ELSEVIER

Journal of Structural Geology 29 (2007) 697–711

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Mass transfer and pressure solution in deformed shale of accretionary complex: Examples from the Shimanto Belt, southwestern Japan

Kuniyo Kawabata [a,*], Hidemi Tanaka [a], Gaku Kimura [a,b]

[a] *Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 1130033, Japan*
[b] *Institute For Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology Center, 3173-25 Showa-machi, Kanazawa-ku, Yokohama-city, Kanagawa 2360001, Japan*

Received 1 January 2006; received in revised form 24 November 2006; accepted 27 November 2006
Available online 25 January 2007

Abstract

This study investigates volume changes in the accretionary complex in southeastern Shikoku, Japan using mesoscopic and microscopic observations and chemical analyses of shale. Three types of deformation in shale were recognized: 1. coherent type (compacted), 2. type I mélange (less deformed), and 3. type II mélange (sheared). Pressure solution seams (PSS) are common and reflect large volume reductions for coherent type (13−50%) and type II mélange (17−54%). Positive correlations exist between PSS density and concentration of the immobile chemical component (TiO_2) and between PSS density and paleotemperature for type II mélange and coherent type. Under constant temperature conditions, the PSS density is higher for type II mélange than for coherent type, indicating more efficient generation of PSS for type II mélange. Based on the analysis of rheological equations, we conclude that generation of PSS may be controlled by differences in differential stress and/or the duration of deformation. The positive correlation between PSS density and TiO_2 concentration indicates that volume change in accretionary complexes can be described by a simple equation using PSS density.

Keywords: Pressure solution; Isocon method; Immobile element; Volume change; Shale; Shimanto accretionary complex

1. Introduction

During accretion in subduction zones, the intense deformation that leads to the formation of structures such as imbricated folds, thrust zones and underplated mélanges is associated with large volume changes. From a microscopical point of view, such volume changes in sedimentary rocks in accretionary complexes arise from four distinct processes: (1) consolidation and cementation attributable to pore volume reduction that occurs during early accretion (e.g. Bray and Karig, 1985; Minshull and White, 1989; Moore, 1992); (2) mechanical wear from intergranular friction during cataclastic breakage of grains (Archard, 1953; Cowan, 1985; Wang and Scholz, 1994; Wong et al., 1997); (3) pressure solution deformation promoted by dissolution-precipitation mechanisms (Bjorlykke et al., 1989; Tada and Siever, 1989), which operates at the middle regime (∼2 km) to the deep regime (10−15 km) in the subduction zone (Rutter, 1983; Moore, 1992); and (4) dilation formed through crack-opening. While processes (1−3) lead to volume reduction, process (4) results in volume increase, as the crack spaces become filled with precipitated secondary minerals (Brace et al., 1966; Scholz et al., 1993).

Volume changes in accretionary complexes have been estimated through observation of porosity (e.g. Bray and Karig, 1985) and finite-strain analyses in both modern accretionary prisms (e.g. Morgan and Karig, 1995) and ancient on-land prisms (Byrne and Fisher, 1987; Bolhar and Ring, 2001). Mass transfer in accretionary prisms has also been calculated through microstructural observations of fiber overgrowths from grain boundaries and deformation of paleofossils by pressure solution (Ring and Brandon, 1999). As these methods require deformation markers, calculating volume change in samples containing few markers is difficult.

* Corresponding author. Tel./fax: +81 3 5841 4599.
E-mail address: kuniyo@eps.s.u-tokyo.ac.jp (K. Kawabata).

0191-8141/$ - see front matter
doi:10.1016/j.jsg.2006.11.009

Another method to measure volume change is the chemical *isocon method*. Gresens (1967) first proposed equations for volume gain and loss based on the chemical composition and specific density of altered and unaltered rocks. Grant (1986) improved and simplified the method, and since then the isocon method has been widely applied to study mass and volume changes in alteration zones (Olsen and Grant, 1991; Petersson and Eliasson, 1997; Widmer and Thompson, 2001; Maghraoui et al., 2002), mineral deposits (Condie et al., 1995) and fault zones (O'Hara, 1988; Goddard and Evans, 1995; Evans and Chester, 1995; Streit and Cox, 1998; Tanaka et al., 2001; Matsuda et al., 2004; Tanaka et al., in press). However, the method has been not applied so far in altered or deformed sedimentary rocks in accretionary complexes.

Pressure solution deformation has been widely recognized in the Shimanto accretionary complexes (Ujiie, 1997; Ikesawa et al., 2005). Diffusive mass transfer associated with pressure solution may contribute to large volume changes of sedimentary rocks in accretionary prisms. A possible method to estimate such volume changes is based on the analyses of grain-shape variations and strain fringes generated by pressure solution (Ring and Brandon, 1999), but these structures are barely observable in our samples. In this study, we show that volume changes in shales from the Shimanto accretionary complex can be investigated by using the chemical isocon method. By referring to the constitutive equation of pressure solution, we discuss the controlling factors for volume changes in sedimentary rocks of accretionary complexes.

2. Geologic setting

The Shimanto Belt is an ancient accretionary complex that is located on the Pacific side of southwest Japan, subparallel to the modern Nankai Trough and the Ryukyu Trench (Fig. 1). The Shimanto Belt includes coherent, mélange, and slope-basin deposits that trend generally ENE-WSW and dip steeply to the north, with younger ages to the south (Taira et al., 1988). The coherent units consist of trench turbidite and the mélange units consist of a mixture of trench turbidite, hemi-pelagic and pelagic sediments, and basalts. The belt is divided into two sub-belts by the Aki Tectonic Line (ATL): the northern sub-belt, of Cretaceous age; and the southern sub-belt, of Tertiary age (Fig. 1a).

Numerous structural and biostratigraphic studies have been carried out in eastern Shikoku. Stratigraphic limits have been described in these studies, largely based on fossil ages. We combined geological maps of Taira et al. (1980), Hibberd et al. (1992), Ditullio and Byrne (1990), and Ishida (1998) for the stratigraphic divisions of eastern Shikoku used in the present study (Fig. 1b,c). Coastal areas from the lowest unit of the northern sub-belt (Mugi mélange) to the lowest unit of the southern sub-belt (Misaki sequence) are examined in this study (Fig. 1b–d). The Mugi mélange is a tectonic mélange of a shale matrix showing a duplex structure that includes blocks of sandstone, tuff, minor amounts of chert and basalts (Fig. 1d; Ikesawa et al., 2005; Kitamura et al., 2005). Among the units of the southern sub-belt, Ebugaike, Naharigawa, Shiina, Gyoto, Tsuro and Misaki formations comprise turbidite and show a coherent structure that includes sand and shale layers (Taira et al., 1980; Hibberd et al., 1992; Ishida, 1998). Sakamoto and Hioki units are mélanges, but their origin remains controversial (Taira et al., 1980; Ditullio and Byrne, 1990; Hibberd et al., 1992). Ditullio and Byrne (1990) argued that mélanges are tectonic in origin, but Sakai (1987) and Osozawa (2005) proposed that they are of sedimentary or diapiric origin. Fundamentally, the matrix of mélange units that have originated from both sedimentary and tectonic processes is comprised of shale.

Geothermometry by vitrinite reflectance (Mori and Taguchi, 1988; Underwood et al., 1992, 1993; Ohmori et al., 1997; Ikesawa et al., 2005) and fluid inclusion analysis (Matsumura et al., 2003) has revealed the following thermal pattern: in both Tertiary and Cretaceous sections, the indices of vitrinite reflectance increased southwards (oceanward); but thermal gaps, corresponding to large tectonic lines, exist between sequences. Paleotemperatures, based on the mean value of vitrinite reflectance, are in the range 140–315 °C in the Tertiary section (Mori and Taguchi, 1988; Underwood et al., 1992). In the Cretaceous section, the paleotemperature of the Mugi mélange formation is approximately 200 °C (Ikesawa et al., 2005). Temperature estimated from the vitrinite reflectance is consistent with those determined from fluid inclusion analysis (Matsumura et al., 2003).

3. Mesoscopic and microscopic shale structures

For this study, samples derived from each unit were classified into coherent type and mélange according to their mesoscopic structures. Cowan (1985) defined two mélange types based on mesoscopic fabrics and lithologic composition; type I mélange includes sequences of originally interbedded sandstone and mudstone; and type II mélange includes deformed, thin layers of green tuff, radiolarian ribbon chert, and minor sandstone originally inter-bedded with shale. The Mugi mélange is therefore classified as type II; Hioki and Sakamoto mélanges are regarded as type I (Fig. 1b–d).

Coherent type consists of alternating layers of sandstone and shale (Fig. 2a). Mesoscopic slump folds and sand dikes are visible (Fig. 2d–e). Microstructural observations indicate that coherent type shale comprises quartz and feldspar grains and clay minerals. Widely developed pressure solution seams (PSS) are visible along with strain fringes in strain shadows (Fig. 2h and k), indicating that pressure solution operated during deformation. The blocks in type I mélanges are composed solely of sandstone, and the shale matrix display incipient cleavage (Fig. 2b). This shale comprises angular quartz, feldspar grains, small amount (<3%) of opaque minerals, and sparsely distributed clay minerals. Minor amounts of PSS are visible along grain contacts (Fig. 2i and l). Type II mélanges are highly sheared in most sampling locations and show asymmetric deformation of the blocks of basalt, chert, and sandstone (Fig. 2c). The shale matrix in type II mélanges is cleaved by shears and PSS and shows S-C structures, in