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Dilatant clayey microstructure in the Barbados décollement zone

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Abstract

Dilatant clayey microstructures in cores from ODP Leg 156, which drilled the basal décollement zone of the northern Barbados accretionary prism, are obtained from freeze-dried samples. The microstructure in the scaly fabric portion shows heterogeneous strain characterized by domains with strong preferred orientation of clay minerals and with sigmoidal, spindle, or tube-shaped coarse pores in fabric domains with random particle orientation. These dilatant microstructures have not been observed in clayey sediments from the Barbados décollement zone or other active shear zones. The dilatancy of the microstructure might be formed under the condition of high pore-fluid pressure in the course of shearing clays and due to tectonic stress.

1. Introduction

Dilatancy of clayey sediments from the décollement zone in the Barbados accretionary prism has been pointed out on the basis of porosity, bulk density, permeability and fluid flow data (ODP Leg 110 Scientific Party, 1987; Shipley et al., 1994; Stephenson et al., 1994; Moore et al., 1995). Recently, a major study of the décollement zone has focussed on the high fluid pressures and scaly fabric, and the relation of these factors to the deformational processes of the sediments in the décollement zone. Dilatancy is an important brittle phenomenon associated with volumetric strains under applied differential stress (e.g. Henkel, 1956; Rowe, 1962; Bridgman, 1949; Brace et al., 1966). Many experimental studies showed that dilatancy in hard rock is due to microcracking which occurs prior to macroscopic failure. In the case of soil, dilatancy is provided by the interlocking grains and the change in packing of the coarse grains during their relative movement (e.g. Rowe, 1962; Terzaghi and Peck, 1967). Dilatancy hardening has been pointed out by Brace and Martin (1968) and discussed in detail by Ismail and Murrell (1976).

Scaly fabric in the décollement zone of the Barbados accretionary prism has been documented by many workers (Cowan et al., 1984; Behrmann et al., 1988; Agar et al., 1989; Brown and Behrmann, 1990; Prior and Behrmann, 1990a,b; Taylor et al., 1990; Labaume et al., 1997). Previous SEM observations showed that microstructures in the scaly zone were defined by strong orientation of clayey particles. Scaly fabric zones are characterized by heterogeneous deformations (Labaume et al., 1997), and are interpreted as resulting from cyclic shear movements. Moore et al. (1986, 1988) and Brown et al. (1994) concluded that dilation of scaly fabric zone occurred by hydraulic fracturing due to high fluid pressure associated with volumetric collapse and fluid expulsion.

In this paper, we report the first observation of dilatant clayey microstructures in cores from the décollement zone, ODP Leg 156. The data for freeze-dried samples suggest that the strongly oriented textures were formed by localization of strain in the course of shearing of clays and that loosening textures and fracture–pore networks were associated with syntectonic high fluid pressure. We propose a formation model of dilatant deformational microstructures in the scaly fabric zone.

2. Geological setting

The Barbados accretionary prism with its décollement zone develops where the Atlantic Ocean crust

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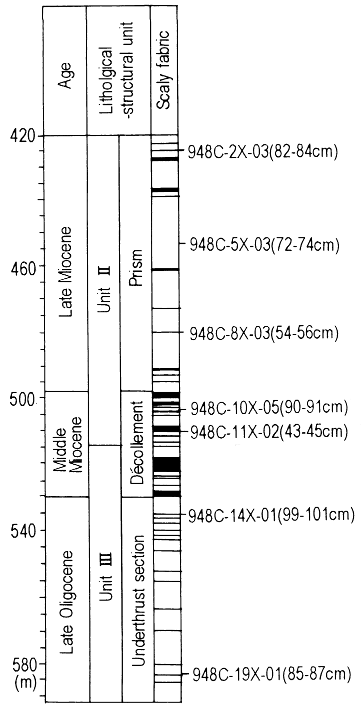

Fig. 1. Sample location and distribution of scaly fabrics in the décollement zone at Hole 948C (after Shipley et al., 1995).

underthrusts the Caribbean plate. Hole 948C is located 4 km west of the thrust front. The rocks intersected consist of about 60% clay minerals (Shipley et al., 1995) (Fig. 1). Unit I and the middle-upper parts of unit II are middle-late Miocene in age and characterized by thrust and folding structures in the accretionary prism. The lower part of unit II and the upper part of unit III, from 498 to 530 m, are late Early–early Middle Miocene in age. The horizon represents the décollement zone and is characterized by strong shearing and stratal disruption. The middle-lower parts of unit III, from 530 to 590 m, are late Oligocene and belong to the underthrust pile of sediments.

3. Sample preparation for SEM

Grain orientation, pore-size distribution, and pore shape change on account of dehydration. Therefore, the specimens for SEM observation and for measurement of pore-size distribution in the present work were carefully prepared using the t-butyl alcohol freeze-drying method described as follows (Takizawa et al., 1995; Takizawa, 1997); after the samples were placed in ethanol, they were dipped into t-butyl alcohol, and finally frozen in liquid nitrogen and dried within a vacuum evaporator. These SEM specimens were investigated by a scanning electron microscope, operating at 5 kV.

4. Deformational texture

The orientations of clay particles were measured from a SEM micrograph and are shown in Fig. 2. Deformational textures of clayey sediments obtained from SEM observation are shown in Fig. 3. The fabric above the décollement is characterized by random to weak bimodal orientation (Fig. 2a–c). In such a case the particle contacts are face to face (FF) or face to edge (FE) (Fig. 3a and b). The void geometry is large and irregular. In the samples from the décollement zone, on the other hand, scaly fabrics and fracture networks are seen by the naked eye or under the optical microscope. The scaly fabric zone is characterized, especially on a microscopic scale, by the spaced foliation, fracture networks and the *S–C* bands (Labaume et al., 1997). Some parts of the microstructure within the spaced foliation or the fracture network represent random particle fabrics (Fig. 3c) with random orientation (Fig. 2d) such as non-salt-flocculation. The microstructure within the closely spaced foliation is characterized by two types of deformational texture. One is strongly oriented parallel or subparallel to the décollement zone. Another is recognized by oriented and compacted particles with large pores, such as sigmoidal, spindle and tube shapes (Fig. 3d and e). The microstructure within the *S–C* band is characterized by high

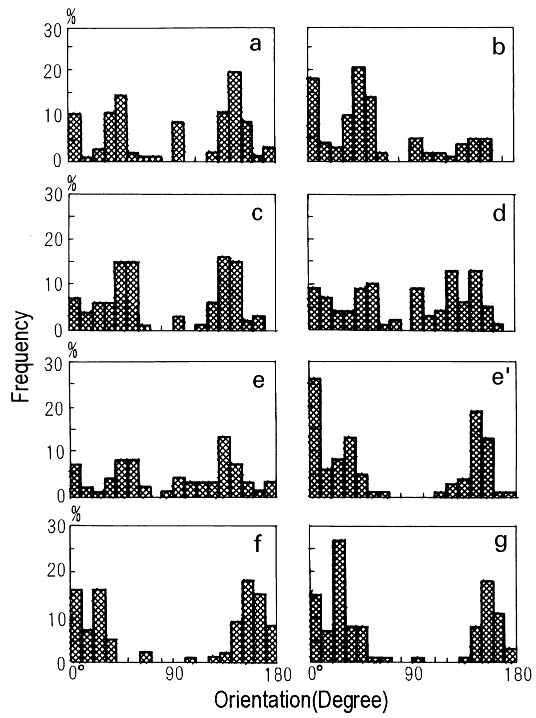

Fig. 2. Histograms showing clay basal trace orientation relative to the horizontal (orientation angle, 0° and 180°). All histograms represent 100 counts. Sampling location of (a)–(g) follows, (a) 948C-2X-03, (b) 948C-5X-03, (c) 948C-8X-03, (d) 948C-10X-05, (e) and (e′) 948C-11X-02, (f) 948C-14-01, (g) 948C-19X-01.

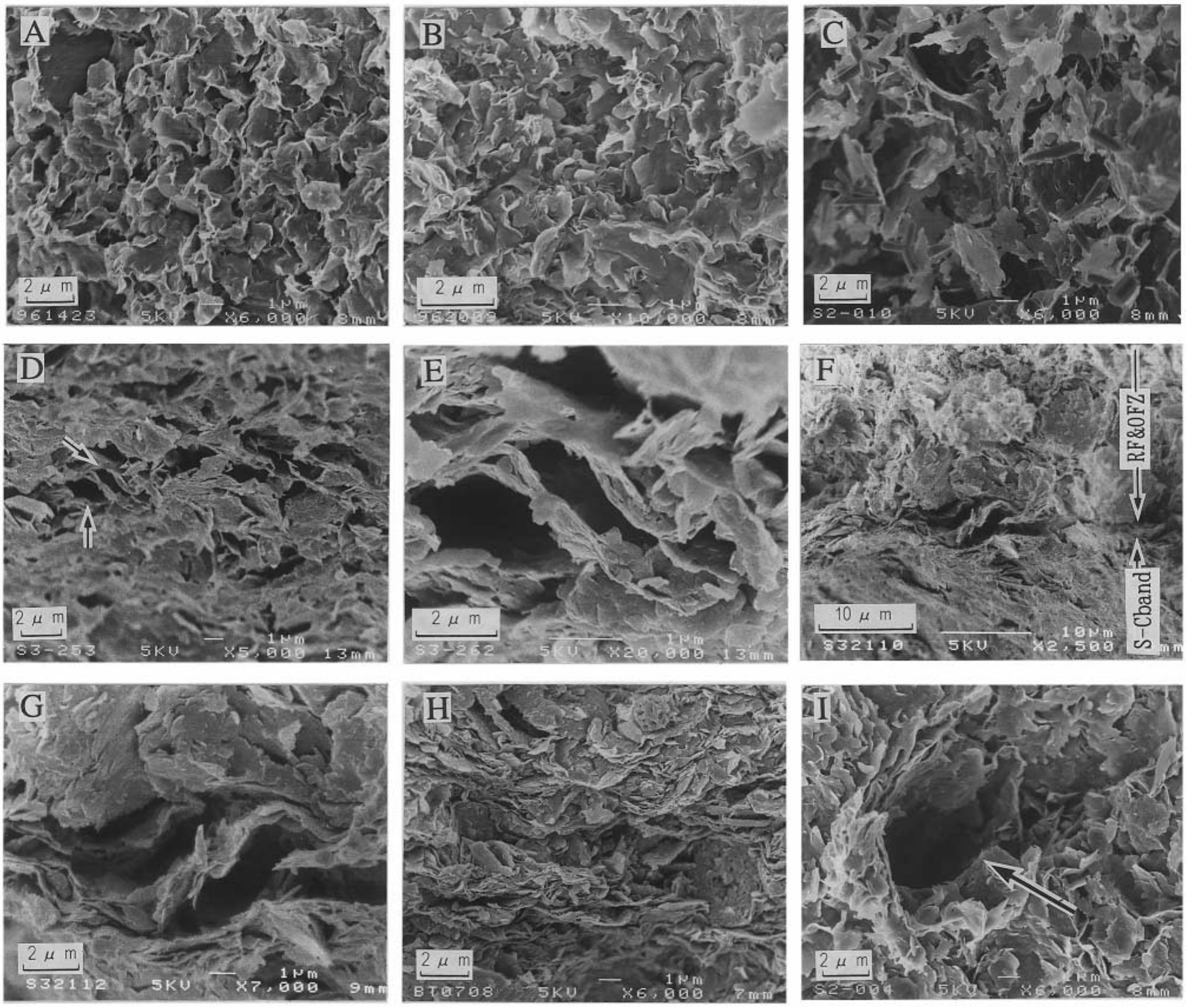

Fig. 3. SEM micrographs showing freeze-dried clay fabrics. (a and b) Random particle orientation. (c) Random particle orientation. Notice the porous fabric similar to the flocculated clay deposited in non-salt water. (d) Heterogeneously mixed texture in both strongly preferred orientations with open sigmoidal and spindle pores (arrow). (e) Dilatant microfracture. Notice the open sigmoidoil shape. (f) *S–C* band and RF & OFZ textures. (g) Open sigmoidal fractures develop along the boundary of *S–C* band RF & OFZ. (h) Preferred particle orientation. Notice the parallel of platy particles. (i) Gas-generated microvoid. Arrow shows vertical 'stressed' microvoid (perpendicular to the horizontal surface). Sampling location of (a–i) follows, (a) 948C-2X-03, (b) 948C-8X-03, (c) and (i) 948C-10X-05, (d–g) 948C-11X-02, (h) 948C-19X-01. Scale bar shows 2 μm.

compaction and a strong subparallel or oblique arrangement with respect to the bedding planes (Fig. 2f, SCZ). Random fabrics with open fractures in the spaced foliation can be observed in the zone of the neighboring *S–C* band (Fig. 3f and g, RF & OFZ). The sigmoidal open fracture developed in the spaced foliation is observed in the dip direction opposite to the *S–C* zone (Fig. 3f). The scaly fabric zone in a microstructure order shows a partitioning of deformation-like flowing metamorphic rocks (Lister and Williams, 1983; Bell, 1985). A gas-derived stressed microvoid (Wartel et al., 1990), less than ten micrometers in diameter, is observed in several samples (Fig. 3i). This microvoid opens in clay particles that are curled and bent outwards (Wartel et al., 1990).

5. Pore size

Measurement of the pore size distribution was carried out for 11 freeze-dried specimens by mercury intrusion porosimetry (Micrometorics-Shimadzu Pore-Sizer 9320). This method is available for determination of pore sizes ranging from 0.01 μm to several tens of micrometers. The grain size of the measured samples is mainly less than 2 μm. The mode of pore size of all specimens are distributed from 0.020 to 0.035 μm in di-

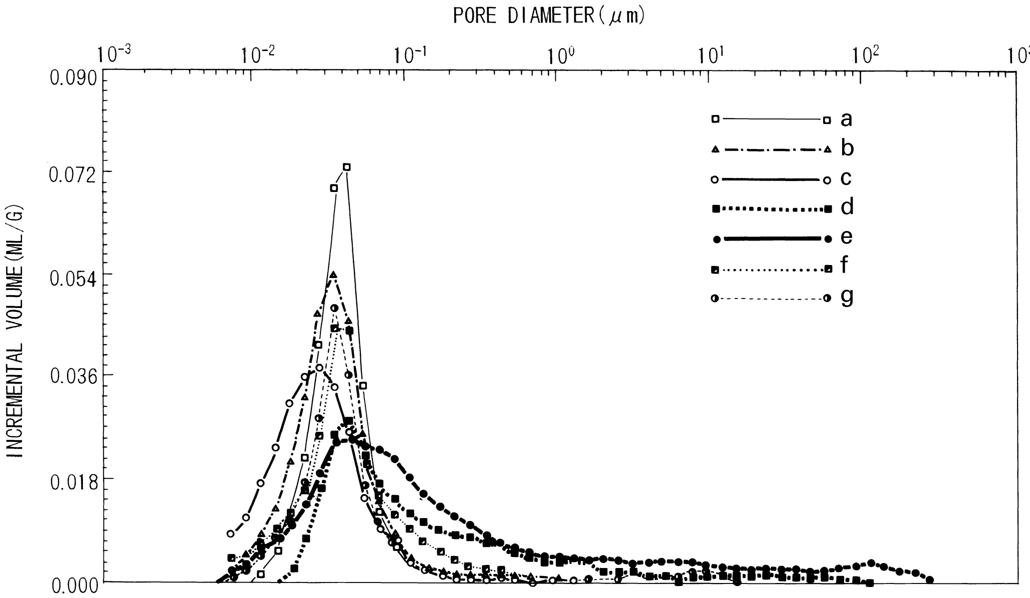

Fig. 4. Pore-size distribution of clayey sediments in Hole 948C. Note that (d) and (e) show larger pore size distribution than other samples. For specimens (a–g) refer to Fig. 2.

ameter (Fig. 4). Mean pore size above the décollement (Fig. 2a–c) ranges from 0.030 to 0.037 μm in diameter, and also from 0.034 to 0.050 μm below the décollement (Fig. 3f and g), whereas in the décollement, it ranges from 0.050 to 0.060 μm (Fig. 2d–e′). Pore size distribution is similar above and below the décollement. In the décollement zone, however, there is a shift towards larger pore sizes.

6. Discussion

Dilatancy of clayey sediments from the décollement zone in the Barbados accretionary prism has been pointed out on the basis of data for low density, high porosity and low resistivity (Moore et al., 1995). In the microstructure of the previous SEM observation by Cowan et al. (1984), Moore et al. (1986), Taylor et al. (1990), Labaume et al. (1997) and Maltman et al. (1997), scaly fabrics in the décollement zone show strong preferred clay orientation related to pore collapse. Those SEM observations are not consistent with high void ratio, low bulk-density and low resistivity in the décollement zone. Our SEM data, however, show variable microstructures such as strongly oriented fabric, closely spaced foliation with large voids and pores and random fabric with large pores, and those structures match with the physical properties. Our data show that pore size in the décollement zone is larger than that on either side of the décollement.

Dilatant microstructures and fluid flow in the Barbados décollement zone have been considered to be caused by shearing (Moore et al., 1986). The drained residual strength of clays seems to decrease when a bentonite increases the mineral composition of clays with salty pore fluids (e.g. Lupini et al., 1981; Skempton, 1985; Di Maio and Fenelli, 1994). A zone of abundance of smectite in the décollement zone appears between 500 and 510 m depth (Underwood and Beng, 1997). This zone roughly correlates with the upper peak of the two high fluid-pressure zones (Moore et al., 1995), and with our two specimens (948C-10X-05 and -11X-02). On the basis of our data, previous observation and experimental results (Tchalenko, 1968; Lupini et al., 1981; Skempton, 1985; Di Maio and Fenelli, 1994; Moore and Tobin, 1997), a plausible model for dilatant clay microstructure could be as follows: initially, clays in the décollement zone might have been normally consolidated as shown in Figs. 3(a) and 5(a). The *S–C* band might be formed by

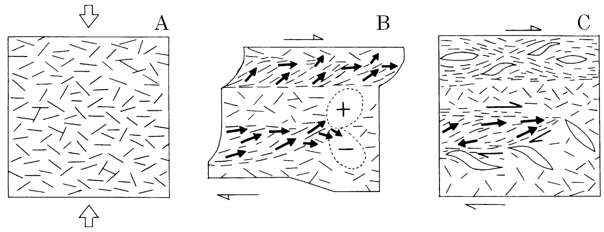

Fig. 5. Schematic formation model for dilatant clay microstructure in the décollement zone. Arrows in the shear zones show fluid flow directions (Stephenson et al., 1994). (a) Initial state of clay microstructure before shearing. (b) Alternation of sheared and non-sheared zone (*S–C* band). Stress-concentration at the shear tip defines tensile (–) and compressive (+) states. (c) Top of the *S–C* band zone shows the dilatant microstructure with the sigmoidal and spindle shape pores and fractures formed by high syntectonic fluid-pressure.

shearing (Fig. 5b). Pore fluid within the *S–C* band builds up due to shear stress and flows mainly along the shear zone and is injected into the neighboring undeformed zone at the shear zone tip (Fig. 5b). Finally, hydrofracture occurs in response to fluid pressure build-up adjacent to the *S–C* band (Fig. 5c). The strongly oriented fabric with open fractures (upper part Fig. 5c) may be formed under the overconsolidated condition during repeated drained shearing.

Our formation model is similar to the 'dilatancy hardening' mechanism (Brace and Martin, 1968; Murrell and Ismail, 1976; Ismail and Murrell, 1976) observed in cataclastic flow of rocks. This discussion is based on the experiments with hydrous minerals and rocks containing pore fluid under undrained conditions. Labaume et al. (1997) pointed out that the scaly fabric foliations and the formation of the fabrics might be accounted for by high pore fluid-pressure and the cumulative displacement. Moore and Tobin (1997) reported that the high fluid-pressure in their experiment builds up near lithostatic pressure in the décollement. Our results bear evidence of small-scale heterogeneties in strain, displacement, and fluid transfer, that builds a unique structural association related to shearing and dewatering processes in a convergent plate boundary.

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