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Tertiary geodynamics of Sakhalin (NW Pacific) from anisotropy of magnetic susceptibility fabrics and paleomagnetic data

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Abstract

Sakhalin has been affected by several phases of Cretaceous and Tertiary deformation due to the complex interaction of plates in the northwest Pacific region. A detailed understanding of the strain is important because it will provide constraints on plate-scale processes that control the formation and deformation of marginal sedimentary basins. Anisotropy of magnetic susceptibility (AMS) data were obtained from fine-grained mudstones and siltstones from 22 localities in Sakhalin in order to provide information concerning tectonic strain. AMS data reliably record ancient strain tensor orientations before significant deformation of the sediments occurred. Paleomagnetically determined vertical-axis rotations of crustal rocks allow rotation of the fabrics back to their original orientation. Results from southwest Sakhalin indicate a ~ N035°E-directed net tectonic transport from the mid-Paleocene to the early Miocene, which is consistent with the present-day relative motion between the Okhotsk Sea and Eurasian plates. Reconstruction of early–late Miocene AMS fabrics in east Sakhalin indicates a tectonic transport direction of ~ N040°E. In west Sakhalin, the transport direction appears to have remained relatively consistent from the Oligocene to the late Miocene, but it has a different attitude of ~ N080°E. This suggests local deflection of the stress and strain fields, which was probably associated with opening of the northern Tatar Strait. A northward-directed tectonic transport is observed in Miocene sediments in southeast Sakhalin, mid-Eocene sediments in east Sakhalin, and in Late Cretaceous rocks of west and northern Sakhalin, which may be associated with northwestward motion and subduction of the Pacific Plate in the Tertiary period. The boundaries of the separate regions defined by the AMS data are consistent with present-day plate models and, therefore, provide meaningful constraints on the tectonic evolution of Sakhalin.
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1. Introduction

The geological evolution of Sakhalin, which lies on the northwest Pacific margin, has been complex, with evidence of several deformation phases. Neogene displacement along N–S-trending strike-slip faults suggests a right-lateral transpressive tectonic regime (Fournier et al., 1994). However, Mesozoic accretionary complex rocks and fore-arc basin sediments exposed in Sakhalin are associated with an ancient episode of subduction (Parfenov et al., 1981; Rikhter, 1984; Kimura, 1994). The timing of the cessation of subduction beneath Sakhalin is currently poorly constrained with suggested estimates that range from Late Mesozoic (Worrall et al., 1996) to mid-Miocene (Zonenshain et al., 1990). Interpretation of the ancient evolution of the area is further complicated by controversy over the present-day plate tectonic configuration of the NW Pacific, which probably involves interaction between the North American, Eurasian, Amurian,

Northern Honshu, Okhotsk Sea, Pacific, and Philippine Sea Plates (Fig. 1) (Takahashi et al., 1999). However, the location of many of the boundaries between these plates and even the existence of some of the plates remains uncertain (Seno et al., 1996).

Several kinematic models have been suggested for the Cenozoic evolution of the east Asian margin. These models consider basin formation either to be the product of large-scale extrusion as a result of India–Eurasia collision (e.g., Tapponnier et al., 1986; Jolivet, 1990; Worrall et al., 1996), or, of roll-back on the Pacific Plate (e.g., Watson et al., 1987; Northrup et al., 1995). Regional studies have been used to test these models (e.g., Allen et al., 1998). In the northwest Pacific, the models are based primarily on data from Japan and the Japan Sea (Otofuji et al., 1991; Jolivet et al., 1994; Altis, 1999). However, in the Sakhalin-Okhotsk Sea region, to the north of Japan (Fig. 1), few data have been documented regarding the geodynamic and tectonic evolution and, therefore, the proposed geodynamic models are underconstrained (Fournier et al., 1994; Worrall et al., 1996; Takeuchi et al., 1999).

Spatial and temporal variation of stress and strain fields are important to help identify and determine the location of past and present plate boundaries and to provide constraints on regional geodynamic models. Stress is the fundamental tectonic force, but it is inherently difficult to determine because only strain, which results from the acting stress, can be observed (e.g., Ramsay and Lisle, 2000). At local scales, for instance, stress and strain become partitioned, which complicates interpretation of geological structures in the field (macrofabrics) and often makes it difficult to link such features with the regional compressive stress. These relationships are further complicated if more than one phase of deformation has occurred. In southern Sakhalin, for example, published fault-analysis data (Fournier et al., 1994) are ambiguous and indicate inconsistent paleostress orientations. A source of uncertainty with fault-derived paleostress data is the possibility of unidentified vertical-axis rotations of crustal blocks and the resulting deflection of fault trends. Fournier et al. (1994) pointed out that supporting paleomagnetic data are needed to provide a robust estimate of the paleostress in this region.

In the present study, anisotropy of magnetic susceptibility (AMS) data from Late Cretaceous–Pliocene rocks in Sakhalin are used to define a microscopic rock
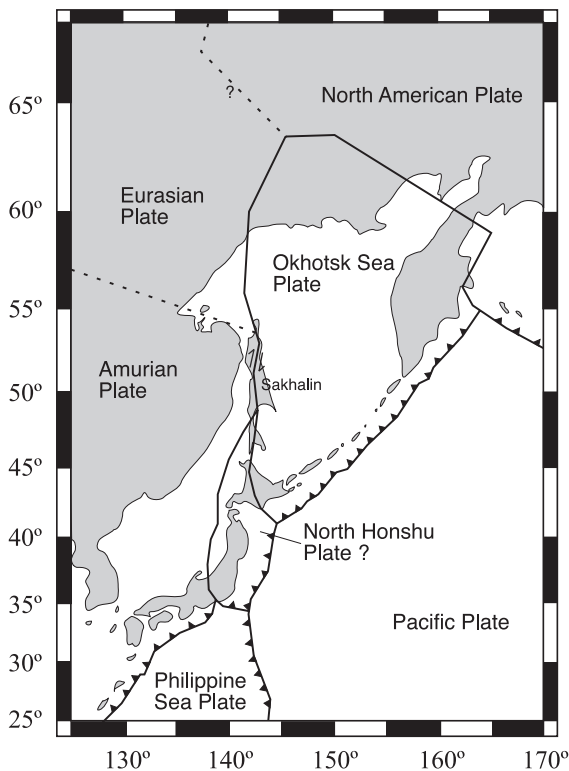

Fig. 1. Plate configuration and location of Sakhalin in NE Asia. Modified after Seno et al. (1996) and Takahashi et al. (1999).

deformation fabric. The microscopic fabric orientation is used as a means for determining the direction of net tectonic transport (e.g., Kissel et al., 1986; Lee et al., 1990; Sagnotti et al., 1994), which can be considered to be independent of the paleostress field and, thus, of the finite strain history of the rocks (e.g., Twiss and Moores, 1992). Rock magnetic fabrics can form in weakly deformed sediments and can provide important constraints on spatial and temporal directional differences in regional tectonic transport.

We combine AMS data with paleomagnetic data, which provide quantitative kinematic constraints for various regions in Sakhalin (Takeuchi et al., 1999; Weaver et al., 2003). Paleomagnetic data suggest that:

1. Sakhalin remained around its present-day latitude for most of the Tertiary (Weaver et al., 2003), except for some accreted allochtonous terranes in eastern Sakhalin (e.g., Bazhenov et al., 2001);
2. the transition from subduction tectonics to strike-slip tectonics may have occurred around the mid-Eocene; and
3. Sakhalin underwent rapid clockwise vertical-axis rotation phases (up to about 40°) in the Miocene. Rifting events in the Japan Sea, Kuril Basin, and Tatar Strait at around this time could have had a significant impact on rotational deformation in Sakhalin (Weaver et al., 2003).

These paleomagnetic data allow the AMS fabrics and, therefore, the interpretation of tectonic transport directions, to be determined relative to geographic north.

2. Geological setting and fieldwork

Sakhalin is located to the east of mainland Russia along the western margin of the Okhotsk Sea (Fig. 1). A north–south-trending system of active right-lateral strike-slip faults transects Sakhalin (Ivash-chenko et al., 1997). The east and west regions of Sakhalin are separated by the Central Sakhalin Fault (Fig. 2). Mesozoic accretionary complex rocks are
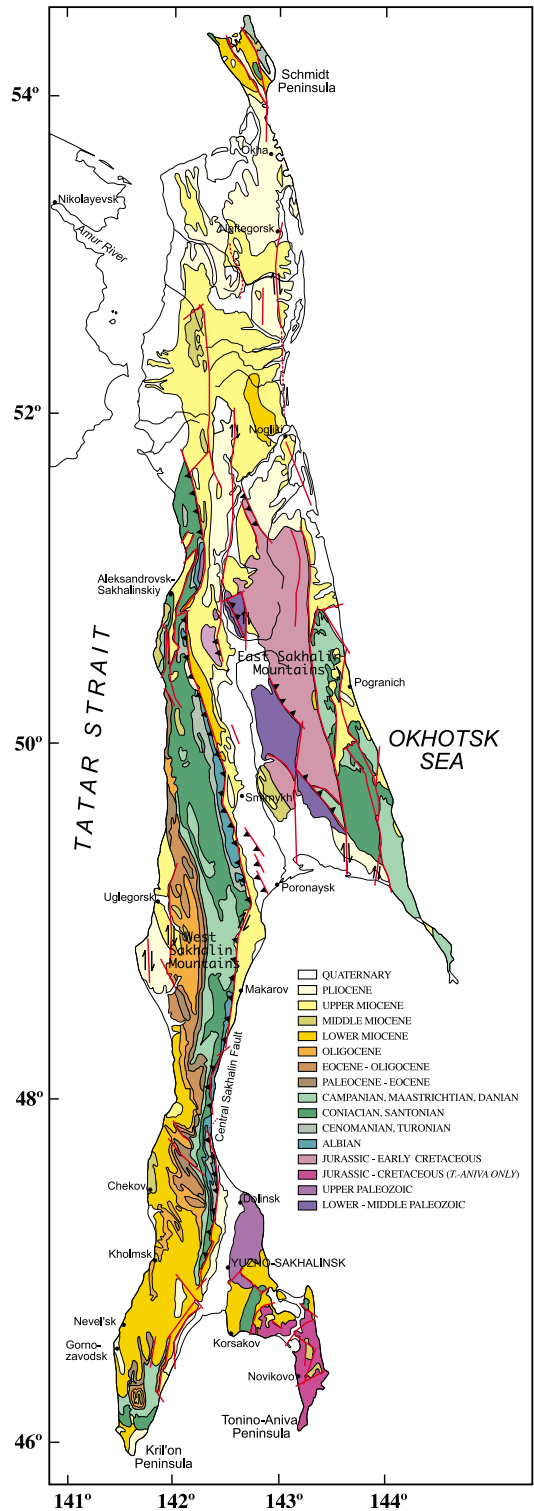

Fig. 2. Geological map of Sakhalin. Compiled from various sources (Vereshchagin, 1969; Rozhdestvenskiy, 1982; Kharakhinov et al., 1985; Fournier et al., 1994; Ivashchenko et al., 1997).

exposed in east Sakhalin, in the East Sakhalin Mountains, Tonino–Aniva Peninsula, and NE Schmidt Peninsula (Fig. 2). Mesozoic fore-arc sediments crop out in west Sakhalin (Parfenov and Natal'in, 1986; Zyabrev and Bragin, 1987). The associated volcanic arc is the Sikhote Al'in belt on the Russian mainland (Zonenshain et al., 1990; Okamura et al., 1998). Many phases of crustal accretion and uplift have affected northeastern Russia since the Permian and tectonic uplift of Sakhalin is

Table 1
Magnetic susceptibility and geological data from sampling localities in Sakhalin

Locality	Lat. (°)	Long. (°)	Suite	Age	Lithology	Avg. Bedding Dip (°)/Strike (°)	N	Range of k_{mean}, SI	k_{mean}, SI
Aleksandrovsk-Due	50.8	142.1	Gennoyshi	Oligocene	Marine siltstone	50 NE/328	15	1.74e−04–2.99e−04	2.23e−04
Aleksandrovsk-Due	50.8	142.1	Krasnoyarkov	Late Cretaceous	Black shale	51 SW/026	16	2.03e−04–2.43e−04	2.30e−04
Aleksandrovsk-Due	50.8	142.1	Upper Due	Early Miocene	Lagoonal siltstone	13 NE/298	8	1.18e−04–2.36e−04	1.55e−04
Avgustovka	49.7	142.2	Gennoyshi	Oligocene	Marine siltstone	45 W/184	29	1.23e−04–2.90e−03	3.44e−04
Balshoya Orlovka	49.6	142.7	Upper Due	Early Miocene	Lagoonal siltstone	29 S/089	23	5.21e−05–2.13e−03	1.17e−03
Chamgu	50.9	143.5	Borsk	Early Miocene	Siliceous siltstone	48 W/175	27	9.39e−05–6.06e−04	1.70e−04
Chamgu	50.9	143.5	Khuzin	Mid-Late Miocene	Siliceous mudstone	10 NE/348	51	8.70e−05–1.24e−04	1.05e−04
Dvoynoye	50.1	143.7	Lyukamen	Middle Eocene	Marine mudstone	15 NW/215	17	1.74e−04–5.02e−04	3.29e−04
Il'inskiy	47.9	142.1	Kurasiy	Late Miocene	Siliceous mudstone	36 NE/317	43	1.75e−05–4.89e−05	3.11e−05
Kholmsk	47.1	142.1	Takaraday, Arakay, Kholmsk	Oligocene-Miocene	Marine volcaniclastic mudstone	28 W/158 to 2 SE/040	32	1.20e−04–1.35e−03	4.03e−04
Kitosiya	46.9	141.9	Sinegorian Beds	Early Paleocene	Marine mudstone	31 W/187	11	1.27e−04–2.80e−04	2.13e−04
Kongi	51.1	143.4	Borsk	Early Miocene	Sandy marine mudstone	65 E/355	25	1.61e−04–2.84e−04	2.12e−04
Kormovaya	48.7	142.7	Kurasiy–Maruyama	Mid-Late Miocene	Marine mudstone	65 E/357	38	1.03e−04–2.14e−04	1.40e−04
Korsakov	46.6	142.8	Kholmsk	Early Miocene	Siliceous mudstone	80 NW/226	18	1.18e−04–5.03e−04	1.75e−04
Malaya Orlovka	49.6	142.7	Nutovsk	Miocene–Pliocene	Mudstone	76 NE/330 to 22 SW/114	20	1.09e−04–2.07e−04	1.51e−04
NE Schmidt	54.2	142.8	Toninsk	Late Cretaceous	Marine mudstone	30 E/356	26	1.30e−04–2.91e−04	2.05e−04
North Aleksandrovsk	51.2	142.2	Sertunay, Okobykay	Middle Miocene	Mudstone	21 SE/058 to 34 NW/208	20	1.31e−04–2.18e−04	1.83e−04
Onnay	49.6	142.2	Arakay	Oligocene	Siliceous black siltstone	40 W/193	18	1.44e−04–3.60e−04	1.97e−04
SE Schmidt	54.0	142.9	Pil'sk	Middle Miocene	Siliceous mudstone	57 SW/126 to 61 NE/340	32	1.06e−05–4.51e−05	2.62e−05
Shakhtnaya	48.8	142.8	Sertunay	Early–Mid Miocne	Mudstone	65 E/005	26	6.16e−05–1.80e−04	1.35e−04
Tunaicha	46.9	143.1	Kholmsk	Early Miocene	Siliceous mudstone	30 W/163	12	3.58e−05–1.63e−04	7.45e−05
Vladimirovka/Yar	47.1	142.3	Kholmsk	Early Miocene	Siliceous mudstone	70 SE/020 to 80 NW/204	50	1.05e−04–8.51e−04	2.01e−04

thought to have been associated with a collisional phase (Natal'in, 1993). Tertiary sediments in Sakhalin were deposited in small basins in the east, which were probably generated by strike-slip fault activity (Worrall et al., 1996). In north Sakhalin, thick successions of deltaic sediments accumulated in the early Miocene–Pliocene. These sediments are thought to have been derived from the paleo-Amur River (Fig. 2) (Varnavskiy et al., 1990), which drains an area of accreted terranes and former continental arcs to the south and east of the Siberian Craton. Tertiary sequences exposed along the West Sakhalin Mountains (Fig. 2) date back to the Paleocene. Cenozoic faulting has resulted in further deformation and uplift throughout Sakhalin (Rozhdestvenskiy, 1982; Kharakhinov et al., 1985).

Extensive sampling of Late Cretaceous to Tertiary fine-grained sediments was carried out in Sakhalin as part of a regional-scale tectonic study. Cylindrical paleomagnetic samples were collected from 28 localities; reliable paleomagnetic data were acquired from only nine of these. AMS results are presented from 22 localities that have well-defined magnetic fabrics. The age, lithology, and bedding attitudes are listed for each sampled locality in Table 1.

3. Methods

AMS measurements were carried out using an AGICO KLY-3S magnetic susceptibility meter at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy. Low-field magnetic susceptibility of oriented cylindrical samples ($h = 2.2$ cm $\times d = 2.5$ cm) was measured during rotation of each sample in three perpendicular planes. This method ensures accurate

Table 2
AMS eigenparameter data from Sakhalin

Locality	Suite	N	k_{min}	$D_{k_{min}}$ (°)	$I_{k_{min}}$ (°)	k_{int}	$D_{k_{int}}$ (°)	$I_{k_{int}}$ (°)	k_{max}	$D_{k_{max}}$ (°)	$I_{k_{max}}$ (°)	ε_{12} (°)	ε_{13} (°)	ε_{23} (°)
Aleksandrovsk-Due	Gennoyshi	15	0.32690	45.7	63.0	0.33552	291.6	11.7	0.33758	196.4	23.9	6.4	5.4	6.5
Aleksandrovsk-Due	Krasnoyarkov	16	0.32873	191.1	85.6	0.33461	321.9	2.9	0.33666	52.0	3.3	9.5	3.3	3.9
Aleksandrovsk-Due	Upper Due	8	0.32963	318.0	78.4	0.33349	105.8	9.8	0.33688	196.8	6.1	6.4	4.6	7.9
Avgustovka	Gennoyshi	29	0.32682	322.9	80.5	0.33455	109.1	7.9	0.33862	199.8	5.2	8.2	5.3	6.0
Balshoya Orlovka	Upper Due	23	0.32349	210.3	79.4	0.33803	119.5	0.2	0.33848	29.4	10.6	67.2	4.4	5.9
Chamgu	Borsk	27	0.32882	15.7	81.5	0.33312	246.2	5.5	0.33807	155.5	6.6	7.5	5.6	9.9
Chamgu	Khuzin	51	0.33027	116.6	84.5	0.33463	248.6	3.7	0.33510	338.9	4.1	36.8	2.7	2.7
Dvoynoye	Lyukamen	17	0.32252	238.2	85.0	0.33811	28.3	4.4	0.33937	118.5	2.5	17.7	6.0	2.2
Il'inskiy	Kurasiy	43	0.32657	131.1	84.6	0.33566	230.0	0.8	0.33777	320.1	5.3	13.2	2.9	3.0
Kholmsk	Takaraday, Arakay, Kholmsk	32	0.33038	192.1	80.5	0.33450	30.5	9.0	0.33511	300.1	3.0	37.2	4.6	5.3
Kitosiya	Sinegorian Beds	11	0.32099	48.6	82.2	0.33853	260.5	6.7	0.34049	170.1	4.1	23.5	8.2	8.7
Kongi	Borsk	25	0.32479	171.7	85.2	0.33597	57.3	2.0	0.33924	327.1	4.4	9.2	5.0	4.0
Kormovaya	Kurasiy-Maruyama	38	0.33048	343.5	78.7	0.33406	84.3	2.1	0.33546	174.7	11.1	9.5	2.1	4.0
Korsakov	Kholmsk	18	0.32741	269.8	87.5	0.33552	152.8	1.1	0.33707	62.8	2.2	24.0	5.9	4.6
Malaya Orlovka	Nutovsk	20	0.33058	285.3	76.8	0.33416	74.1	11.4	0.33526	165.5	6.7	14.0	8.5	9.9
NE Schmidt	Toninsk	26	0.32680	190.9	74.7	0.33453	359.9	15.1	0.33867	90.7	2.8	9.9	4.6	5.5
North Aleksandrovsk	Sertunay, Okobykay	20	0.32923	149.1	82.7	0.33403	262.8	3.0	0.33674	353.1	6.7	12.7	6.3	11.3
Onnay	Arakay	18	0.32889	126.7	85.0	0.33453	303.2	5.0	0.33658	33.3	0.3	17.5	4.5	10.4
SE Schmidt	Pil'sk	32	0.33007	271.1	85.5	0.33464	24.2	1.7	0.33529	114.3	4.1	26.2	5.1	6.2
Shakhtnaya	Sertunay	26	0.32870	224.4	83.3	0.33472	77.2	5.7	0.33658	346.8	3.6	9.9	4.6	5.1
Tunaicha	Kholmsk	12	0.33000	210.6	71.4	0.33332	6.3	17.1	0.33668	98.5	7.2	6.7	7.7	11.3
Vladimirovka/Yar	Kholmsk	50	0.32480	239.7	83.4	0.33579	29.6	5.7	0.33941	119.9	3.3	10.3	2.6	5.1

ε_{12}, ε_{13}, and ε_{23} represent the 95% confidence semi-angles in the $k_{max}-k_{int}$, $k_{max}-k_{min}$, and $k_{int}-k_{min}$ planes, respectively (Jelinek, 1978).

determination of the AMS to around 5×10^{-6} SI. The eigenvalues of the susceptibility (k_{max}, k_{int}, k_{min}) were calculated by solving the second rank symmetrical susceptibility tensor (e.g., Tauxe, 1998). Eigenvectors were calculated and statistical treatment was carried out following the method of Jelinek (1978). The mean susceptibility (k_{mean}), the degree of anisotropy, P', where:

$$P' = \exp\sqrt{2\left[(\ln k_{max} - \ln k_{mean})^2 + (\ln k_{int} - \ln k_{mean})^2 + (\ln k_{min} - \ln k_{mean})^2\right]},$$

and the shape of the AMS ellipsoid (T):

$$T = \frac{2(\ln k_{int} - \ln k_{min})}{(\ln k_{max} - \ln k_{min})} - 1,$$

were used to characterize the anisotropy of individual samples (Jelinek, 1981). Mean directions of the principal eigenvectors and eigenvalues are listed in Table 2.

Hysteresis measurements were carried out on representative samples from each locality using a Princeton Measurements vibrating sample magnetometer (μVSM) at the Institute for Rock Magnetism (IRM), Minneapolis, MN, USA. Samples were measured up to maximum fields of 1 T. Such data are useful for assessing the relative contribution of paramagnetic and ferrimagnetic minerals to the susceptibility.

4. Results

4.1. Rock magnetic results

Hysteresis loops for samples from throughout Sakhalin have clear positive slopes, which indicate a significant contribution from paramagnetic minerals (Fig. 3). Mean susceptibility values that range from 26 to 403 μSI suggest that paramagnetic matrix minerals dominate the susceptibility and that the ferrimag-
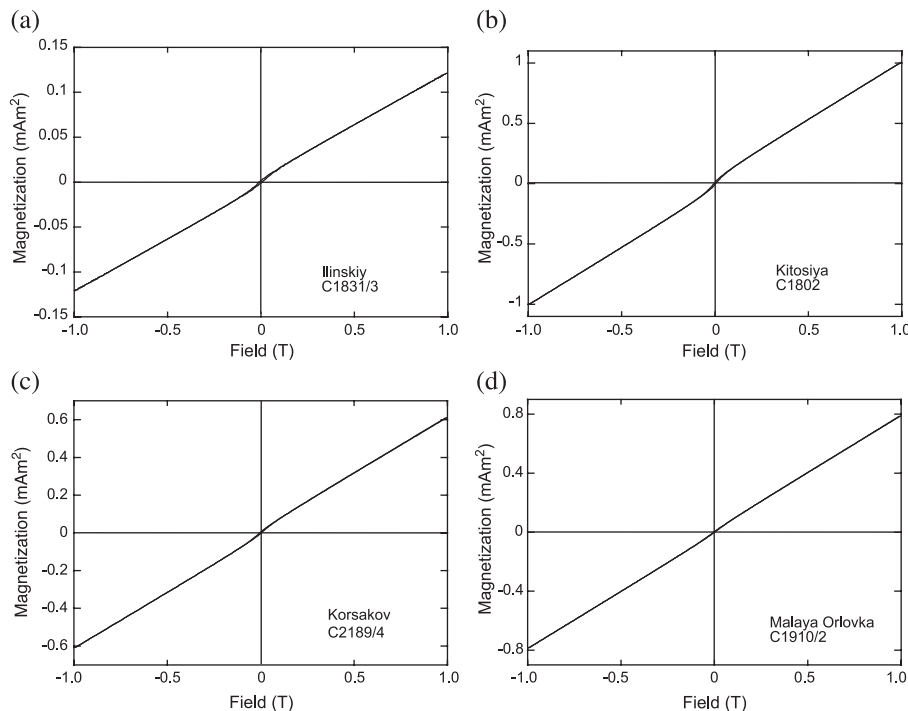

Fig. 3. Hysteresis loops without paramagnetic slope correction indicate a significant fraction of paramagnetic grains for representative samples from Sakhalin; (a) Ilinskiy Coast (sample C1831/3), (b) Kitosiya River (sample C1802), (c) Korsakov (sample C2189/4), (d) Malaya Orlovka River (sample C1910/2).

netic fraction of grains is unlikely to be important when considering the bulk magnetic fabric (Rochette, 1987; Hrouda and Kahan, 1991; Borradaile and Henry, 1997). However, it cannot be ruled out that particular orientation distributions of ferrimagnetic particles within individual samples could control the AMS (e.g., Borradaile and Henry, 1997).

Rock magnetic data from localities where the natural remanent magnetization (NRM) was reliable for tectonic purposes (i.e., stable and not remagnetized) indicate the presence of pseudo single-domain (PSD) magnetite, and, at two localities, a ferrimag-

netc iron sulphide mineral is present (Weaver et al., 2002, 2003). NRM intensities are generally low (10^{-7}–10^{-5} A/m).

4.2. Magnetic fabrics

The majority of samples have an AMS fabric with a near-vertical clustering of k_{min}, together with k_{int} and k_{max} axes that lie in the paleohorizontal (bedding) plane. This indicates a sedimentary origin of the fabrics (e.g., Rees and Woodall, 1975). At each sampled locality, oblate fabrics (i.e., $T>0$, $P'>1.00$) are consis-
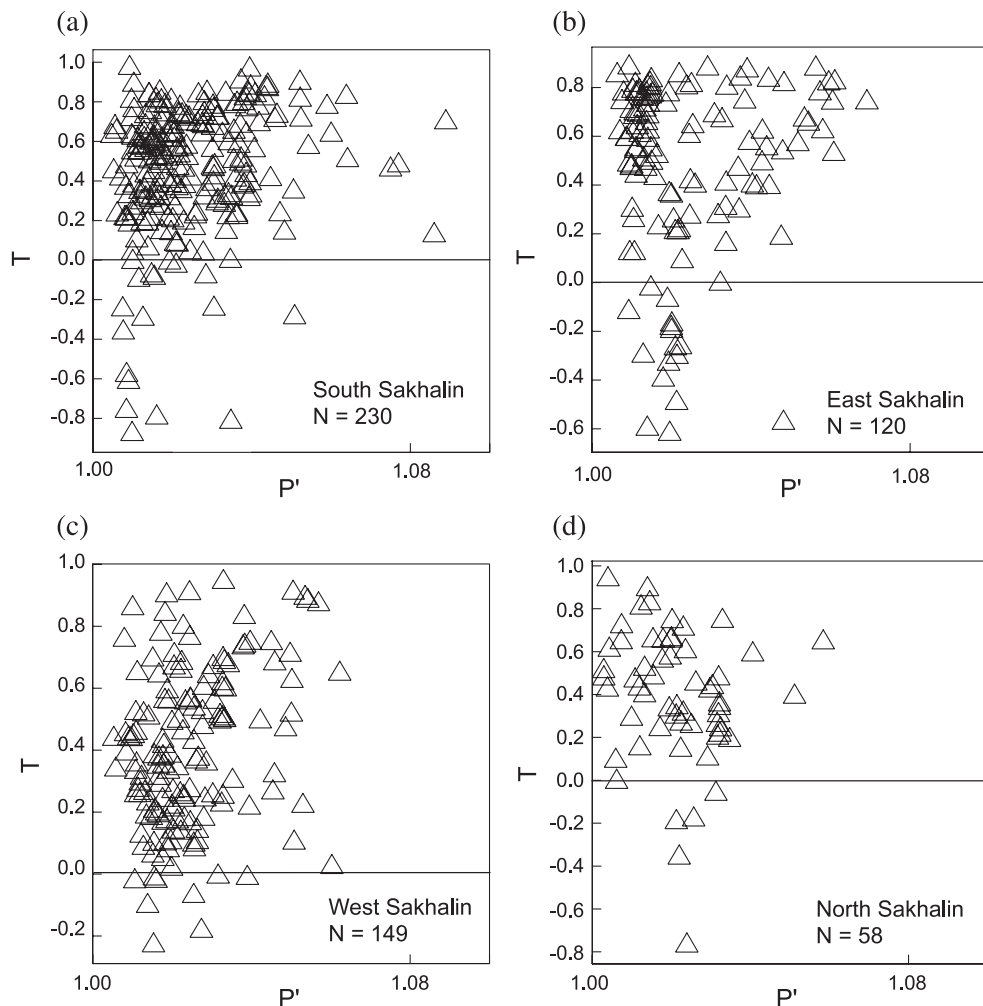

Fig. 4. Anisotropy of magnetic susceptibility (AMS) plots for samples from Sakhalin (Jelinek, 1981). T is the shape parameter of the AMS ellipsoid and ranges from -1 (prolate) to 0 (sphere) to $+1$ (oblate). P' is the corrected anisotropy degree which has values $>+1$ (sphere); (a) south Sakhalin, (b) east Sakhalin, (c) west Sakhalin, (d) north Sakhalin.

tent with flattening due to compaction (Fig. 4) (Jelinek, 1981). Most samples have a weak anisotropy with P' <1.04, the value of which is consistent between regions and suites containing different lithologies (Fig. 4). This suggests that the degree of anisotropy is not strongly correlated to the amount of finite strain or to lithology (e.g., Housen et al., 1995) (Table 1). Additionally, the majority of fabrics have a well-defined clustering of bedding corrected k_{max} directions (Table 2), which has been reported in areas of less intense deformation and tectonic strain (e.g., Parés et al., 1999). Anomalous AMS ellipsoids that were measured in some samples (Fig. 4) and the resulting scatter around the mean eigenvector directions, are probably due to subtle variations in the mineralogical composition (Rochette, 1987; Rochette et al., 1992).

Evidence from sediments in Italy indicates that AMS lineations could be controlled by the direction of the maximum horizontal stress (Mattei et al., 1997; Sagnotti et al., 1999). Regional coherence of AMS fabrics from mudrocks in Taiwan also suggests that lineation development may have been controlled by the regional stress (Kissel et al., 1986; Lee et al., 1990). In these regions, deformation and folding has occurred virtually perpendicular to the maximum horizontal stress. Other studies report AMS fabrics from strongly deformed rocks with orientations that appear to be closely controlled by folding (e.g., Borradaile, 1988; Averbuch et al., 1992; Aubourg et al., 1999). In Sakhalin, however, there appears to be no consistent relationship between bedding strike and the orientation of k_{max} for any given age or region (Fig. 5). This suggests that the k_{max} lineation is not directly related to the finite strain observed in the field (macrofabrics).

Alternatively, the observed fabrics might have formed due to paleocurrent alignment of sedimentary particles (Hamilton and Rees, 1970). This appears unlikely, however, because of the spatial and temporal consistency of the AMS fabrics in samples from
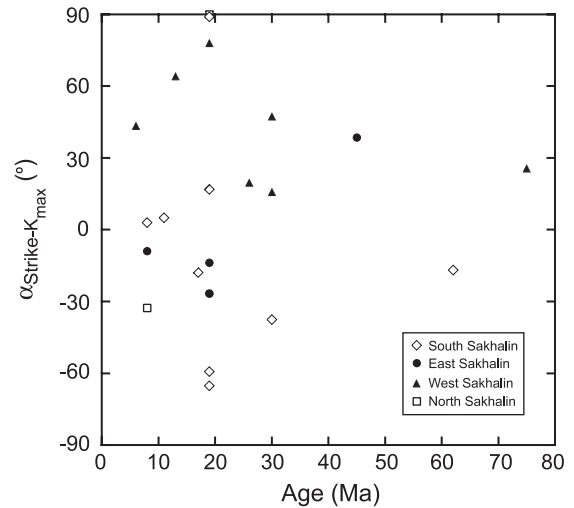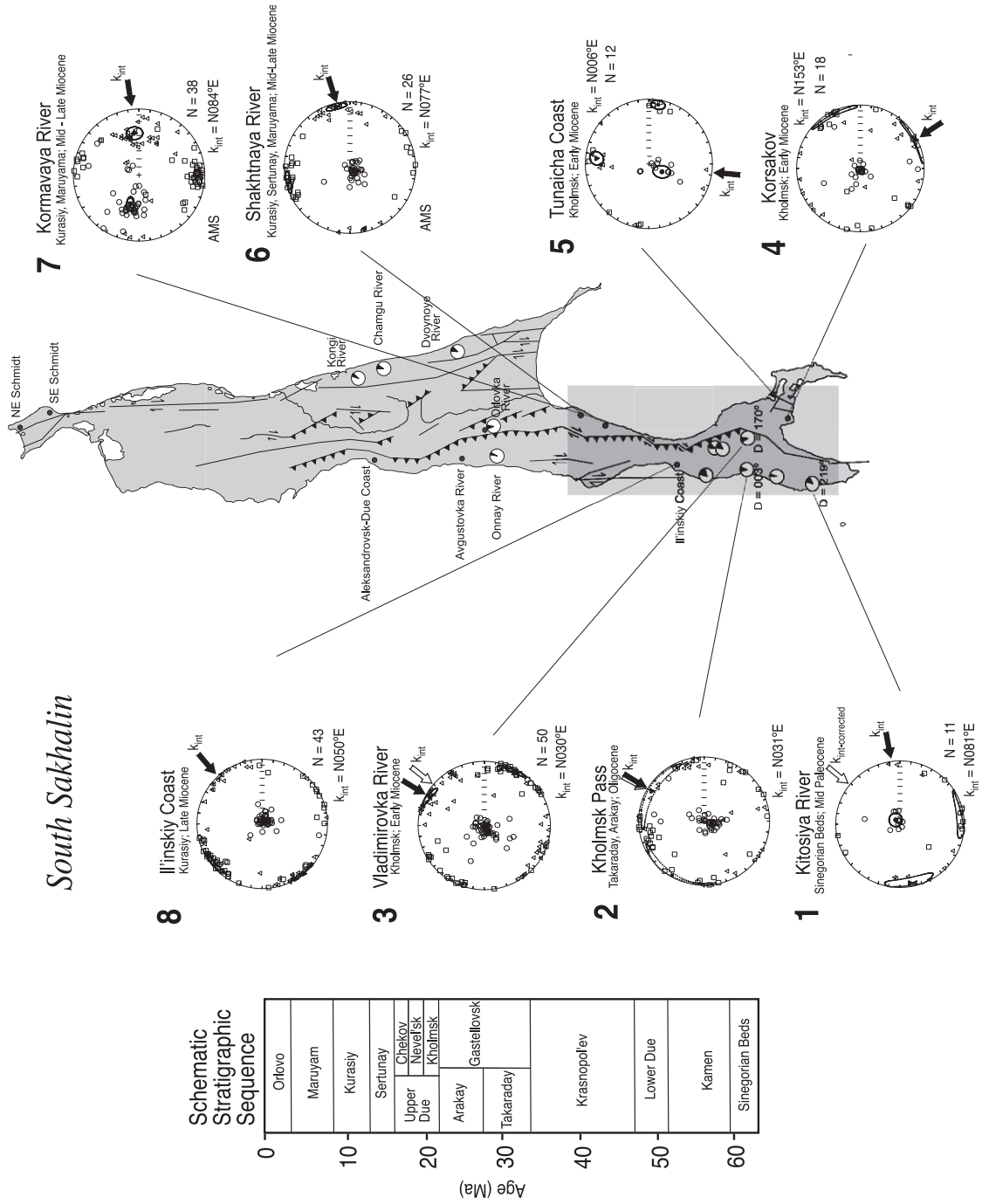

Fig. 5. Dependence plot of k_{max} on the bedding strike versus age of the sampled sediments in Sakhalin. $\alpha_{strike-k_{max}}$ is the angle between the bedding strike and k_{max}. Intermediate angles of $\alpha_{strike-k_{max}}$ between $0°$ and $90°$ or between $-90°$ and $0°$ suggest that neither the direction of k_{max} (the magnetic lineation) nor the direction of k_{int} is dependent on the strike of the bedding.

different sedimentary settings and ages (Table 1; Figs. 6–9).

The cumulative evidence from Sakhalin suggests that magnetic fabrics from different types of fine-grained sedimentary rocks developed pre-folding during an early phase of plastic deformation in response to tectonic forces. Paleomagnetic data indicate that rotational deformation about a vertical axis affected Sakhalin during the Tertiary. In light of a complex deformational history, consistent horizontal components of the magnetic fabrics are interpreted in terms of the net tectonic transport direction. Anisotropic minerals may have chemically grown in the sediment in response to stress. However, it is unlikely that a chemical mineral growth has affected all the sediments equally from such varied sedimentary environments. Electron microscopic observations also

Fig. 6. AMS fabrics from south Sakhalin. Solid arrows indicate the direction of k_{int} (uncorrected for vertical-axis rotation and perpendicular to lineation), which is the AMS-inferred orientation of the net tectonic transport. White arrows indicate the net tectonic transport direction determined from AMS data after correction for paleomagnetically determined vertical-axis rotations. On the map, white circles with shaded sectors indicate the vertical-axis rotation and 95% confidence band. Mean declinations are indicated on the map for localities where reliable paleomagnetic and AMS fabric data were obtained. On the stereoplots, bold numbers indicate the age progression from 1—oldest to 8—youngest. Circles represent k_{min} data points, triangles represent k_{int} data points and squares represent k_{max} data points. Solid lines on the map represent faults. Strike–slip components are indicated by arrows and the direction of thrust components are indicated by toothed symbols on the hanging wall.

South Sakhalin

7 Kormavaya River
Kurasiy, Maruyama; Mid - Late Miocene
N = 38
k_{int} = N084°E
AMS

6 Shakhtnaya River
Kurasiy, Sertunay, Maruyama; Mid-Late Miocene
N = 26
k_{int} = N077°E
AMS

5 Tunaicha Coast
Kholmsk; Early Miocene
k_{int} = N006°E
N = 12

4 Korsakov
Kholmsk; Early Miocene
k_{int} = N153°E
N = 18

8 Il'inskiy Coast
Kurasiy; Late Miocene
k_{int}
N = 43
k_{int} = N050°E

3 Vladimirovka River
Kholmsk; Early Miocene
k_{int}
N = 50
k_{int} = N030°E

2 Kholmsk Pass
Takaraday, Arakay; Oligocene
k_{int}
N = 50
k_{int} = N031°E

1 Kitosiya River
Sinegorian Beds; Mid Paleocene
$k_{int-corrected}$
k_{int}
N = 11
k_{int} = N081°E

Schematic Stratigraphic Sequence

Orlovo		
Maruyam		
Kurasiy		
Sertunay	Chekov	
	Nevel'sk	
	Kholmsk	
Upper Due	Gastellovsk	
Arakay		
Takaraday		
Krasnopol'ev		
Lower Due		
Kamen		
Sinegorian Beds		

Age (Ma)
0
10
20
30
40
50
60

indicate that the rocks have a clastic sedimentary matrix without obvious authigenic mineral growth textures. Therefore, physical alignment of "plate-like" minerals appears to be a more feasible mechanism for creation of the magnetic fabrics. AMS fabrics that have recorded both a vertical k_{min} axis and a k_{max} lineation in the horizontal plane are regarded as "early" tectonic fabrics. In such cases, a lineation forms in response to horizontal force components acting perpendicular to the lineation trend (e.g., Parés et al., 1999).

5. Discussion

5.1. Tectonic transport in Sakhalin

5.1.1. South Sakhalin

AMS-based fabric analyses from south Sakhalin are presented in Fig. 6. Paleomagnetic data from Kitosiya River, Kholmsk Pass, and Vladimirovka River allow the fabric to be restored relative to north and allows a tectonic transport direction to be estimated for the post mid-Paleocene (see white arrows in Fig. 6). Counter-clockwise back-rotation of the Kitosiya River fabric by 40° gives a corrected k_{int} direction of about N041°E. Clockwise rotation of the Vladimirovka data by 10° indicates a corrected direction of N040°E. Furthermore, the corrected data from Kholmsk Pass have a direction with k_{int} around N028°E in the Oligocene, although the confidence ellipse associated with the AMS data is large. After correction, the fabric orientations are regionally consistent and suggest a net tectonic transport direction in south Sakhalin that has remained almost constant at around N035 ± 5°E since the Paleocene (Fig. 6). Data from Il'inskiy Coast are within error of this estimate, but the amount of vertical-axis rotation at this locality is uncertain.

Magnetic fabric k_{int} orientations are closer to E–W in mid-late Miocene rocks at Kormavaya River and Shakhtnaya River (Fig. 6). Fournier et al. (1994) noted that there is evidence for clockwise deflection of folds in the vicinity of the Central Sakhalin Fault, although the amount of rotation is not specified. This suggests that the mid-late Miocene data might be in closer agreement with the localities to the southwest after correction for the inferred clockwise vertical-axis rotation (∼ 20°).

The AMS fabrics observed at Tunaicha and Korsakov, both on the Tonino-Aniva Peninsula (Fig. 2), indicate a clear N–S-trending k_{int} direction. This is in contrast to the fabrics elsewhere in south Sakhalin (Fig. 6). It is difficult to explain such a difference in orientations from rocks of the same age by assuming a single tectonic regime and coherent deformation across the whole south Sakhalin region (Fig. 6). Our observations suggest that these localities may have been part of different crustal blocks. This possibility is discussed further below.

5.1.2. East Sakhalin

AMS data from early and mid-Miocene rocks at Chamgu River in east Sakhalin have k_{int} mean directions of N066°E and N069°E, respectively (Fig. 7). At Kongi River, k_{int} from the Upper Borsk Suite clusters at around N057°E (Fig. 7). The Miocene data are within error of each other and are consistent with paleomagnetic results, which suggest that there was negligible relative rotation between these localities from the Eocene to the Miocene (Weaver et al., 2003). However, the paleomagnetic declinations are clockwise deflected by 20–30°, which yields a corrected k_{int} of ∼ N040 ± 8°E at the Chamgu River and Kongi River localities (Fig. 7).

The uncorrected k_{int} direction for Eocene sediments at Dvoynoye River (N028°E) is within error of the corrected k_{int} directions from Kongi River and Chamgu River (Fig. 7). However, paleomagnetic data suggest that the Dvoynoye River locality has rotated 32° clockwise since the Eocene (Weaver et al., 2003), which suggests a N–S-trending corrected k_{int} direction (Fig. 7). Therefore, there appears to be ∼ 40° difference in fabric orientation, which suggests that a change in tectonic regime may have occurred between the mid-Eocene and early Miocene in East Sakhalin.

5.1.3. West Sakhalin

Paleomagnetic data from Onnay River and Malaya Orlovka River allow magnetic fabrics from West Sakhalin to be corrected for vertical-axis tectonic rotations (Fig. 8). After correction, the late Miocene magnetic fabric at Malaya Orlovka River has k_{int} = N077°E. This is consistent with data from North Aleksandrovsk, where k_{int} = N083°E. The AMS fabrics from Gennoyshi Suite (Oligocene) mudstone at
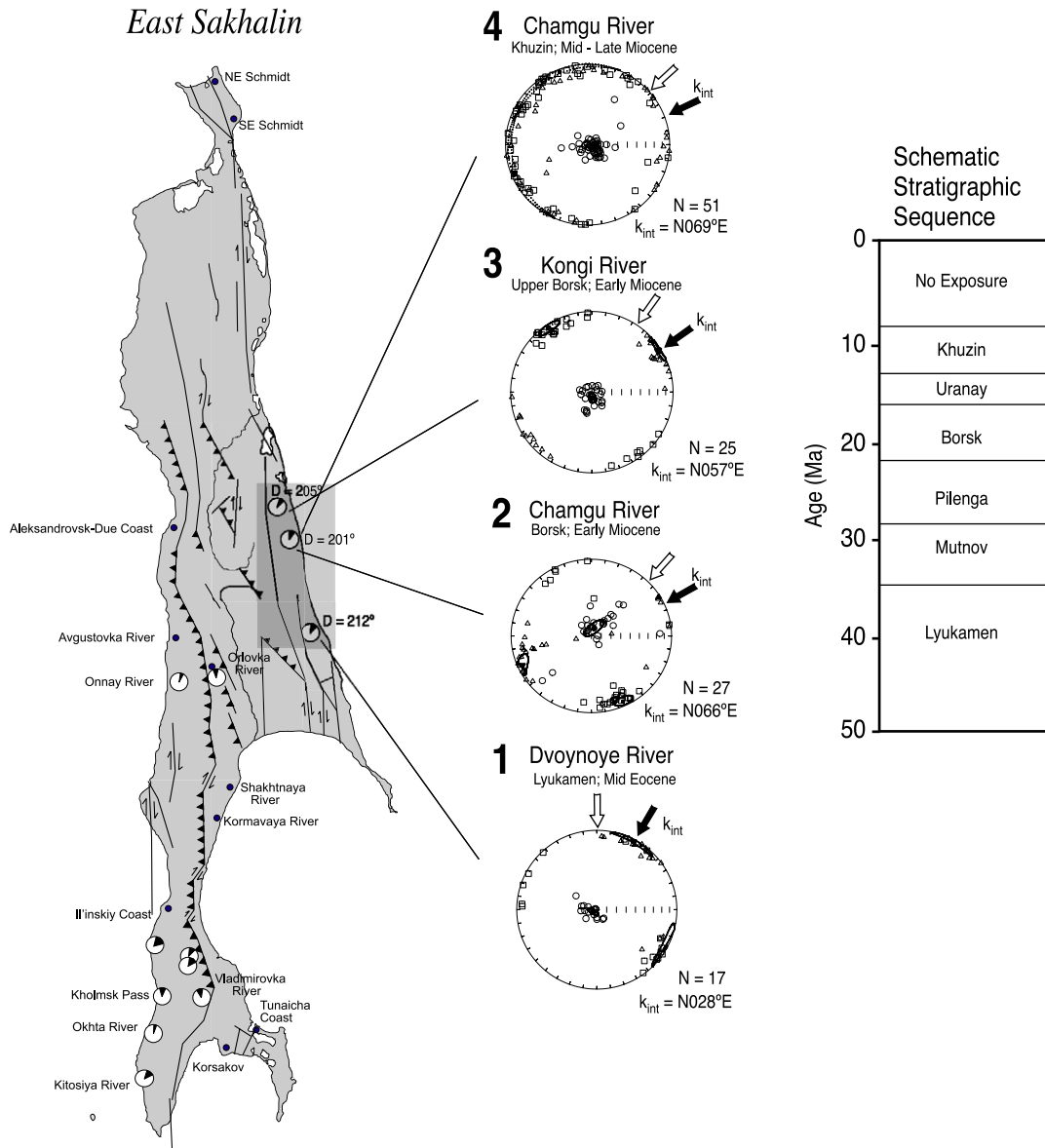
Fig. 7. AMS fabrics from east Sakhalin. Conventions are the same as in Fig. 6.

Avgustovka and Aleksandrovsk-Due Coast yield a mean k_{int} direction of N109°E and N112°E, respectively (Fig. 8). A similar k_{int} direction (k_{int} = N106°E) is obtained from the early Miocene (Upper Due) AMS data set from Aleksandrovsk (Fig. 8). Thus, early Oligocene-early Miocene sediments have consistent k_{int} trends (~ N110°E). In the early to mid-Miocene, the trends change to k_{int} ~ N080°E. AMS data from

different localities suggest that the direction of net tectonic transport remained relatively fixed spatially from the late Eocene to the early Miocene.

Paleomagnetic data (Weaver et al., 2003) indicate that localities in west and southwest Sakhalin rotated clockwise by ~ 20–30° between the early Miocene and mid-Miocene. It is likely that the observed change in magnetic fabric orientation for west

West Sakhalin
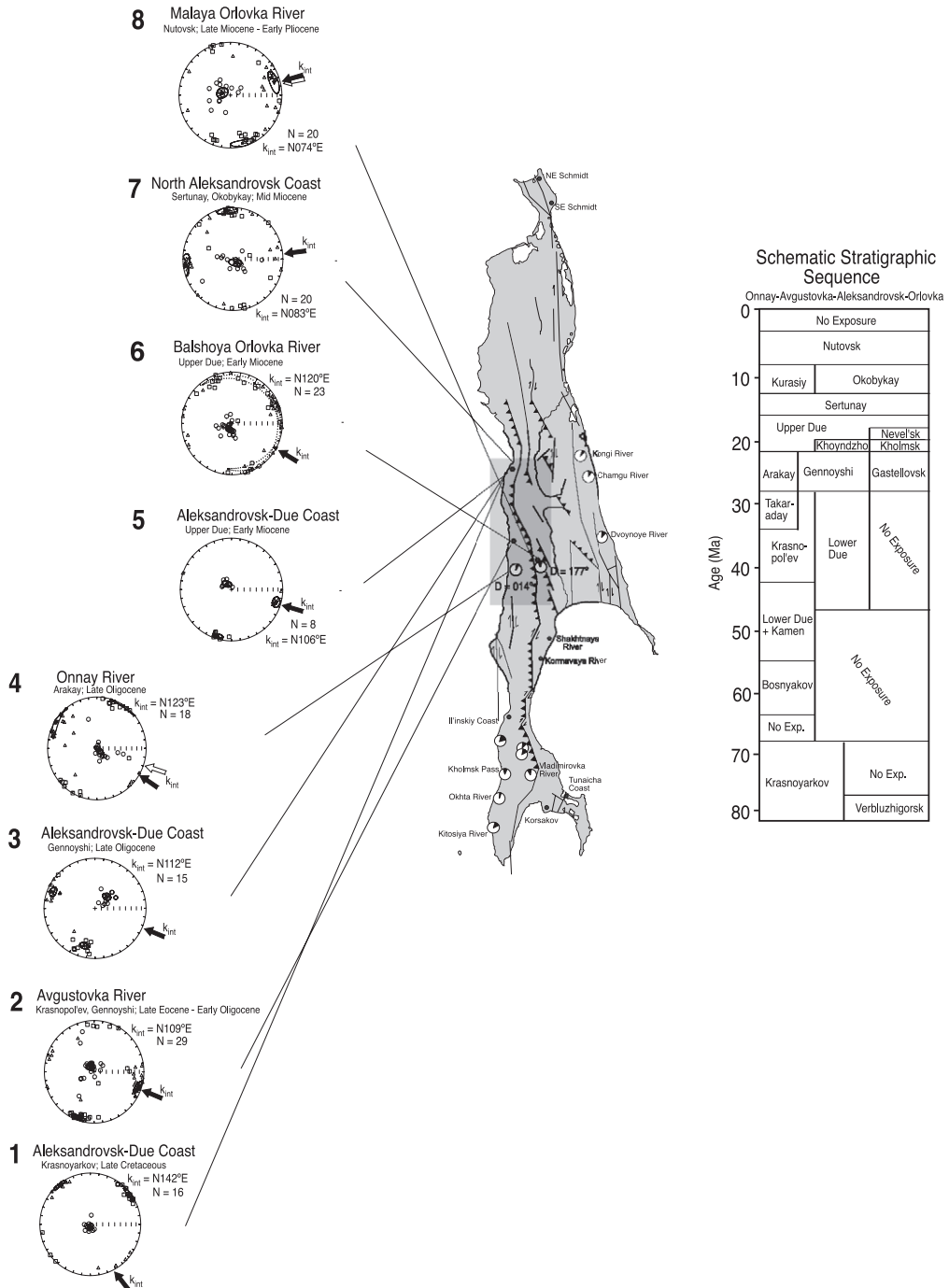
Fig. 8. AMS fabrics from west Sakhalin. Conventions are the same as in Fig. 6.

Sakhalin is due to a regional vertical-axis rotation event (with a fixed stress field) around the middle Miocene. This is supported by the magnetic fabric at Onnay River, which, after back-rotation, has a k_{int} direction that is in better agreement with mid-late Miocene fabric orientations (Fig. 8).

Alternatively, the stress field could have changed orientation, which might have yielded a tectonic transport direction that changed from ESE–WNW to become ENE–WSW-trending in the early Miocene (Fig. 8). In this case, the clockwise vertical-axis rotation observed at Onnay River could be
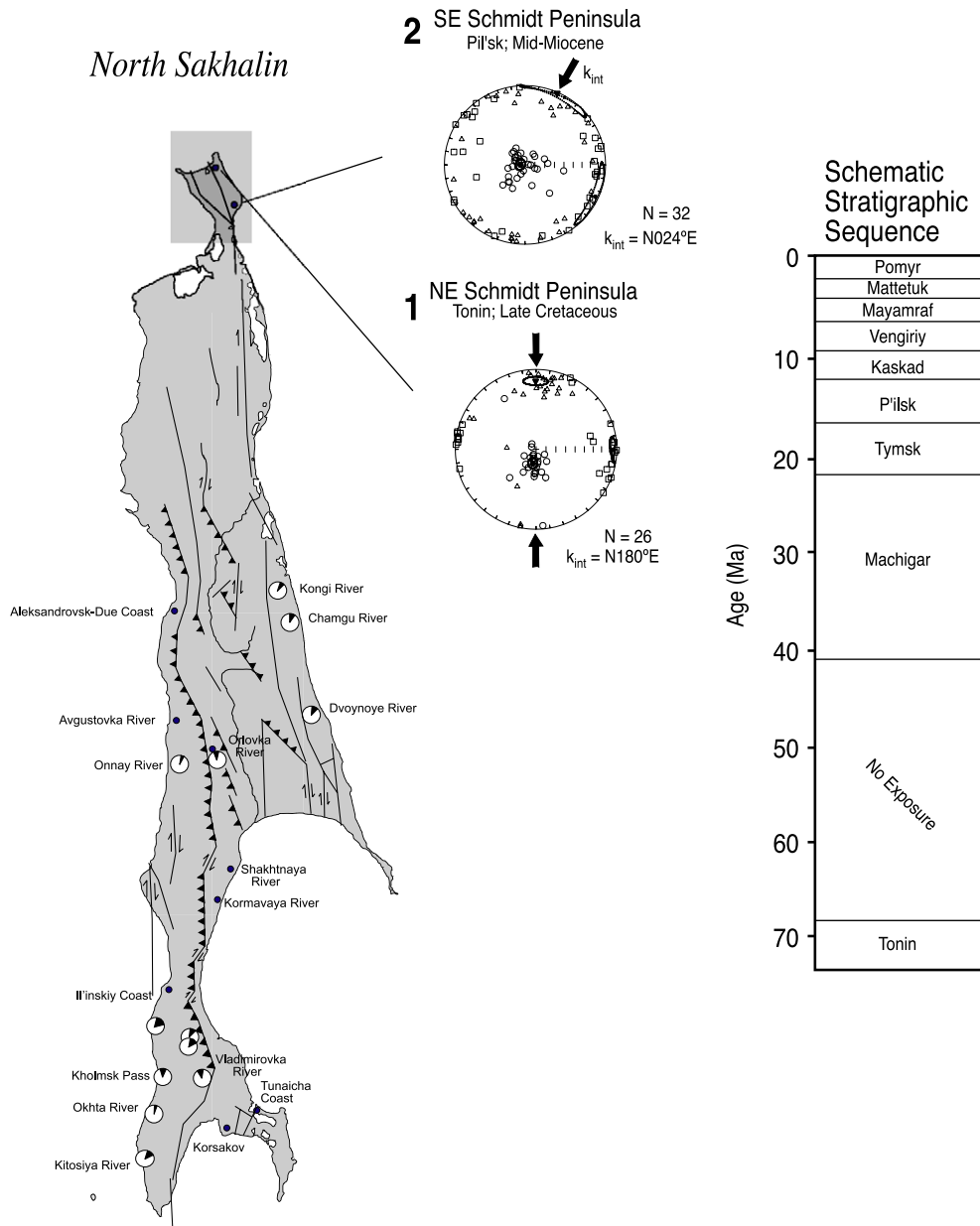
Fig. 9. AMS fabrics from north Sakhalin. Conventions are the same as in Fig. 6.

interpreted as a local-scale rotational event. Without useful paleomagnetic data from Aleksandrovsk–Sakhalinskiy, this possibility cannot be ruled out.

AMS data from Late Cretaceous black shales from the Aleksandrovsk-Due Coast suggest a k_{int} direction of N142°E (Fig. 8). Assuming that these sediments belong to the same tectonostratigraphic block as the other Due Coast localities, the data seem to indicate a counterclockwise change in direction of the net tectonic transport of around 30° between the Late Cretaceous and the Early Oligocene.

5.1.4. North Sakhalin

AMS fabric data for mid-Miocene sediments from SE Schmidt Peninsula, North Sakhalin (Fig. 9), indicate a NE–SW-trending k_{int} direction of ∼ N024°E, which is consistent with directions determined elsewhere in Sakhalin (Figs. 6–8), as well as with paleo-stress trends expected for Neogene transpression (Fournier et al., 1994). On the NE Schmidt Peninsula, a Late Cretaceous transport direction appears to trend directly N–S. This suggests an apparent clockwise rotation of around 25° of the NE Schmidt AMS fabric relative to SE Schmidt between the late Cretaceous and mid-Miocene (Fig. 9), which could be due to a vertical-axis block rotation or to a change in transport direction. The significance of any relative rotation is uncertain in the absence of paleomagnetic data.

5.2. Geodynamic significance of tectonic transport estimates from Sakhalin

AMS fabric results presented above suggest that the k_{int} direction in the horizontal plane may be taken to represent the net tectonic transport direction close to the time of sediment deposition. Magnetic fabric orientations from localities on the Kril'on Peninsula (Fig. 2) in south Sakhalin are consistent and suggest a net transport direction of ∼ N035°E (Fig. 6). The data suggest that this region has deformed coherently from the mid-Paleocene to the late Miocene, which is consistent with paleomagnetic data that indicate con-
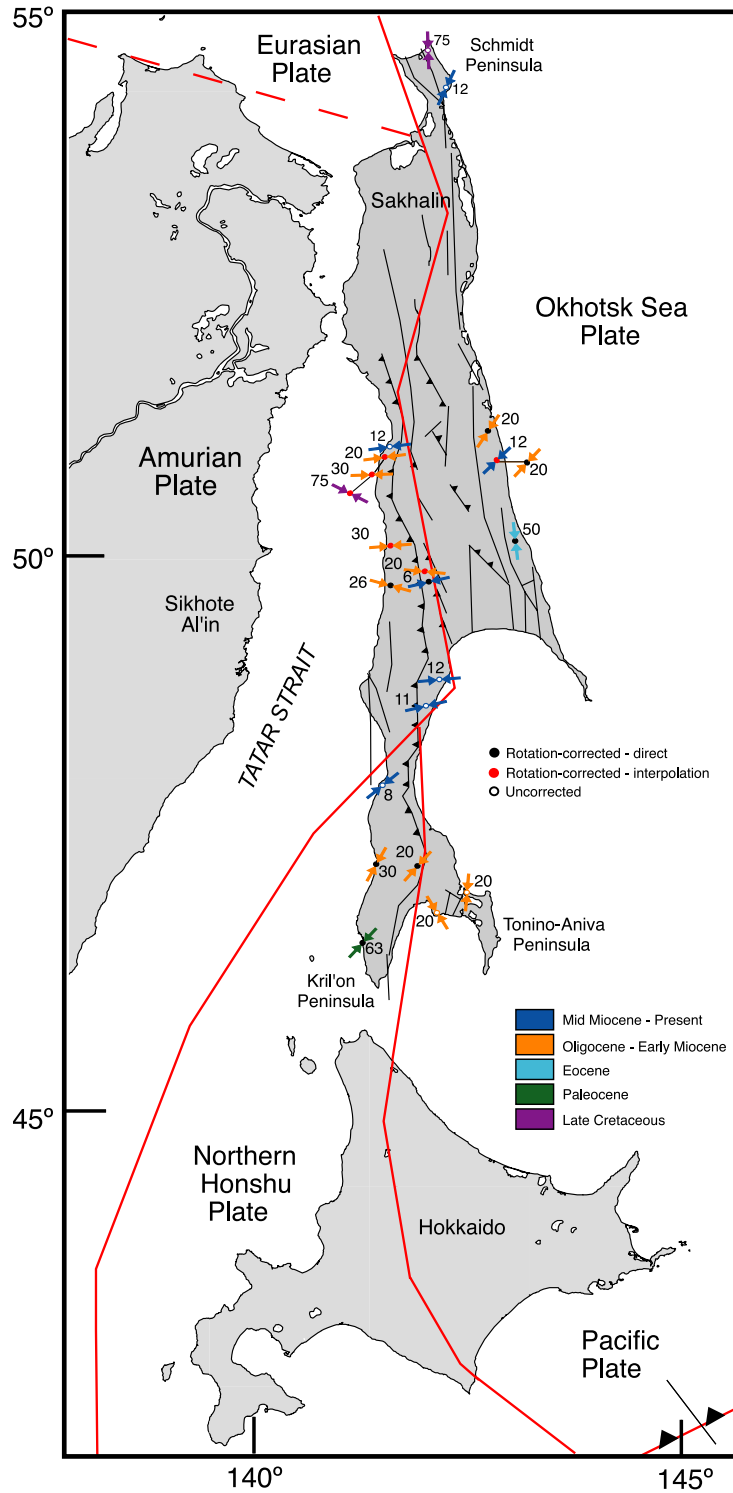
sistent clockwise vertical-axis rotations during this period (Takeuchi et al., 1999; Weaver et al., 2003). Oblique compression and deformation on Tertiary strike-slip faults probably accommodated this deformation (Fournier et al., 1994).

A N–S to NNW–SSE direction of the net tectonic transport observed in Early Miocene rocks on the Tonino–Aniva Peninsula suggests that this region belongs to a different tectonic block compared to the adjacent Kril'on Peninsula (Fig. 6). Several ancient exotic terranes that originated from southerly latitudes have accreted onto the Tonino–Aniva Peninsula (e.g., Zonenshain et al., 1990). Paleomagnetic data indicate that a Late Cretaceous island arc terrane travelled northward with the Pacific Plate and accreted onto Sakhalin in the mid-Eocene (Bazhenov et al., 2001). Some models of the NW Pacific and NE Asia suggest that plate or micro-plate boundaries divide the west and east parts of southern Sakhalin (Fig. 1) (Seno, 1985; Seno et al., 1996; Takahashi et al., 1999). Our analysis of the AMS fabrics supports the suggestion that these regions evolved independently as part of different plates or micro-plates after mid-Paleocene deposition of the sediments on the Kril'on Peninsula.

In west Sakhalin (Fig. 8) and at Makarov further to the south (localities 6 and 7, Fig. 6), the back-rotated orientation of the AMS fabric is consistently N080°E–N110°E from the late Eocene to early Miocene. This regionally coherent direction indicates a tectonic transport direction that is different to that of south Sakhalin, and suggests that these localities may belong to a different tectonic block, as some plate models suggest (e.g., Takahashi et al., 1999). Another possibility is that the E–W-directed opening of the Tatar Strait during this period (Jolivet et al., 1994) could account for local deflection of the strain tensor in west Sakhalin. AMS data and paleomagnetic data indicate a phase of rapid clockwise vertical-axis rotation in the mid-Miocene, which may be linked to the opening of the Tatar Strait (Fig. 8) (Weaver et al., 2003).

Consistent fabrics from Miocene localities in east Sakhalin reveal a tectonic transport direction of

Fig. 10. Interpretation of AMS fabric data from Sakhalin. Arrows indicate the direction of net tectonic transport. AMS fabric orientations are plotted after correction for paleomagnetically determined, Miocene vertical-axis rotations. Interpolated vertical-axis rotation corrections were applied at some localities that lack paleomagnetic data. In west Sakhalin, 20° of regionally coherent clockwise vertical-axis rotation was assumed to have occurred in the early to mid-Miocene (see text). Present-day plate boundaries (solid red lines) are shown following the models proposed by Seno (1985), DeMets (1992), Seno et al. (1996) and Takahashi et al. (1999).

around N040°E (Fig. 7), which is similar to the direction obtained for southwest Sakhalin. Miocene clockwise vertical-axis rotation observed in paleomagnetic data probably occurred through oblique compression along N–S-trending strike-slip faults that were active in the Neogene. AMS data from mid-Eocene sediments at Dvoynoye River indicate a N–S-directed net tectonic transport direction, which suggests that early deformation in this area may have been controlled by a Pacific-type motion similar to the Tonino–Aniva Peninsula and in contrast to southwest Sakhalin (Figs. 6 and 7). This remains uncertain in the absence of reliable paleomagnetic results for Tertiary sediments from the Tonino–Aniva Peninsula.

6. Conclusions

Magnetic fabrics observed in Late Cretaceous to Late Miocene sedimentary rocks from Sakhalin have clustered k_{max} axes in the bedding plane together with k_{min} axes normal to the bedding plane. After correction for paleomagnetically determined vertical-axis rotations, the fabrics are regionally consistent and define regions with characteristic directions of net tectonic transport. Data from the Kril'on Peninsula in south Sakhalin indicate a consistent tectonic transport direction of around N035°E observed in rocks of mid-Paleocene to late Miocene age. In west Sakhalin, magnetic fabrics indicate a tectonic transport direction of around N080°E from the late Eocene to the early Miocene (Fig. 10). A rapid phase of clockwise rotation in the early–mid-Miocene may be linked with opening of the Tatar Strait, which might explain the consistent E–W-oriented k_{int} axes of the magnetic fabrics, and, thus, a different direction of transport for west Sakhalin. The direction of post-early Miocene tectonic transport in east Sakhalin is around N040°E. In east Sakhalin and southwest Sakhalin, clockwise vertical-axis rotations appear to have been accommodated by oblique NE–SW compression along N–S-trending strike-slip faults. On the Tonino–Aniva Peninsula (early Miocene) and at Dvoynoye River (mid-Eocene) in east Sakhalin, a contrasting N–S-directed net tectonic transport suggests that the regions may have evolved with different tectonic blocks or micro-plates. The boundaries between the separate regions defined by the AMS data

are consistent with present-day plate models (Seno, 1985; DeMets, 1992; Seno et al., 1996; Takahashi et al., 1999). AMS data, therefore, provide meaningful, regionally consistent information concerning plate-scale tectonic processes in Sakhalin.

In the transpressional Sakhalin shear zone, the AMS method for determining ancient transport directions from ''early'' tectonic fabrics is ideal because deformation is significantly oblique to the regional stress in a region where there has been several phases of deformation and vertical-axis rotations. Previous AMS studies have concentrated on regions where the regional compressive stress is near-perpendicular to the strain axes of macroscopic structures. In these cases, it is inherently uncertain whether the AMS develops as a result of stress or strain. In Sakhalin, the magnetic fabrics appear to have been recorded during an early stage of plastic deformation in different fine-grained clastic sedimentary lithologies that were deposited in different environments. This suggests that the AMS technique may be more generally applicable and not necessarily restricted to ''undeformed'' clay-rich sediments.

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