In: Marine Sediments
Editor: Shirley Williams
ISBN: 978-1-63485-127-5

Chapter 2

EVALUATION OF MICRO-FABRIC NETWORK WITHIN MARINE SEDIMENTS BASED ON A ROCK MAGNETIC TECHNIQUE

Yasuto Itoh[1,*], Osamu Takano[2]
and Machiko Tamaki[3]
[1]Graduate School of Science,
Osaka Prefecture University, Sakai, Osaka, Japan
[2]JAPEX Research Center,
Japan Petroleum Exploration Co., Ltd., Chiba, Japan
[3]Japan Oil Engineering Co., Ltd., Tokyo, Japan

ABSTRACT

Magnetic techniques that use anisotropy of magnetic susceptibility (AMS) act as a proxy of preferred permeable orientation in basin-filling sediments, when it is applied on samples impregnated with a magnetic suspension. The unique method for quantifying heterogeneity in rocks is reviewed and its value for reconstruction of the preferred direction of pore fluid flow is reassessed critically. The authors also present results of their experiments, which dealt with secondary fracture networks developed in tight sandstones burying a foreland basin on an arc-arc collision zone. Directional analysis of AMS ellipsoid implies tectonic

---

[*] Correspondence: yasutokov@yahoo.co.jp.

control on rupture development under strong trans-compressive regime. Micro-focus three-dimensional density imaging of test pieces has shown a substantial variation in pore fabric reflecting inhomogeneous impregnation of magnetic fluid within rocks.

1. INTRODUCTION

Micro-fabric of marine sediments is a versatile petrophysical information reflecting clast alignment for the reconstruction of sediment transport mechanism, direction of paleoflow and preferred permeable orientation of formation fluids since basins remote from hinterlands are filled with fine deposits lacking in visible manifestation of sedimentary structure. Hence many studies have explored standardized procedures for acquisition of grain fabric through conventional microscopy, which was summarized as an extensive review (Baas et al., 2007).

Baas et al., (2007) also evaluated a brand-new method utilizing magnetic techniques based on anisotropy of magnetic susceptibility (AMS) as a proxy for grain orientation, which benefits greatly from being able to measure a large number of grains in a three-dimensional space, in a short amount of time and with a lower sensitivity to user bias. The magnetic technique applied on samples impregnated with liquid containing suspension of ferromagnetic powder was originally developed for the purpose of oil exploration by Hailwood and his colleague (e.g., Hailwood et al., 1999) on the theoretical background of Pfleiderer and Halls (1994).

Because the rock magnetic method was first applied to continental setting where high porous sediments are widely distributed, previous studies tend to concentrate on evaluation of fabric of intact detrital grains and their interstitial pore geometry, omitting tectonic control on fracture generation and enhancement of effective permeability. The authors' preliminary study (Itoh et al., 2014a) on collision-related turbidite samples showed wider variety in micro-fabric reflecting secondary fracture network under strong tectonic stress. In this paper, we aim at verification of AMS usability as a textural indicator of rocks, with special emphasis on origin of fluid pathway within tight turbidite sandstones burying a foreland basin.

2. METHODOLOGY: A REVIEW

2.1. Anisotropy of Magnetic Susceptibility

To measure the initial magnetic susceptibility, a rock sample is placed in a low-intensity magnetic field of strength H, and the intensity of the induced magnetization (J) is measured for different orientations of the field. The induced magnetization is related to the field strength through the magnetic susceptibility (*K*) of the sample, where:

$$J=K$$

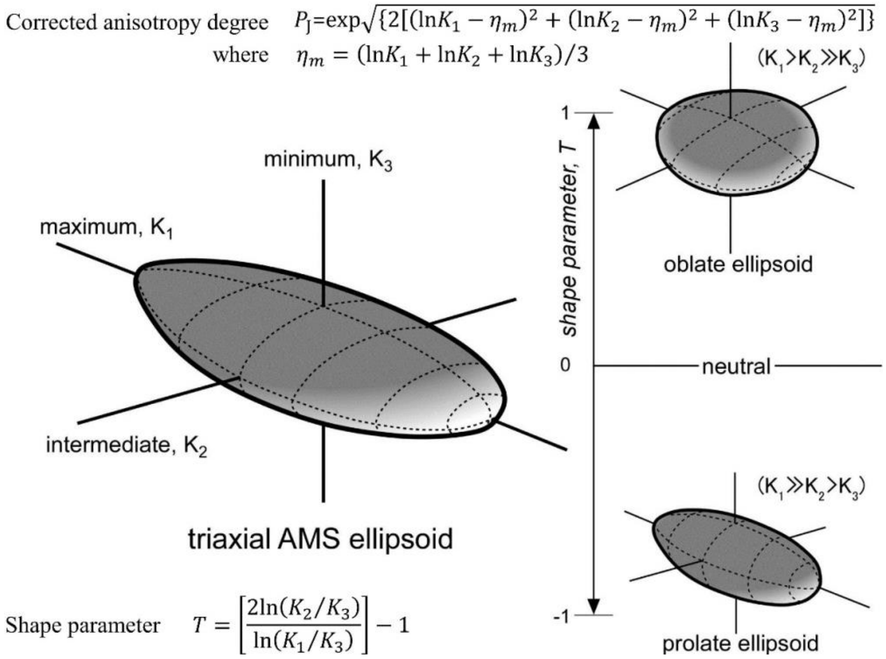

Figure 1. The susceptibility ellipsoids. Significant parameters of anisotropy of magnetic susceptibility (AMS), such as P_J and T, are calculated based on orthogonal principal susceptibilities (K_1, K_2, K_3).

The magnetic susceptibility of a sample is the summation of the susceptibilities of all mineral species within rock samples, and magnetic susceptibility is rarely identical in all directions of measurement; it more or less is an anisotropic parameter. The degree of anisotropy of magnetic susceptibility (AMS) is dependent primarily on mineral type, but even for a single type of mineral species the magnitude and anisotropy of magnetic susceptibility may considerably vary with many physicochemical properties (Tarling and Hrouda, 1993). Figure 1 presents significant parameters of AMS with typical types of susceptibility ellipsoids.

2.2. Conventional Method

As for common sedimentary rocks with low content of ferromagnetic minerals, AMS fabric generally reflects alignment of iron-rich silicates such as biotite and amphibole, of which orientations are bound to sedimentary structure. Based on azimuth of untilted AMS principal axes of fine sediments, Itoh et al., (2006) argued that the AMS is controlled by shape anisotropy of minerals laid on bedding plane.

Most igneous rocks are magnetically isotropic in primary state. Secondary structure may, however, cause detectable AMS trend. Based on intensive rock magnetic experiments, Itoh and Amano (2004) found that an enhanced AMS trend near a major fault cutting a granitoid pluton is originated from fine-grained authigenic magnetite grains precipitated on fracture surface.

Although such conventional methods are effective in case the possible AMS-carrying minerals are rather restricted, anisotropy of individual particles is brought about by the magnetocrystalline anisotropy or by the shape anisotropy, of which contributions vary with mineral species. Therefore more direct analytical method is necessary for quantitative description of micro-fabric of rocks.

2.3. Ferrofluid Method

Figure 2 shows a generalized scheme of analytical method utilizing liquid containing suspension of magnetic powder (hereafter referred to as ferrofluid). Since ultrafine ferromagnetic minerals in ferrofluid (mainly magnetite) are under superparamagnetic limit, coercive force (H_C) is actually negligible. As a result, maximum axis of AMS (K_1) of a rock sample impregnated with ferrofluid reflects elongate azimuth of pore network and most permeable direction.

Since the pioneering work of Hailwood, many researchers have applied the attractive method to various research areas. Nabawy et al., (2009) evaluated permeability and magnetic pore fabrics of an aquifer, and stated that pore fabrics of most formations in the Tushka Basin, Egypt are closely linked to paleocurrent directions with minor exception showing structural control (affinity for the main fault trends around the study area).

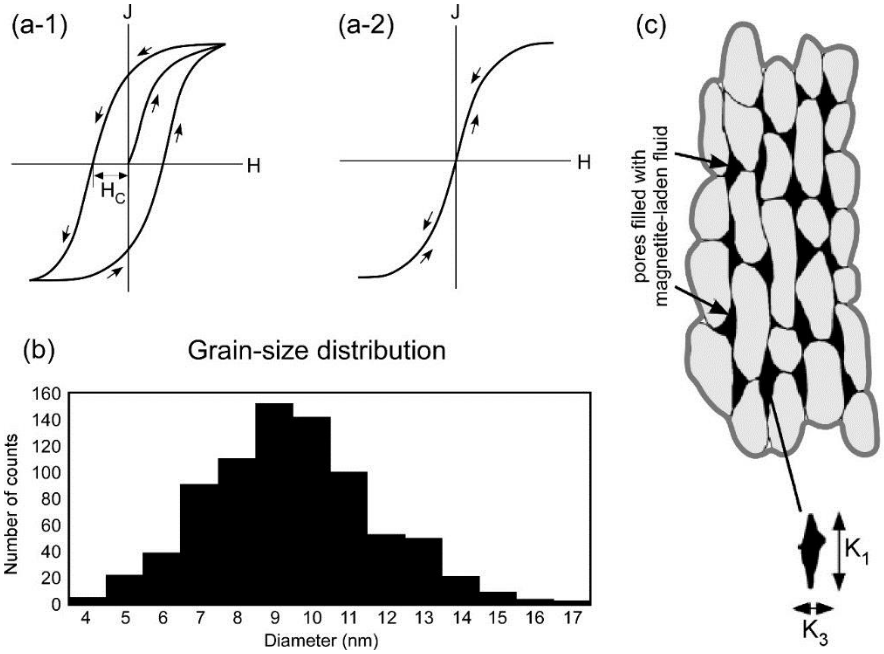

Figure 2. Generalized basis of analytical method utilizing ferrofluid. (a) Comparison of magnetic hysteresis between conventional ferromagnetic body (a-1) and ferrofluid (a-2). Ultrafine ferromagnetic minerals (mainly magnetite) are under superparamagnetic limit, and Hc is negligible. (b) Grain size distribution of a ferrofluid (provided by FerroTec Co., Ltd.). (c) Schematic view of a rock sample impregnated with ferrofluid (darkened parts).

Almqvist et al. (2011) utilized AMS-derived pore shape geometry for prediction of elastic properties for porous and anisotropic synthetic aggregates. It is noted that they adopted X-ray micro-tomography density contrast imaging, where attenuation of X-rays is related to the density contrast of the material, of dry and ferrofluid-processed specimens, and visually evaluated completeness of fluid saturation. At the end of this paper, we attempt to visualize various patterns of impregnation using similar apparatus.

Reflecting highly porous nature of samples in continental setting, the above studies used a vacuum chamber to impregnate ferrofluid. Although Baas et al., (2007) made a comment on high pressure treatment for complete saturation with ferrofluid, detailed experimental condition was not shown.

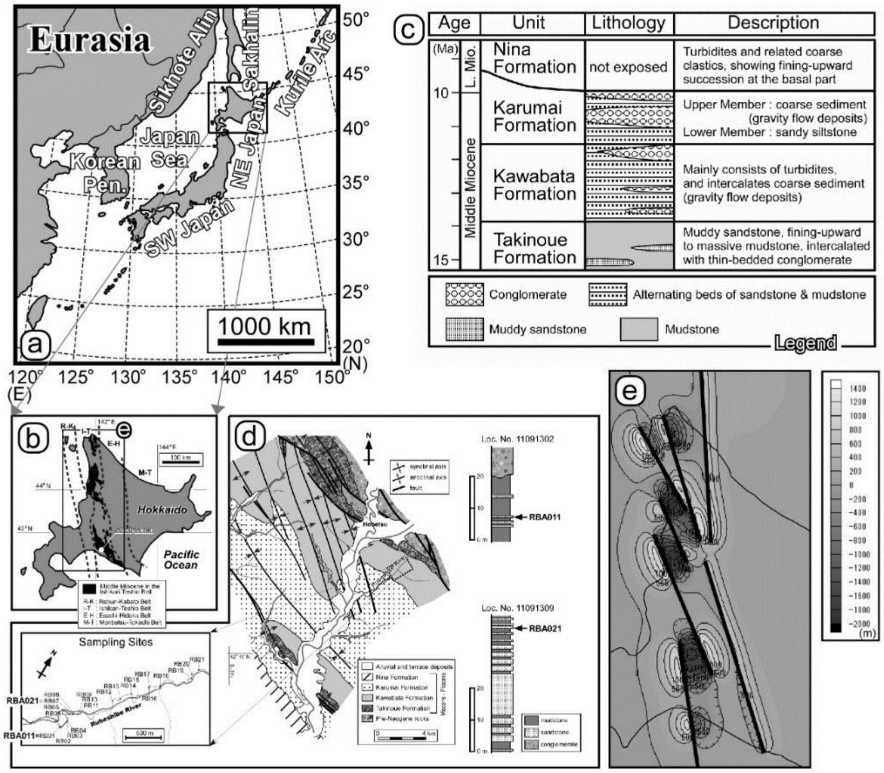

Figure 3. Geological background of the case study area. (a) Regional index. (b) Cenozoic tectonic context of central Hokkaido. (c) Neogene stratigraphy of the study area. (d) Geology of the study area (simplified from Kawakami et al., 1999), and locations of rock magnetic samples (modified from Itoh et al., 2014a). (e) Dislocation modeling of the Kawabata sedimentary basin (modified from Itoh et al., 2014b). Mapped area is shown by an envelope in (b).

3. CASE STUDY

3.1. Geological Background

Sedimentary basins on convergent margins are rapidly filled by voluminous clastics, part of which is volcaniclastic reflecting active volcanism, then deformed and exhumed under compressive stress provoked by various tectonic events. On such condition, tight sedimentary rocks suffering diagenesis are less porous and instead studded by numerous secondary fractures. One presumable theory is that micro-fabrics of rocks are different from those in stable continental setting.

Our focus is set on a turbidite sequence, Kawabata Formation, widespread in central Hokkaido, which deposited during a middle Miocene arc-arc collision event. Figure 3 presents geological background of the case study area. Hokkaido is located on the northeastern margin of Eurasia, and has suffered various tectonic events through the Cenozoic. Reflecting backarc spreading and subsequent collision events, Neogene sequence of the study area shows a transgression-regression cycle (see Figure 3c). Recently a numerical modeling was executed on the Kawabata sedimentary basin (Itoh et al., 2014b) and clarified that transpressional regime followed by strong compression on the NNW-SSE regional fault zone is essential to restore the basin configuration (Figure 3e).

3.2. Previous Studies

The authors executed preliminary rock magnetic studies on the Kawabata Formation (Itoh et al., 2013, 2014a). Rock magnetic samples were taken along the Rubeshibe river in Hobetsu district in central Hokkaido, where Kawakami et al., (1999) reported detailed stratigraphic and structural data (see Figure 3d).

Itoh et al., (2013) collected samples of the Kawabata Formation with a battery-powered electric drill at 21 sites along the Rubeshibe route. The bedding attitudes were measured on outcrops to compensate for tectonic tilting later. Between seven and sixteen independently oriented cores 25 mm in diameter were obtained at each site using a magnetic compass. Cylindrical specimens 22 mm in length were cut from each core and the natural remanent magnetization (NRM) of each specimen was measured using a cryogenic magnetometer (model 760-R SRM, 2-G Enterprises). Low-field magnetic susceptibility was measured on a Bartington MS2 susceptibility meter, and the AMS was measured using an AGICO KappaBridge KLY-3 S magnetic susceptibility meter.

Their sedimentological results are shown in Figure 4. AMS fabrics of most raw samples of the Kawabata Formation are highly oblate, as shown by positive T parameters near unity. This fabric is essentially confined to the bedding plane under gravitational force, and the authors considered the fabric as being governed simply by the shape anisotropy of paramagnetic minerals, i.e., alignments of elongate or platy grains such as amphibole or mica based on hysteresis study indicative of a negligible amount of ferromagnetic material.

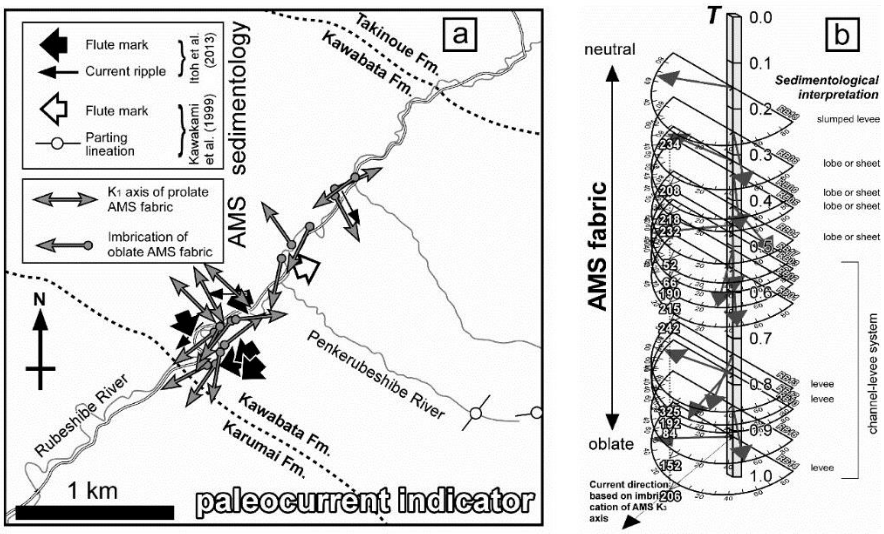

Figure 4. Summary of previous sedimentological analyses modified from Itoh et al., (2013). (a) Paleocurrent map of the Kawabata Formation around the Rubeshibe River route. Formation boundaries are after Kawakami et al., (1999). (b) AMS paleocurrent indicators of the Kawabata Formation. Directions of K_1 (gray arrows) are shown as acute angles from the dotted baseline of K_3 axis imbrication. Downcurrent orientations based on imbrication data are depicted as outlined numbers on the baseline. Vertical positions of the data represent degree of AMS oblateness shown by the T parameter. Samples with negative T values are excluded from the diagram because such cases have a large scatter in the K_3 directions.

Notably, the imbrication of the oblate AMS fabric matches visible sedimentary structures (Figure 4a), suggesting that AMS data can serve to indicate paleocurrents after the contributors to the magnetic fabric have been identified. It is also indicated that K_1 of prolate samples (with negative T parameters) tend to align perpendicular to the paleocurrent direction, implying that elongate grains roll on the sediment surface.

Figure 4b shows a series of paleocurrent indicators identified in the Kawabata Formation as a function of the AMS shape parameter (T). The intensity of alignment forcing inferred from AMS data is closely related to sedimentary facies (shown on the right in the figure) determined by field observation. For example, weak hydrodynamic forcing corresponds to fine rhythmically alternating facies in channel-levee systems. Thus, the sedimentological context of muddy sediments' AMS fabric can be interpreted in the light of sandy sediments' facies analysis.

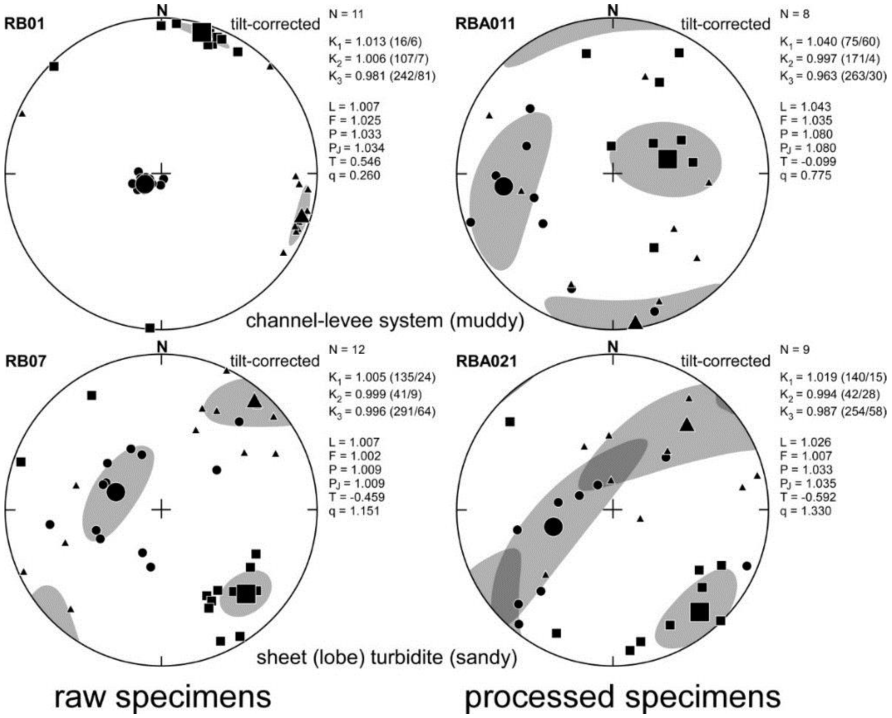

Figure 5. Tilt-corrected AMS fabric for the Kawabata Formation samples in raw (left) and ferrofluid-soaked (right) states. All the data are plotted on the lower hemisphere. Square, triangular and circular symbols represent orthogonal maximum (K_1), intermediate (K_2), and minimum (K_3) AMS principal axes, respectively, and larger symbols show their mean directions. Shaded areas are 95% confidence limits of Bingham statistics. Anisotropy parameters posted on the equal-area diagrams are calculated based on Tarling and Hrouda (1993). Generally, ferrofluid impregnation results in enhanced anisotropy degree. In site RB01 (upper), processed specimen (RBA011) shows prolate fabric and quite different spatial arrangement of principal axes from the raw data, whereas site RB07 (lower) is characterized by similar AMS trend after ferrofluid treatment (RBA021).

Based on the sedimentological discussion above, Itoh et al., (2014a) executed ferrofluid experiments on selected Kawabata samples in the Rubeshibe route. Hand samples oriented using a magnetic compass were taken from two sites, RBA011 (muddy channel and levee turbidite) from RB01 and

RBA021 (sandy sheet turbidite) from RB07. They were cut into cubic specimens with an approximate volume of 4 cm^3. Their permeability measured by a Pressure Decayed Profile Permeameter ranges 0.014~0.030 md for RBA011 and 0.053~0.151 md for RBA021, respectively. After evacuation for one day, all the samples were soaked in water-based ferrofluid (MSG W10 with saturation magnetization of 185 Gauss; provided by FerroTec Co., Ltd.) contained in a pressure vessel and impregnated under 5 MPa for 30 days.

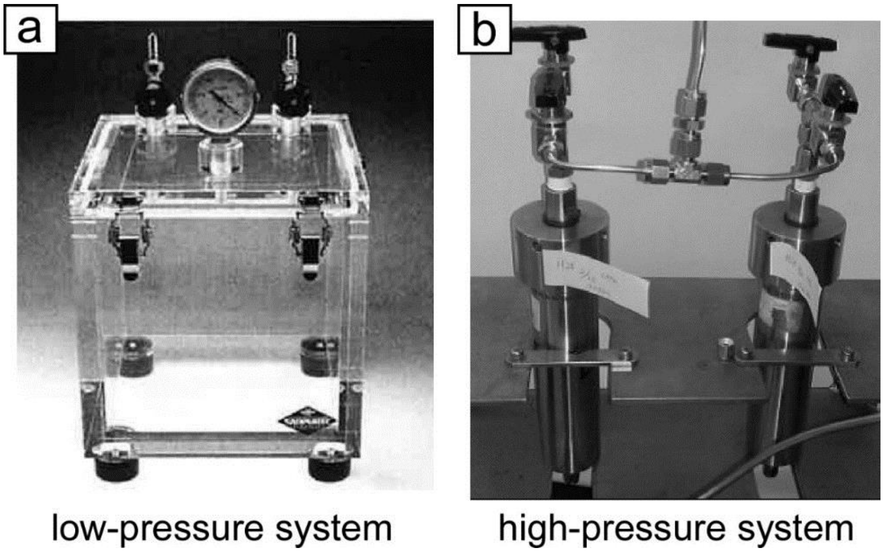

Figure 6. Experimental apparatuses to impregnate ferrofluid. (a) Vacuum chamber for low-pressure treatment. (b) Pressure vessel for high-pressure treatment.

Impregnated samples were washed with purified water, dried and then contained in plastic capsules. Their AMS data were measured using an AGICO KappaBridge KLY-3 S magnetic susceptibility meter, and much more than one digit larger bulk susceptibility indicates successful impregnation of ferrofluid. Measured AMS parameters were compared with those for raw samples in the same sites reported by Itoh et al., (2013). Figure 5 presents tilt-corrected AMS fabrics for the Kawabata Formation samples before and after ferrofluid treatment. Generally speaking, ferrofluid impregnation results in enhanced anisotropy degree (P_J). In site RB01, processed specimen (RBA011) shows prolate fabric and quite different spatial arrangement of principal axes from the raw data, whereas site RB07 is characterized by similar AMS trend after ferrofluid treatment (RBA021). They attributed such a variety in magnetic fabric to difference in microscopic sedimentary structure.

3.3. Experimental Scheme

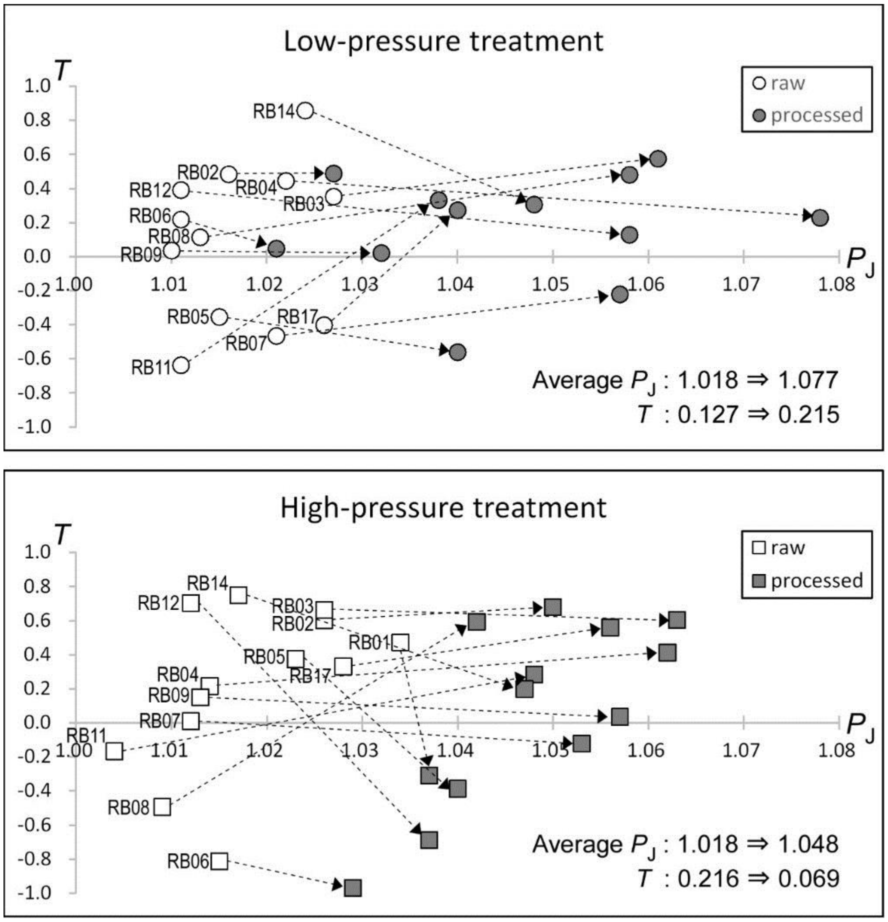

Figure 7. Magnitudes of magnetic fabrics in raw samples (open symbol) and ferrofluid-impregnated samples (solid symbol) for 13 sites of the Kawabata Formation. As for the low-pressure treatment, site RB01 is omitted because its processed P_J (1.448) is out of the range of transverse axis. Average P_J and T are arithmetic means of specimen data.

In the present study, the authors prepared two specimens (4 cm^3 oriented cubes cut from 25 mm diameter cores originally taken by Itoh et al., 2013) from 13 sites of the Kawabata Formation to observe lithofacies effect on the AMS fabrics. Using the water-based ferrofluid (MSG W10), one was impregnated in a vacuum chamber (Figure 6a) for 30 days, the other was impregnated in a pressure vessel (Figure 6b) under 5 MPa for 30 days. They were washed with purified water, dried and then contained in plastic capsules. Their AMS data were measured using an AGICO KappaBridge KLY-3 S magnetic susceptibility meter.

4. RESULTS

Bulk susceptibility of the processed samples were one to two digits larger than raw state indicating successful impregnation of ferrofluid. As shown in Figure 7, magnitudes of magnetic fabrics in ferrofluid-impregnated samples (solid symbol) are much greater than raw samples (open symbol) for 13 sites of the Kawabata Formation. Low-pressure treatment did not so much affect shape parameter *T*, whereas some specimens show clear prolate fabric after high-pressure treatment. Thus we investigate a directional trend of AMS axes in the next section.

5. DISCUSSION

5.1. AMS Fabric

Figure 8 delineates tilt-corrected AMS axes for 13 sites of the Kawabata Formation samples in raw (left) and ferrofluid-soaked (right) states. Generally, ferrofluid impregnation results in enhanced anisotropy degree. In case of low-pressure treatment (upper), AMS trend is more or less similar before and after ferrofluid experiment, whereas high-pressure treatment (lower) results in considerable decrease in *T* parameter although spatial arrangement of principal axes remained unchanged. This implies that pressurized ferrofluid was impregnated via a pathway which is impermeable under atmospheric pressure.

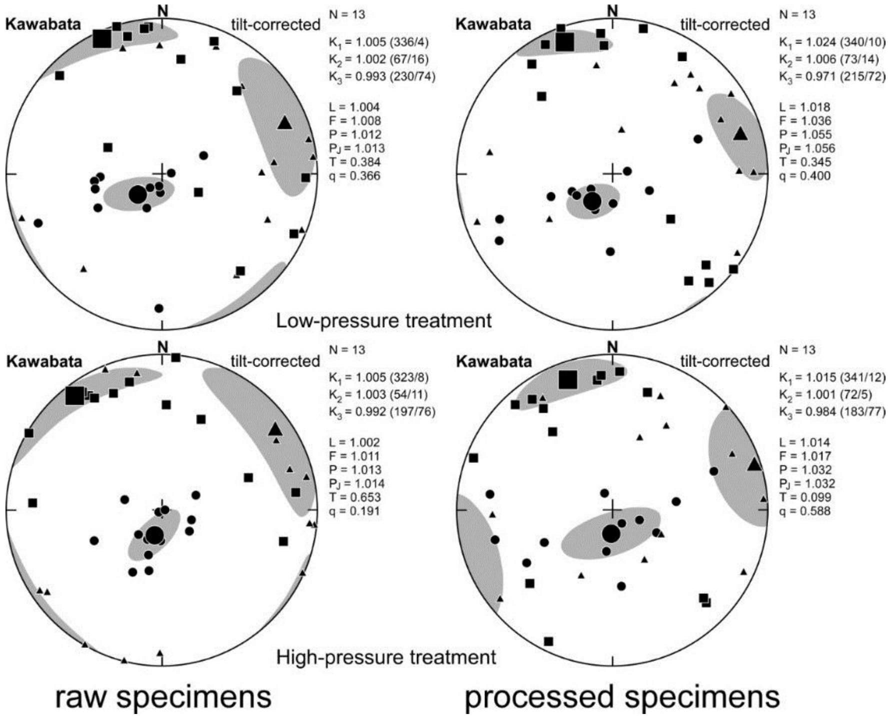

Figure 8. Tilt-corrected AMS fabric for 13 sites of the Kawabata Formation samples in raw (left) and ferrofluid-soaked (right) states. All the data are plotted on the lower hemisphere. Square, triangular and circular symbols represent orthogonal maximum (K_1), intermediate (K_2), and minimum (K_3) AMS principal axes, respectively, and larger symbols show their mean directions. Shaded areas are 95% confidence limits of Bingham statistics. Anisotropy parameters posted on the equal-area diagrams are calculated based on Tarling and Hrouda (1993). Generally, ferrofluid impregnation results in enhanced anisotropy degree. In case of low-pressure treatment (upper), AMS trend is more or less similar before and after ferrofluid experiment, whereas high-pressure treatment (lower) results in considerable decrease in T parameter. It is noted that azimuth of the K_1 axis, which is the most permeable direction, is coincident with regional fault system in central Hokkaido (see Figure 3).

5.2. Tectonic Implication

It is noted that azimuth of the K_1 axis after the high-pressure treatment, which is the most permeable direction in subsurface condition, is coincident with regional fault system in central Hokkaido (see Figure 3). Not only in the intensive collision event during the Kawabata stage, the NNW-SSE fault system has been intermittently activated with dextral slips throughout the Cenozoic era (Kusumoto et al., 2013). Thus the AMS data with ferrofluid treatment may delineate an invisible weakness in rocks in quantitative way.

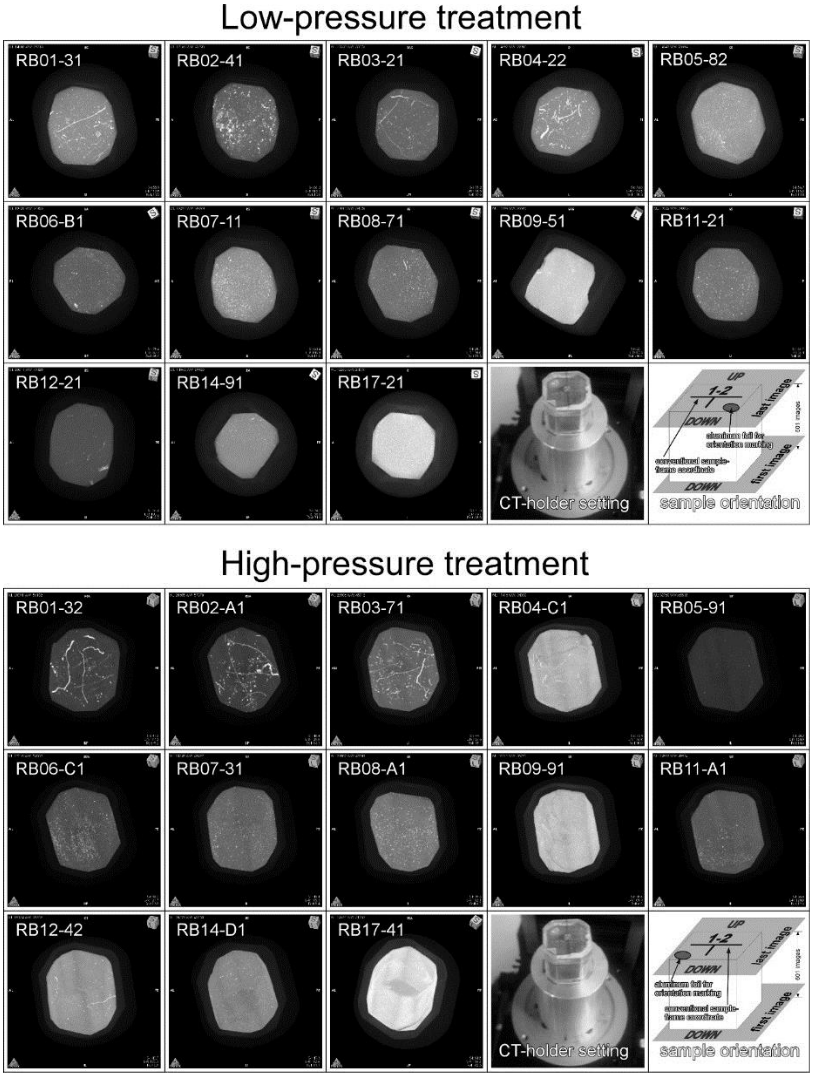

Figure 9. Three-dimensional maximum intensity projection (MIP) images of ferrofluid-processed specimens generated by OsiriX MD. Original image sequences (601 images per sample) were acquired using HMX225-ACTIS+3 Micro-Focus X-Ray CT Scanner at Center for Advanced Marine Core Research, Kochi University with 30 μm spatial resolution.

CONCLUSION

Well-organized magnetic experiments utilizing ferrofluid revealed wide variety in microscopic fabric of sedimentary rocks. Visualized spatial distribution of permeable pore spaces in rocks shows considerable diversity reflecting experimental methods (low or high pressure) and variety in lithologic facies. Figure 9 presents three-dimensional maximum intensity projection (MIP) images of ferrofluid-processed specimens generated by OsiriX MD. It is obvious that efficiency of impregnation differs even in the same site reflecting small-scale structural disturbance, some amount of which should be owing to bioturbation that is delineated by sinuous pathway of the dense fluid. A series of movies (13 files in .mov format each for low- and high-pressure treatments) of micro-focus X-ray CT scanning images (601 per sample at 30 μm spatial resolution) are available at OPERA: Osaka Prefecture University Education and Research Archives (http://hdl.handle.net/10466/14732).

ACKNOWLEDGMENTS

The authors are grateful to N. Ishikawa for the use of the rock-magnetic laboratory at Kyoto University and for thoughtful suggestions in the course of the magnetic analyses. Thanks are also due to Y. Yamamoto and support staffs for their kind backup during experiments at Center for Advanced Marine Core Research, Kochi University. We thank M. Nakano and EOR Group staffs of JAPEX Research Center for their kind collaboration and superb operation during preparation of impregnated samples. This work was supported in part by the Grant-in-aid (No. 25400456) from Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT).

REFERENCES

Almqvist, B. S. G., Mainprice, D., Madonna, C., Burlini, L., & Hirt, A. M. (2011). Application of differential effective medium, magnetic pore fabric analysis, and X-ray microtomography to calculate elastic properties of porous and anisotropic rock aggregates. *Journal of Geophysical Research*, 116, B01204, doi:10.1029/2010JB007750.

Baas, J. H., Hailwood, E. A., McCaffrey, W. D., Kay, M., & Jones, R. (2007). Directional petrological characterisation of deep-marine sandstones using grain fabric and permeability anisotropy: Methodologies, theory, application and suggestions for integration. *Earth-Science Reviews*, 82, 101-142.

Hailwood, E. A., Bowen, D., Ding, F., Corbett, P. W. M., & Whattler, P. (1999). Characterizing pore fabrics in sediments by anisotropy of magnetic susceptibility analyses, In D. H. Tarling and P. Turner (Eds.), Palaeomagnetism and Diagenesis in Sediments. *Geological Society, London, Special Publications*, 151, 125-126.

Itoh, Y., & Amano, K. (2004). Progressive segmentation and systematic block rotation within a plutonic body: palaeomagnetism of the Cretaceous Kurihashi granodiorite in northeast Japan. *Geophysical Journal International*, 157, 128-140.

Itoh, Y., Amano, K., & Kumazaki, N. (2006). Integrated description of deformation modes in a sedimentary basin: A case study around a shallow drilling site in the Mizunami area, eastern part of southwest Japan. *Island Arc*, 15, 165-177.

Itoh, Y., Tamaki, M., & Takano, O. (2013). Rock magnetic properties of sedimentary rocks in central Hokkaido - insights into sedimentary and tectonic processes on an active margin. In Y. Itoh (Ed.), Mechanism of Sedimentary Basin Formation - Multidisciplinary Approach on Active Plate Margins. Rijeka (Croatia): InTech. http://dx.doi.org/10.5772/56650.

Itoh, Y., Takano, O., & Tamaki, M. (2014a). Quantitative analysis of pore network in rocks utilizing ferrofluids: Application of rock magnetic data for oil exploration. *Journal of the Japanese Association for Petroleum Technology*, 79, 339-348.

Itoh, Y., Takano, O., Kusumoto, S., & Tamaki, M. (2014b). Mechanism of long-standing Cenozoic basin formation in central Hokkaido: an integrated basin study on an oblique convergent margin. *Progress in Earth and Planetary Science*, 1:6. doi:10.1186/2197-4284-1-6.

Kawakami, G., Yoshida, K., & Usuki, T. (1999). Preliminary study for the Middle Miocene Kawabata Formation, Hobetsu district, central Hokkaido, Japan: special reference to the sedimentary system and the provenance. *Journal of the Geological Society of Japan*, 105, 673-686.

Kusumoto, S., Itoh, Y., Takano, O., & Tamaki, M. (2013). Numerical modeling of sedimentary basin formation at the termination of lateral faults in a tectonic region where fault propagation has occurred. In Y. Itoh (Ed.), Mechanism of Sedimentary Basin Formation - Multidisciplinary

Approach on Active Plate Margins. Rijeka (Croatia): InTech. http://dx.doi.org/10.5772/56558.

Nabawy, B. S., Rochette, P., & Geraud, Y. (2009). Petrophysical and magnetic pore network anisotropy of some cretaceous sandstone from Tushka Basin, Egypt. *Geophysical Journal International*, 177, 43-61.

Pfleiderer, S., & Halls, H. C. (1994). Magnetic pore fabric analysis: a rapid method for estimating permeability anisotropy. *Geophysical Journal International*, 116, 39-45.

Tarling, D. H., & Hrouda, F. (1993). The Magnetic Anisotropy of Rocks. London: Chapman & Hall, 217pp.