokkaido, migrated northerly during the Early Cretaceous. Previous research studies of paleomagnetism and numerical basin modeling of burial processes indicate that some crustal blocks experienced delayed transportation and eventually amalgamated with the mother continent by the end of the Paleogene.

Acknowledgements

The authors extend their appreciation to Naoto Ishikawa for use of the rock magnetic laboratory at Kyoto University. We thank Yuki Bito and Takashi Inoue for their earnest help during field work and experiments.

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