Supplementary information for

# *The progressive development of microfabrics from initial deposition to slump deformation: an example from a modern sedimenary mélange on the Nankai prism*

by Mebae Kuranaga, Kiichiro Kawamura & Toshiya Kanamatsu

The microfabrics of argillaceous sediments change substantially at shallow burial depths (several metres) as a result of particle reorientation through dewatering. This process is associated with a decrease in pore volume (Bennett *et al*. 1981). The compaction model described in previous studies can be summarized as follows with respect to increasing burial depth. First, clay platelets are linked by edge-to-edge (E–E), edge-to-face (E–F), or stepped face-to-face (F–F) contact in a random arrangement, forming a long flocculation chain (Fig. 1). This structure is known as a ‘cardhouse’ fabric (Fig. 1). Next, during further burial, the contacts in the flocculation chain change to F–F contacts as a ‘bookhouse’ fabric, and so form finally a preferred horizontal orientation (Fig. 1; Bennett & Hulbert 1986). These fabric changes in argillaceous sediments can be detected in the reduction in the inclination of the remanent magnetization, which is caused mainly by small magnetite grains of single-domain size of less than about 0.1 µm in diameter (e.g., Tarling & Hrouda 1993) being reoriented into the preferred horizontal orientation by vertical compaction (Fig. 1; Anson & Kodama 1987; Deamer & Kodama 1990).

At the sediment–water interface, argillaceous sediments do not have a homogeneous cardhouse fabric but show heterogeneous fabrics caused by bioturbation, bottom-current disturbance, local crystallization, and mineral dissolution (Fig. 1; Bennett *et al*. 1991; Reynolds & Gorsline 1992). For example, fine-grained particles can be aggregated into heterogeneous fabrics by various processes and mechanisms, such as benthic animals eating organic matter in mud and creating an aggregation of fine-grained particles in their gut (Fig. 1; Reynolds & Gorsline 1992). Agitation by bioturbation and bottom currents at the sediment–water interface reaggregates fine-grained particles via adsorption by organic matter and electrostatic attraction (Fig. 1; Bennett *et al*. 1991; Stolzenbach *et al*. 1992; Kase *et al*. 2016). This reaggregation leads to the fine-grained particles being reoriented from E–F and E–E contacts to F–F contacts by the shear stress caused by the internal flow that occurs during the bioturbation or bottom-current disturbance, even at the sediment–water interface (O'Brien & Slatt 1990; Bennett *et al*. 1991).

Through these complicated processes at the sediment–water interface and at shallow burial depths, fine-grained particles are eventually aggregated into what are referred to as ‘peds’ (Fig. 1; Yong 1972; Collins & McGown 1974; Reynolds & Gorsline 1992). Although these peds play an important role in the early compaction process of argillaceous sediments (Yong 1972; Velde 1996), few studies (e.g., Collins & McGown 1974; Reynolds & Gorsline 1992; Kawamura & Ogawa 2004) have thoroughly investigated microfabrics in deep-sea sediments.

Following burial, the compacted microfabrics are further folded and sheared, if slumping occurs. According to Martinsen (1993), slumps are downslope movements of sediments above a basal shear surface where there is significant internal distortion of the bedding. Nevertheless, the bedding should still be recognizable. The moving slump causes intense internal deformation and produces a wide variety of deformational structures. This ductile phase is followed by a very late brittle phase during which faults form. Common structures in slumps include folds, boudins, faults of various size, and internal shear surfaces (Martinsen 1993). It is common to see strain overprinting where early-formed folds are truncated by late faults (Martinsen 1993).

**Fig. 1.** A conceptual model of the formation processes of microfabrics in muddy deep-sea sediments. A microfabric in muddy sediments is composed of clay aggregations and connectors. According to Collins and McGown (1974), the clay aggregations are divided into regular-shaped and irregular-shaped aggregations, and these are linked by connectors. Intergroup pores are found in the clay aggregations, and interassemblage pores are found between the clay aggregations (Collins & McGown 1974). The clay flakes in the muddy sediments have three types of contact: E–E (edge-to-edge), E–F (edge-to-face), and F–F (face-to-face; Ingles 1968). There are three types of formation processes of clay aggregations: physico-chemical, biological, and mechanical processes (Bennett *et al*. 1991). In the physico-chemical process, clay flakes are bonded to each other electrostatically to assemble with E–F and/or F–F contacts. In the biological process, clay flakes are moulded by planktonic and/or benthic animals to form dense clay aggregates as bioflocs (Reynolds & Gorsline 1992). Some of the clay flakes are bioturbated by benthic animals in the superficial layer. In the mechanical process, the initial microfabrics are developed from a random orientation into a preferred horizontal orientation with burial consolidation (Bennett *et al*. 1981). The clay aggregations are consolidated and flattened by overburden pressure (Kawamura & Ogawa 2004). Thus, the muddy sediments develop into a shale.

## References

Anson, G.L. & Kodama, K.P. 1987. Compaction-induced inclination shallowing of the post-depositional remanent magnetization in a synthetic sediment. Geophysical Journal of the Royal

Astronomical Society, 88, 673–692.

Bennett, R.H., Bryant, W.R. & Keller, G.H. 1981. Clay Fabric of Selected Submarine Sediments: Fundamental Properties and Models. Journal of Sedimentary Petrology, 50, 217–232

Bennett, R.H. & Hulbert, M.H. 1986. Clay microstructure. International Human Resources Corporation Press, Boston.

Bennett, R.H., O'Brien, N.R. & Hulbert, M.H. 1991. Determinants of Clay and Shale Microfabric Signatures: Processes and Mechanisms. In: Bennett, R.H., Bryant, W.R. & Hulbert, M.H. (eds) Microstructures of fine-grained Sediments from Mud to Shale. Springer-Verlag, New York, 5–32.

Collins, K. & McGown, A. 1974. The form and function of microfabrics features in a variety of natural soils. Geotechnique, 24, 223–254.

Deamer, G.A. & Kodama, K.P. 1990. Compaction-induced inclination shallowing in synthetic and natural clay-rich sediments. Journal of Geophysical Research, 95 (B4), 4511–4529.

Kase, Y., Sato, M., Nishida, N., Ito, M., Muhammad, M.M., Ikehara, K. & Takizawa, S. 2016. The use of microstructures for discriminating turbiditic and hemipelagic muds and mudstones. Sedimentology, doi: 10.1111/sed.12296.

Kawamura, K. & Ogawa, Y. 2004. Progressive change of pelagic clay microstructure during burial process: examples from piston cores and ODP cores. Marine Geology, 207, 131–144.

Martinsen O. 1993. Mass movements. In: Maltman, A. (ed) The geological deformation of sediments, London, 127–65.

O’Brien, N.R. & Slatt, R.M. 1990. Argillaceous rock atlas. Springer-Verlag, New York.

Reynolds, S. & Gorsline, S.S. 1992. Clay microfabric of deep-sea, detrital mud (stone)s, California continental borderland. Journal of Sedimentary Petrology, 62, 41–53.

Stolzenbach, K.D., Newman, K.A. & Wong, C.S. 1992. Aggregation of Fine Particles at the Sediment–Water Interface. Journal of Geophysical Research, 97 (C11), 17889–17898.

Tarling, D.H. & Hrouda, F. 1993. The magnetic anisotropy of rocks, Chapman & Hall, London.

Yong, R.N. 1972. Soil technology and stabilization. Proceedings of 4th Asia Regional Conference on Soil Mechanics and Foundation Engineering, 2, 111–124.