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Flow path of the 1993 Hokkaido-Nansei-oki earthquake seismoturbidite, southern margin of the Japan sea north basin, inferred from anisotropy of magnetic susceptibility

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SUMMARY

A magnetic fabric analysis has been carried out on standard cube samples from one gravity and three multiple cores extracted from the Shiribeshi trough and Okushiri basin in the southern margin of the Japan sea north basin. It is aimed at tracing the flow path of turbidites that are assumed to have deposited in response to the 1993 Hokkaido-Nansei-oki earthquake. Magnetic remanence was used for reorientation to the geographic coordinates. Magnetomineralogical investigations including low-temperature magnetometry, magnetic hysteresis loops and isothermal remanent magnetization (IRM) acquisition experiments indicate that pseudo-single domain to multidomain magnetite is the principal magnetic carrier and is, therefore, capable of providing reliable anisotropy of magnetic susceptibility (AMS) palaeocurrent direction estimates. A well-developed near-horizontal magnetic foliation and minimum susceptibility axes lying close to vertical are recorded at all sites reflecting an original depositional fabric. Clearly defined magnetic lineation was observed at all sites and is considered to reflect the palaeocurrent direction. Down-core changes of susceptibility and key AMS parameters show good correspondence to occurrences of turbidite layers marking the increase of input of influx materials. In agreement with results from recent marine surveys and IZANAGI side-scan sonar images, an NNE transportation trend has been estimated for sediments at sites from the Shiribeshi trough with a possible depositing path initiating from the slope bounding the south and southeastern margin down to the trough floor. Similarly, a SSE palaeocurrent direction has been estimated for sediments from the Okushiri basin with evidence for a relatively strong transporting current flowing through the canyons along the steep slope bounding the north and northeastern margins of the basin. The present results agree with the view that slope failure is the most probable mechanism for the down-slope transport of the sand from the shelves and upper slopes down to floors of basins and troughs in the southern margin of the Japan sea north basin. They further support the ongoing assumption that the 1993 Hokkaido-Nansei-oki and other strong historical earthquakes together with associated tsunamis are the principal triggering forces for the down-slope mass gravitational transport and formation of turbidites in this seismically active area.

Key words: AMS, deep-sea sediments, Japan sea, palaeocurrent, seismoturbidite.

INTRODUCTION

There has been a growing number of deep-sea coring studies on the sediments of the Japan sea including Ocean Drilling Project (ODP) legs 127 and 128 (e.g. Tada *et al.* 1992; Follmi *et al.* 1992) and various cruises carried out either separately by Japanese institutions or through joint work with other Russian and Canadian counterparts. The Geological Survey of Japan (GSJ), in particular, has been interested in such studies for the past 15 yr: aiming for an overall evaluation of the palaeoceanographic development of the Japan sea (e.g. Ikehara *et al.* 1994), the GSJ has independently collected many Holocene deep-sea sediment cores from various parts of the Japan seafloor to study their provenance and condition of sedimentation.

The Japan sea generally constitutes three main basins, the Japan, Yamato and Tsushima; the first, to the north, is larger and deeper than the other two. In the northeastern margin, earthquakes and tsunamis have been frequent and yielded characteristic sedimentological records that are defined as seismoturbidites (e.g. Nakajima & Kanai 2000). Such records have recently been recognized and

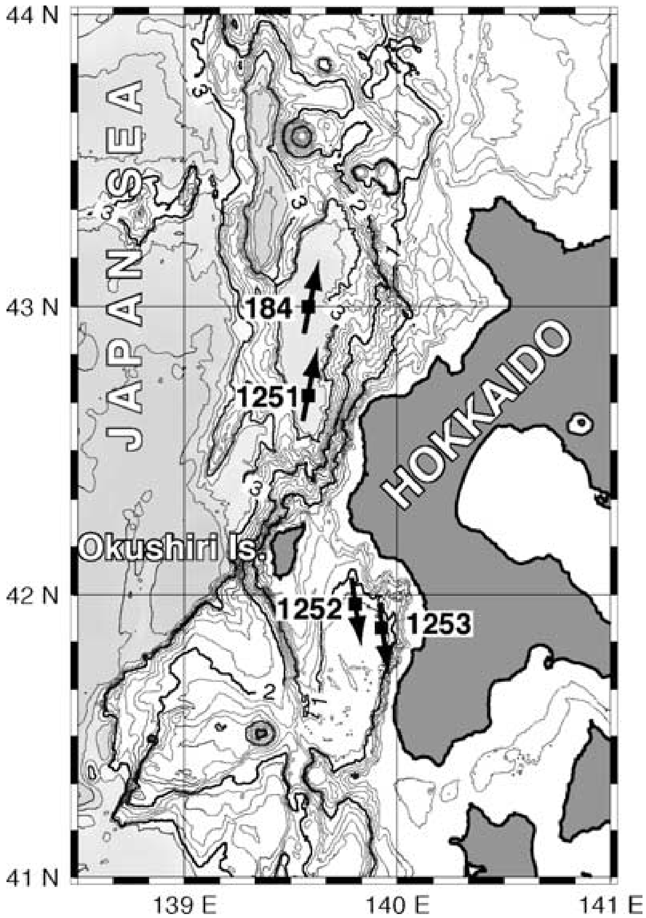

Figure 1. Bathymetric map of the Japan sea north basin with site locations and palaeocurrent directions inferred from AMS measurements. Contours are at 200 m intervals.

used to assess recent and geohistoric seismic hazards and determine recurrence intervals of earthquakes (Ujiie *et al.* 1997; Shiki *et al.* 2000).

This study focuses on using the anisotropy of magnetic susceptibility (AMS) as an efficient petrofabric tool to study the provenance and sedimentation mechanism of some of the Holocene deep-sea sediments retrieved from the southeastern margin of the Japan sea basin and throw more light on their depositing path in relation to recent earthquakes. Sediments from the gravity core GH95-0184 (327 cm) and three multiple cores GH99-1251 (38 cm), GH99-1252 (33 cm) and GH99-1253 (22 cm) extracted at water depths between 1217 m and 3325 m during two of GSJ cruises of the R/V Hakurei-maru represent the target of the present work. Both the gravity core and multiple core at site GH99-1251 were raised from the Shiribeshi trough, while the remaining two multiple cores were raised from the Okushiri basin (Fig. 1) . Sediments from these cores are generally composed of silt and clay with frequent occurrences of turbidite layers that are assumed to have been deposited by turbidity currents triggered by the 1993 Hokkaido-Nansei-oki (42°47′N, 139°12′E) and other historical earthquakes (Takeuchi *et al.* 1998; Nakajima & Kanai 2000). AMS was therefore called on to try to trace the assumed transportation path that these sediments may have followed during their journey soon after the occurrence of the 1993 Hokkaido-Nansei-oki earthquake until they reached their final destination at the floor of the two depressions.

The present area is considered as a semi-enclosed basin that is separated from the bordering large coastal sedimentary basin to the NE (not shown in the location map in Fig. 1) by highly elevated ridges that encompass coarse detrital sediments trapped along the bounding steep slopes (Ikehara *et al.* 1994). The 1993 Hokkaido-Nansei-oki earthquake with a magnitude of 7.8 in Richter scale occurred at approximately 30 km beneath the Okushiri ridge (Fig. 1) and caused the well-known southwestern Hokkaido tsunami of 1993 July 12 that devastated Okushiri Island and created waves as high as 8.6 m where several residents drowned and buildings were moved as much as 30 m inland (Nakanishi *et al.* 1993; Tsuji *et al.* 1994).

Early theoretical and laboratory studies indicate that AMS of sediments arises from the preferred orientation of elongate and/or flattened magnetic grains and could, therefore, be used as a measure of the degree and orientation of particle alignment, which in turn helps depicting palaeocurrent directions and associated sedimentation conditions (Hamilton & Rees 1970). Further comparative studies indicate that sedimentary fabric and palaeocurrent estimated using AMS are in good agreement with those obtained from photometric, optical and other related methods (Taira & Lienert 1979; Taira & Niitsuma 1986; Schieber & Ellwood 1988). More recently, AMS studies of deep-sea sediments have permitted the depiction of transport and depositional mechanisms of various types of these sediments (Shor *et al.* 1984; Kissel *et al.* 1997, 1998; Joseph *et al.* 1998).

SEDIMENT DISTRIBUTION AND AGE CONTROLS

Recent surveys in the southeastern margin of the Japan sea basin by Inouchi *et al.* (1995, 1996) and Sagayama *et al.* (2000) reveal the clustering of sandy-sediment bodies on shelves and upper slopes at depths shallower than 200–300 m, while silty or clayey sediments (hemipelagic mud) are widely distributed on mid to lower slopes and basin plain. Some other sandy-layer occurrences were also identified in surface sediment samples collected from the lower slope and basin plain (Ikehara & Inouchi 1998; Ikehara *et al.* 2001). The sand layers are in sharp contact with underlying oxidized hemipelagic mud and clearly exhibit sedimentological features of turbidites with upward-fining graded structures and parallel and/or cross lamination at the lower part (Ikehara & Inouchi 1998; Ikehara 1999; Ikehara *et al.* 2001). Carbonate remains could be seen in some of the turbidite layers despite their presence below the Carbonate Composite Depth (CCD), estimated at around 2000 m in the Japan sea (Ichikura & Ujiie 1976), implying that they were originally deposited in shallow water depth, probably shallower than several hundred meters, before being driven to their present locations. Also, the brown oxidized mud that is usually encountered at seafloor depths greater than 1000 m could not be found in the surface sediments suggesting a rapid sedimentation and very recent age for these turbidite layers. Moreover, a reworked tephra layer that is correlative to the volcanic ash of the 1640 Hokkaido-Komagatake volcanic eruption was recognized below the uppermost turbidite layer with intercalation of brown hemipelagic mud of a few cm thickness (Ikehara & Inouchi 1998). Kanai & Nakajima (1995) reported a cesium-137 radiometric measurement for the oxidized mud layer in a grab sample taken to the south of the gravity core from the Shiribeshi trough and concluded that this layer was deposited after 1954. No strong earthquakes, other than the 1993 Hokkaido-Nansei-oki earthquake, have been reported after 1954. Utilizing IZANAGI side-scan sonar images, Okamura & Kato (2002) recognized a cluster of slope failures and landslides around the hypocentral region of the 1993 Hokkaido-Nansei-oki earthquake. All these observations have led to the assumption that the uppermost turbidite layer is the seismoturbidite formed as a result of the 1993 Hokkaido-Nansei-oki earthquake.

Preliminary sedimentological investigations indicate that the assumed seismoturbidite layer forms most parts of the multiple cores and the top part of the gravity core (Fig. 2). It is composed principally of very fine sand that is slightly coarser (fine to very fine sand) at site GH99-1251. The same layer was also observed at some sites to the northern margin of the Shiribeshi trough, however, with a thickness less than a few centimeters indicating a minor down-slope transport probably as a result of the 1993 Hokkaido-Nansei-oki earthquake. Similar occurrences of the seismoturbidite layer could also be identified in the Okushiri basin (Ikehara 1999; Shimokawa & Ikehara 2002) with grain size becoming finer southward (Inouchi *et al.* 1995), reflecting coarser sediment supply from the northern slopes.

As a result of the shallow CCD in the Japan sea, no radiocarbon age determination using carbonate fossil records could be carried out for the present sediments. Instead bulk organic carbon in the hemipelagic mud was used for radiocarbon age determination. In general, age estimate of bulk organic carbon is older than real age estimation because of contamination of old terrigenous organic matter in sediments. A linear relationship between radiocarbon ages of planktonic foraminifer and bulk organic carbon were established for the Holocene sediments of northern Japan sea basin by Ikehara (2000). Therefore, if the difference between real age and ^{14}C age of bulk organic carbon could be estimated, the depositional ages might be inferred. Consequently, radiocarbon age determination for bulk organic carbon was conducted for 14 horizons from the gravity core at site GH95-0184 (Fig. 2). Conventional ^{14}C age below the Ko-d ash erupted in 1640 was found to be 2010 BP. Therefore, there is a difference of approximately 1700 yr between real depositional age and the obtained radiocarbon age. Using this estimate, a depositional age below the turbidite layer at bottom of this core is inferred to be approximately 8000 yr.

SAMPLING AND LABORATORY MEASUREMENTS

A total of 205 discrete samples were taken for AMS measurements through continuous subsampling by pressing standard 7 cm^3 plastic cubes into the split working half of each of the cores. Two sets of samples were taken from the three multiple cores in order to obtain as much information as possible from these short cores. Low-field magnetic susceptibility and its anisotropy were first measured for all samples using a KLY-3S AGICO (Brno, Czech Republic) magnetic anisotropy meter (sensitivity 2×10^{-8} SI), then the programme ANISO (Jelinek 1981) was used for calculation of anisotropy axes and parameters. To retrieve palaeocurrent directions from sediments of cores presently lacking orientation, magnetic remanence was measured for all samples using a three-axis 2G-Enterprises (California, USA) cryogenic magnetometer and demagnetized stepwise at steps of 5, 10, 15, 20, 25, 30, 40, 50, 60, 70 and 80 mT with an in-line AF demagnetizer with a peak field strength of 80 mT. Isolated characteristic remanent magnetization was then used for the restoration of cores into the geographic coordinates.

Rock magnetic measurements were carried out on a group of representative samples from each core to identify the type and grain size of magnetic carriers. Low-temperature magnetometry was conducted using a quantum design magnetic property measurement system (MPMS-XL5 – Quantum Design, San Diego, California, USA). First, an isothermal remanent magnetization (IRM) of 2.5 T was imparted to the sample at 300 K then magnetization changes with temperature were measured by cycling the temperature between 300 and 6 K in a nearly zero field. Next, an IRM of 2.5 T was

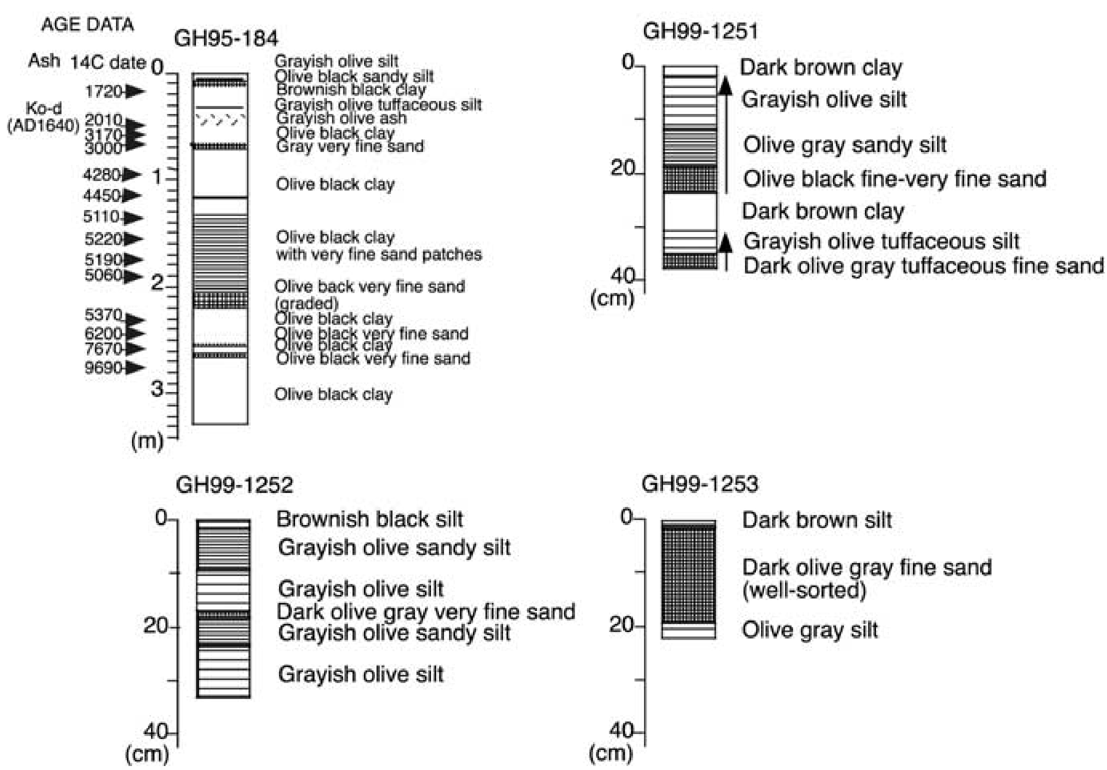

Figure 2. Lithological columnar sections of the studied cores. The concerned turbidite layer forms most of the multiple cores and top part of the gravity core. Conventional radiocarbon ages for bulk organic carbon and the correlative tephra layer for core GH95-0184 are also shown.

given to the sample after being cooled down to 6 K in a zero field then the thermal demagnetization of the IRM up to 250 or 300 K was measured. An IRM acquisition experiment was also performed using a pulse magnetizer where an IRM of 0.3 T was imparted on a sample in the opposite direction after an IRM of 2.5 T was given. The *S* ratio ($S_{-0.3T}$) was then calculated according to the definition of Bloemendal *et al.* (1992). Finally, magnetic hysteresis loops were measured on representative dried samples using a vibrating sample magnetometer (Molspin VSM) – Molspin Ltd, Newcastle, UK to determine the dominant magnetic grain size.

RESULTS AND ANALYSIS

Magnetic mineralogy and grain size

Magnetization curves during zero-field low-temperature cycling of IRM imparted at 300 K show that magnetization during cooling down was larger than during warming up above approximately 100 K (Fig. 3a). This magnetization loss was caused as a result of passing through the magnetic isotropic point of magnetite (T_I) and the Verwey transition known to occur at 110–120 K for pure magnetite (Verwey 1939). The temperature T_I is about 130 K for pure magnetite and is often lowered by substitution of Ti^{4+} (Dunlop & Özdemir 1997). Another sign of magnetite was an increase in the slope of the warming up curves around 100 K, which was clearly detected in the derivative ($-\Delta M/\Delta T$) (Fig. 3a). This could be yet another manifestation of the Verwey transition. There is no sign of pyrrhotite in the present sediments as its characteristic transition at 30 to 34 K (Rochette *et al.* 1990) could not be observed. Calculated *S* ratios ($S_{-0.3T}$) from IRM acquisition experiments also support the assumption that magnetite is the principal magnetic carrier. The ratios are very high and uniform, ranging from 0.98 to 0.99, indicating the predominance of low-coercivity magnetic minerals such as magnetite.

Magnetic domain state was estimated from the hysteresis parameters: the ratio of saturation magnetization to saturation remanence (Mrs/Ms) and the ratio of coercivity of remanence to coercivity (Hcr/Hc). On the plot of Mrs/Ms versus Hcr/Hc (Day *et al.* 1977), most samples lie within the pseudo-single- to multi-domain range (Fig. 3b) with three out of the four samples used from the multiple core at site GH99-1253 giving a large multidomain size that fell outside the range denoted in the standard plot. These results imply that the AMS of grains of most of the studied sediments should faithfully represent their preferred dimensional orientation without inverse fabric effect resulting from single-domain magnetite-grain presence (Stephenson *et al.* 1986; Potter & Stephenson 1988).

Demagnetization of remanent magnetization

The natural remanent magnetization direction was measured for the entire sample collection and progressively demagnetized. Most samples from the four cores exhibited high stability throughout the entire course of AF treatment and, apart from the first few steps, displayed a single component that heads toward the origin of the orthogonal plot. Fig. 4 shows that typical examples of Zijderveld (1967) orthogonal directional and intensity changes occurred during demagnetization of these samples. Some samples from core at site GH99-1253 and few others from the remaining cores behaved in an erratic manner during demagnetization and yielded no credible records. These unstable records were excluded from further analysis and were not used for reorientation of AMS directions. Generally, AF demagnetization at 20 mT was found to be sufficient to

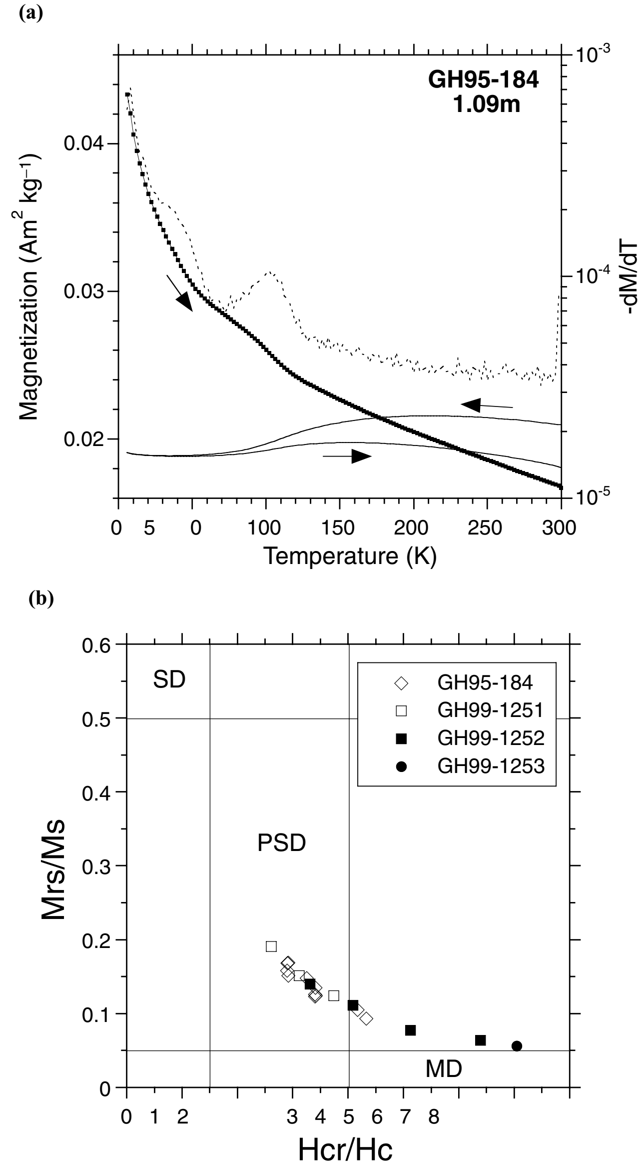

Figure 3. Representative examples of (a) low temperature demagnetization of Saturation Isothermal Remanent Magnetization (SIRM) and (b) hysteresis loops.

remove the soft viscous remanence and isolate the characteristic component using the principal component analysis (Kirschvink 1980). Table 1 lists mean characteristic relative declination and inclination for each core. Inclinations were shallower than the recent geomagnetic field inclination at both the central Shiribeshi trough, 59°, and northern Okushiri basin, 56°. This is attributed to inclination shallowing known to accompany rapidly deposited coarse materials like the present turbidites: particularly those from multiple cores at sites GH99-1251 and GH99-1253 (Table 1). Unlocked records in top soft parts of cores may also contribute to this deviation. Such inclination shallowing should not affect AMS records as remanence is carried mainly by single-domain grains that take a longer time to lock than the larger pseudo-single- to multidomain grains that carry AMS components. Declinations, on the other hand, were consistent within each core and averages calculated from linear fitting were used for restoring cores to geographic north to enable retrieval of palaeocurrent directions.

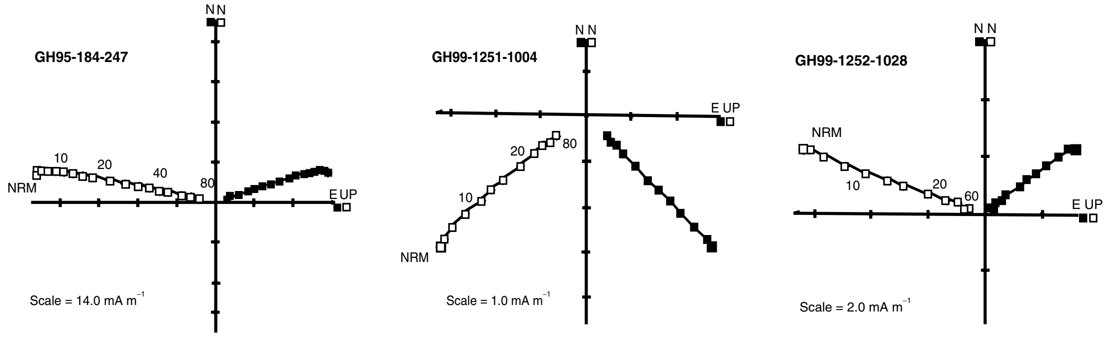

Figure 4. Typical examples of orthogonal Zijderveld plots of stepwise AF demagnetization data of representative samples. Closed (open) squares are projections on horizontal (vertical) planes. Sample name is labelled according to core number. Scale unit is fixed for both vertical and horizontal axes.

Table 1. Core-mean characteristic relative palaeomagnetic data for sediments from the four cores.

Cruise	Core	N/n	Dec.	Inc.	α_{95}
GH95	0184	127/121	81.2	40.8	2.1
GH99	1251	34/28	153.9	26.7	7.4
	1252	26/7	51.4	52.6	5.1
	1253	18/11	143.3	34.5	7.6

N/n is the ratio of the number of total measured samples to samples used for core-mean calculations.
Dec., Inc.: palaeomagnetic declination and inclination angles in degrees; α_{95}: semi-angle cone of confidence about core-mean direction (Fisher 1953).

Table 2. Core-mean values of magnetic susceptibility and AMS parameters for sediments from the four cores.

Cruise	Core	N/n	$K \times 10^{-6}$	*Pj*	*L*	*F*	*q*
GH95	0184	127/121	1163.2	1.102	1.006	1.084	0.085
GH99	1251	34/28	2183.7	1.070	1.006	1.056	0.130
	1252	26/7	1889.2	1.057	1.013	1.041	0.296
	1253	18/14	9823.9	1.069	1.013	1.051	0.271

N/n is the number of total measured samples to samples carrying primary fabric.

Anisotropy of magnetic susceptibility

The AMS (magnetic fabric) can be approximated by a second-rank tensor that can be represented as a triaxial ellipsoid whose magnitude and direction are described by the principal susceptibilities $K_1 \geq K_2 \geq K_3$, which are the maximum, intermediate and minimum susceptibility axes, respectively (Hrouda 1982; Tarling & Hrouda 1993). The AMS ellipsoid is described in terms of the magnetic foliation plane ($K_1 - K_2$), which is normal to K_3 and the magnetic lineation within the foliation plane and lies along the K_1-axis. The degree of grain alignment is expressed through the anisotropy magnitude. Many AMS parameters have been proposed and used variously to describe the magnetic fabric of rocks. In this study we followed the recommendations of Ellwood *et al.* (1988) and Tarling & Hrouda (1993) and used the following set of parameters to characterize the magnitude and shape of the susceptibility ellipsoid:

$$K = (K_1 + K_2 + K_3)/3 \quad \text{(mean susceptibility, Nagata 1961)},$$

$$Pj = \exp\sqrt{\left\{2\left[(n_1 - n_m)^2 + (n_2 - n_m)^2 + (n_3 - n_m)^2\right]\right\}},$$

where $n_1 = \ln K_1$, $n_2 = \ln K_2$, $n_3 = \ln K_3$;

$$n_m = (n_1 + n_2 + n_3)/3 \quad \text{(anisotropy degree, Jelinek 1981)},$$

$$L = K_1/K_2 \quad \text{(magnetic lineation, Balsley et al. 1960)},$$

$$F = K_2/K_3 \quad \text{(magnetic foliation, Stacey et al. 1960)},$$

$$q = (K_1 - K_2)/[(K_1 + K_2)/2 - K_3] \quad \text{(shape parameter, Granar 1958)},$$

Studies of laboratory deposited and natural sediments have demonstrated that a primary fabric induced by flowing water should posses a well-defined magnetic foliation in or near the bedding plane and a pole to bedding (K_3) that is close to vertical. Lineation is usually subordinate to foliation with low anisotropy and uniform q values that are <0.7. In the present study, q values <0.7 together with K_3 directions lying within 25° of the vertical were considered indicative of a primary fabric that can provide credible records of palaeocurrent direction and depositional conditions (Hamilton & Rees 1970).

Magnetic susceptibility and its anisotropy were measured for all samples from the four cores (Table 2) and down-core plots of the mean magnetic susceptibility (K), K_3 inclinations and the key anisotropy parameters q, Pj, L and F against lithologic column obtained for each core are displayed in Fig. 5. The two sets of plots displayed for each of the three multiple cores show consistent down-core variation pattern except for L records at site GH99-1251 probably as a result of its very weak measurement signals (Fig. 5). Magnetic susceptibility is rather inhomogeneous and varies in sediments from both within and between cores (Fig. 5) reflecting changes in concentration of magnetic minerals. It is high to moderate with values generally higher than 10^{-3} SI indicating a predominant ferromagnetic contribution (Rochette *et al.* 1992). The two sets of measurements from the three multiple cores show identical magnetic susceptibility behaviour reflecting measurement consistency and within-core homogenous distribution of magnetic minerals. The highest recorded magnetic susceptibility values are obtained for sediments from the core at site GH99-1253 that is close to main land Hokkaido, while the lowest values are from sediments of the core at site GH95-0184 (Fig. 5) that is located deeper into the basin (Fig. 1).

Inspection of down-core array of K_3 inclinations, q, L and F, indicates a clear predominance of highly foliated AMS ellipsoids that reflect a well-preserved primary depositional fabric marked by very steep K_3 axes and q values <0.7 in sediments from all cores (Fig. 5). Samples from the top part of the gravity core, most parts of multiple core at site GH99-1252 and few samples from the middle part of the multiple core at site GH99-1251 seem to have developed a secondary fabric marked by prolate ellipsoids ($L > F$ and $q > 0.7$) and K_3 inclinations well away from vertical (Fig. 5). Such

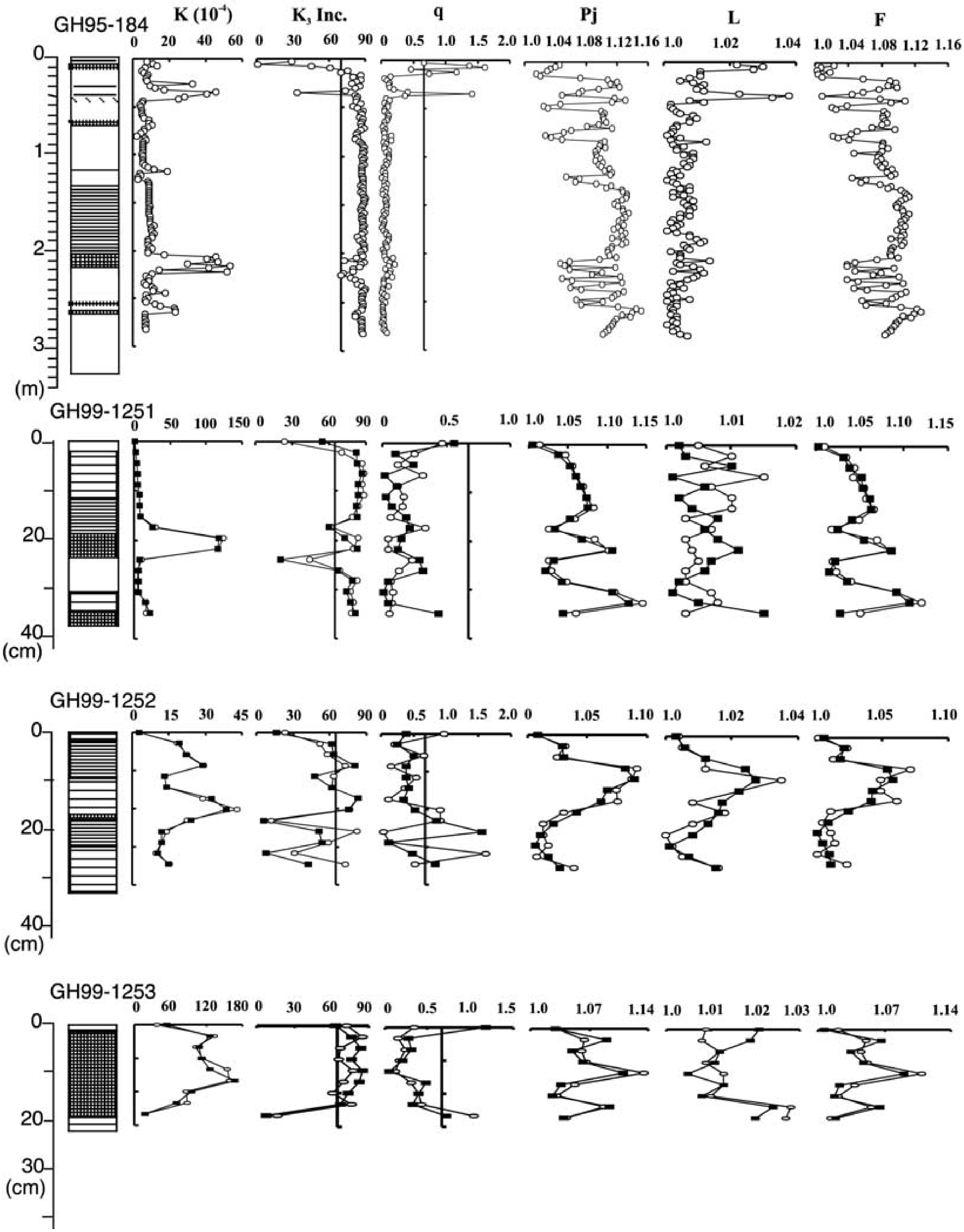

Figure 5. Down-core variations of mean magnetic susceptibility, K_3 inclination, q, Pj, L and F. Simplified lithologic columns are also shown.

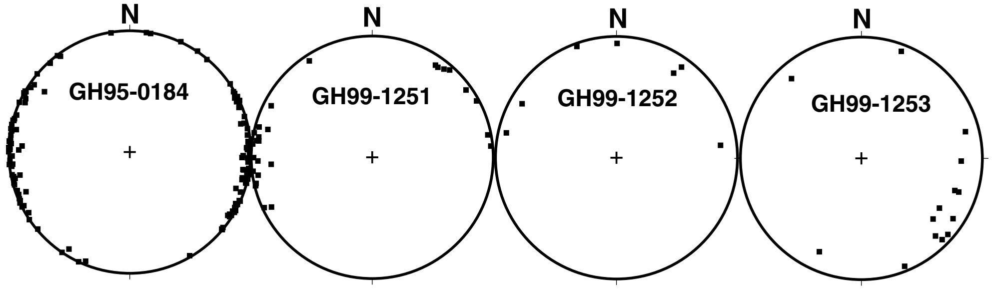

Figure 6. Lower hemisphere equal-area stereographic projections of unrestored K_1 axes from sediments of the four cores.

anomalous fabrics are attributed to either natural or induced sediment deformation as a result of coring and subsampling disturbances commonly reported for deep-sea sediment cores (Rees & Frederick 1974; Kent & Lowrie 1975; Rosenbaum *et al.* 2000). Data from these samples were not used for palaeocurrent estimations. Plots of unrestored K_1 directions for each core showed no correspondence with the sampling pressing axis (Fig. 6). This rules out possible systematic sampling disturbance either within or between cores.

The depositional fabric-carrying samples exhibit rather inhomogenous within- and between-site Pj values with the highest values, i.e. a better degree of statistical grain alignment, encountered in sediments from cores raised from the floor of the Shiribeshi trough (Fig. 1, Table 2). The q values, on the other hand, are generally low with the highest average values found in sediments from cores at sites GH99-1252 and GH99-1253 raised from the Okushiri basin that also have higher L values relative to those from the Shiribeshi trough (Table 2, Fig. 7). These parameter magnitude variations seem to reflect current intensity changes through time across the studied part of Japan sea north basin where the strongest current pulses are encountered in sediments raised from the floor of the Shiribeshi trough compared to those from the Okushiri basin. A complimentary directional view of these variations comes from the axial distribution discussed below.

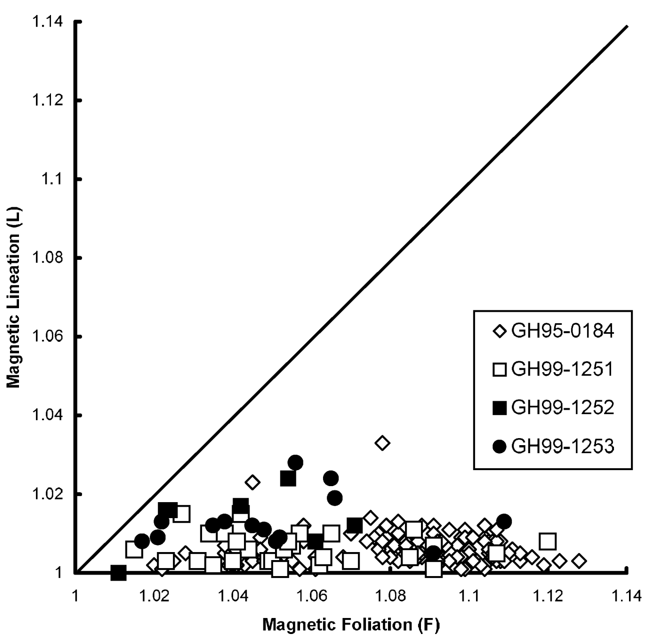

Figure 7. Flinn-type diagram of lineation versus foliation plots of samples carrying primary fabric from different cores.

Down-core similarity in variation patterns of Pj and F for all cores (Fig. 5) indicates that anisotropy is principally the result of foliation development. The slight overall down-core increase of F at sites GH95-0184 and GH00-1251 reflects a marginal compaction role in the foliation development of sediments in the Shiribeshi trough. It is also noticeable that magnetic susceptibility seems to vary in close correspondence with changes in the q and Pj for sediments from most cores. Closer inspection of these variations, particularly in plots of samples from the gravity core, indicates that they are lithologically controlled and generally tend to increase in correspondence with the turbidite occurrences encountered in all cores (Fig. 5). These variations, therefore, seem to highlight possible episodic changes in the amount and speed of influx materials derived to the studied part of the Japan sea north basin.

Palaeocurrent estimated from AMS

The palaeomagnetically oriented stereographic plots of the principal K_1 and K_3 susceptibility axes that satisfy the criteria for a primary fabric at each site (Fig. 8) show that there is a clear grouping of K_3 axes near the vertical in sediments from all cores: reflecting a well-developed near-horizontal magnetic foliation throughout the studied parts of the basin. Except for samples from the core at site GH99-1252, a good cluster of K_1 axes that marks a well-defined long-grain alignment, i.e. magnetic lineation, can also be seen at all sites. These alignments are brought up more clearly in the associated rose diagram in Fig. 8. Such good alignment of long grain axes reflects preferred palaeocurrent directions along these trends. Moreover, an observable preferred grain imbrication can also be seen at the three multiple core sites (Fig. 8) enabling absolute palaeocurrent direction determination.

The distribution of K_1 axes for samples from the gravity core shows a remarkable preferred long-grain alignment, palaeocurrent direction along the NNE–SSW direction in parallelism with the local bathymetric contours and elongation of the trough floor (Fig. 1). The persistence of this lineation direction throughout the entire thickness of the core indicates a sole source for most sediments at this site. In an attempt to define the absolute palaeocurrent direction at this site, it was decided to plot separately the K_1 and K_3 directions for samples from each of the three encountered major turbidite sections that might have some obscured grain imbrication. It is noticeable that although plots from all three sections confirm the presence of an axial NNE–SSW magnetic lineation, those from the middle section show a slight imbrication for some of the K_3 axes (average = 81°) that suggests a NNE sediment transport direction (Fig. 9). On the bathymetric map (Fig. 1) this trend suggests that the principal source for these sediments is most likely the upper-slope shelf of Okushiri

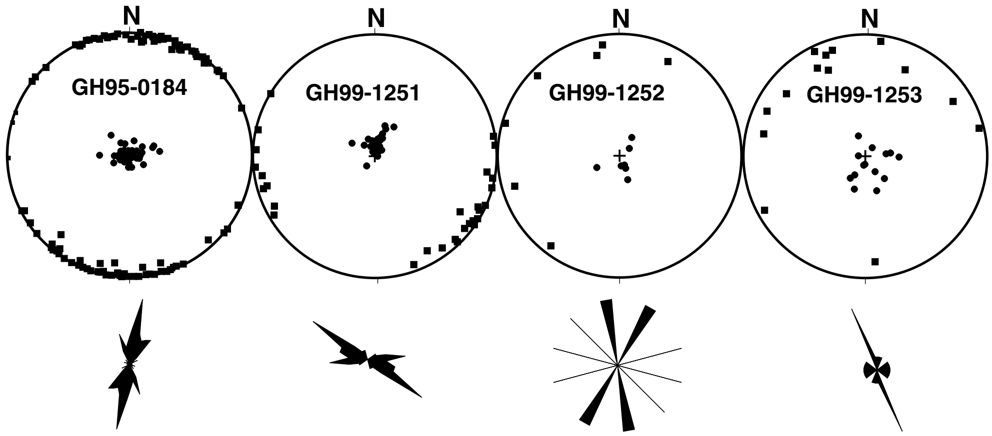

Figure 8. Lower hemisphere equal-area stereographic projections of K_1 (squares) and K_3 (circles) axes and rose diagrams showing azimuthal distribution of K_1 axes from primary fabric carrying sediments in the four cores.

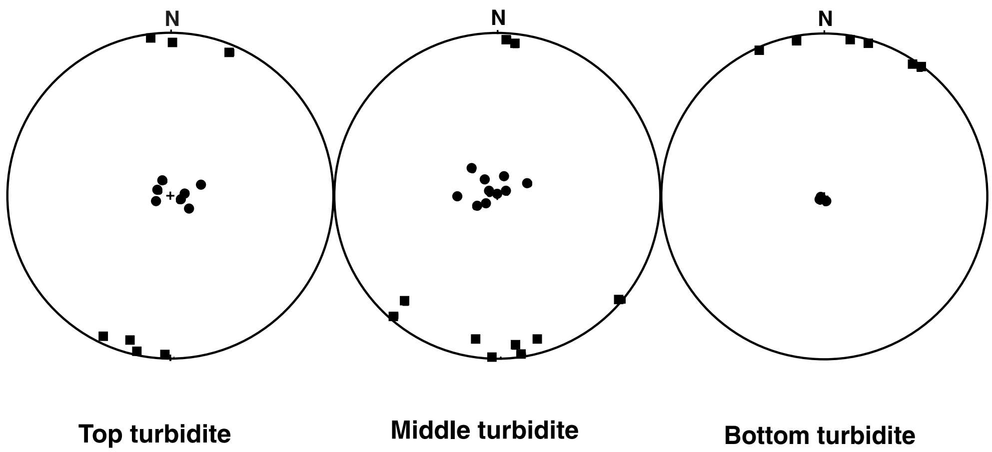

Figure 9. Lower hemisphere equal-area stereographic projections of K_1 (squares) and K_3 (circles) axes for samples from the three main turbidite sections in core at site GH95-0184.

Island and the southerly bounding steep slope. At the nearby GH99-1251 site, the imbrication of some of the K_3 axes (average $I = 81^\circ$) implies a palaeocurrent direction running toward the same NNE direction. The long-grain WNW–ESE alignment defined by the K_1 axes at this site represents either a possibly high-velocity depositing current ($ca \geq 1$ cm s^{-1}) or a down-slope long-grain rolling normal to the transporting current direction (Ellwood & Ledbetter 1979; Tarling & Hrouda 1993). The really high anisotropy degree, *Pj*, recorded at this site and the nearby GH95-0184 site (Table 2, Fig. 5), however, favours the assumption of a relatively high-energy depositing environment for the sediments occupying the floor of the Shiribeshi trough.

At site GH99-1252, although the number of K_1 axes that satisfy the criteria for a primary fabric is not statistically significant and their distribution reflects no definitive preferred palaeocurrent alignment, there is still a general tendency for a higher concentration along the NNW–SSE direction with a possible weak grain imbrication (average $I = 83^\circ$) that indicates a transporting current that previously headed toward the SSE (Fig. 8). A similar, however, more pronounced trend with a slightly larger imbrication (average $I = 80^\circ$) could be recorded at the nearby site GH99-1253. The estimated SSE palaeocurrent direction at these two sites, as presented on the bathymetric map in Fig. 1, indicates that the coarse materials at these two sites may have originated from the canyons along the steep slope bounding the north and northeastern margins of the Okushiri basin.

DISCUSSION AND CONCLUSIONS

The presence of pseudo-single domain to multidomain magnetite as the principal carrier in the present sediments indicates that the obtained long-grain preferred dimensional orientations are not influenced by inverse fabric effect known to result from single domain magnetite. It is, therefore, believed that the present sediments are capable of providing reliable AMS estimated palaeocurrent directions.

Within- and between-core variations in the magnetic susceptibility reflect distribution inhomogeneity of the amount and grain size of magnetic constituents. The observation that the highest values are recorded in sediments close to main land Hokkaido (site GH99-1253) while the lowest ones are from sediments located deeper into the basin (site GH95-0184) corresponds to probable variations in continental detrital content with more possible influx at sites close to main land Hokkaido. These susceptibility variations are in concert with sedimentological results and grain size analysis that showed that the turbidite sands in core GH99-1253 are coarser than those at the other sites.

The observed magnetic lineation at all sites demonstrates the persistent act of the depositional current on long-grain alignment at the studied sites. The depositional fabric-carrying samples exhibition of inhomogenous within- and between-site *Pj* patterns reflects time-variations in the depositing current intensity throughout the basin with the highest pulses encountered in sediments from the floor of the Shiribeshi trough, which also show better degree of long-grain alignment, i.e. consistent current flow direction throughout time. The variable AMS axial distribution of sediments from the Okushiri basin relative to those from the Shiribeshi trough, on the other hand, signifies the control of local current variations during some deposition stages.

The down-core changes of susceptibility and the key AMS parameters, *q* and *Pj*, and their tendency to increase in correspondence with occurrences of turbidite layers reflect sensitivity of AMS parameters to changes in depositional conditions and bulk of influx materials. It is, therefore, believed that these variations mark the episodic changes mostly related to occasional gigantic earthquakes known to have occurred in the Japan sea north basin and are held responsible for the deposition of turbidites. These AMS parameters may, therefore, serve as an indirect reliable tool for palaeoseismicity recording.

The obtained NNE transportation trend for sediments at sites from the Shiribeshi trough implies that these coarse materials may have followed a depositing path from the nearby coast to the steep slope bounding the south and southeastern margin of the trough and then were recently remobilized and carried down to the trough floor most probably as a result of the strong turbidity current associated the 1993 Hokkaido-Nansei-oki earthquake. This result is in good agreement with findings from recent marine surveys and IZANAGI side-scan sonar image (Okamura & Kato 2002) where the strongest reflectance was found in the southern slope of the Shiribeshi trough indicating coarser sediment distribution and probable source of sands to the trough floor.

The estimated SSE palaeocurrent direction at the two sites from the Okushiri basin both with evidence of a relatively strong transporting current indicate that the canyons along the steep slope bounding the north and northeastern margins of the basin are the most likely source of the coarse materials that were probably carried by the turbidity current resulting as a consequence of the 1993 Hokkaido-Nansei-oki earthquake. This is also in good agreement with the IZANAGI side-scan sonar image of Okamura & Kato (2002) that shows clear lobes on the basin floor near the mouths of canyons to the northern and eastern slopes of the basin confirming coarse sediment transport through these canyons.

In conclusion, the present results are in harmony with the assumption that slope failure at the southern and southeastern margins of the Shiribeshi trough and sand transport through submarine canyons in the northeastern margin of Okushiri basin are the most probable mechanisms for the down-slope transport of sand from the shelf and upper slope to floors of the basin and trough. They consequently support the ongoing view that the 1993 Hokkaido-Nansei-oki and other strong historical earthquakes together with associated tsunamis are considered as the principal triggering forces for the down-slope mass gravitational transport of most sediments at the southeastern margin of the Japan sea north basin and, in particular, the frequently encountered turbidite layers.

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