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Source and sink of fluid in pelagic siliceous sediments along a cold subduction plate boundary

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ABSTRACT

Subduction zones where old oceanic plate underthrusting occurs are characterized by thick pelagic sediments originating from planktonic ooze as well as cold thermal conditions. For a better understanding of dehydration from pelagic sediments and fluid behavior, which would play a key role in controlling the dynamics in the shallow portion of the subduction zone, as observed in the 2011 Tohoku earthquake and tsunami, we investigate cherts in a Jurassic accretionary complex in Japan. The microstructure and microchemistry of these cherts indicate dissolution of SiO_2 from a pressure solution seam and precipitation of SiO_2 to the "white chert layer," which would act as a fluid conduit. The amount of water necessary to precipitate SiO_2 in the white chert is ~10^2 times larger than that produced by compaction and silica/clay diagenesis. Other fluid sources, such as hydrated oceanic crust or oceanic mantle, are necessary to account for this discrepancy in the fluid budget. A large amount of external fluid likely contributed to rising pore pressure along cold plate boundaries.

1. Introduction

Fluid along a plate interface in a subduction zone has a significant effect on seismicity and fault slip. In the early stages of diagenesis, compaction-derived fluid plays an important role in subduction plate interfaces. Fluids derived from hydrous minerals contribute to the fluid budget in a much deeper portion after mechanical compaction has completed. Various origins for this fluid, including diagenesis and dehydration reactions of smectite–illite and saponite–chlorite, have been investigated in detail (Moore and Saffer, 2001; Kameda et al., 2011; Saffer and Tobin, 2011). The origin of fluids estimated by those studies were closely linked to "seismogenic zone", which is controlled mainly by temperatures ranging from ~150 °C to ~350–450 °C (Hyndman and Wang, 1993; Hyndman et al., 1995, 1997; Oleskevich et al., 1999). In addition to dehydration at seismogenic depths, dehydration in shallow zones cooler than ~150 °C along plate boundaries is also important to understand the propagation of fault slips occurring in deeper seismogenic zones. Shallow fault slips along a décollement reaching the seafloor generate tsunamis, such as in the 2011 $M_w = 9.0$ Tohoku-Oki Earthquake (Fujiwara et al., 2011; Kodaira et al., 2012). The mechanism for a rupture breaking through the updip limit of a typical seismogenic zone is, however, still unknown although, for example, Kimura et al. (2012a) proposed a hypothesis that extremely high fluid pressure might occur in that portion. Thus, it is necessary to study fluid behavior along shallow plate boundaries in order to understand the mechanisms behind tsunamigenic earthquakes.

There are two types of subduction zone, classified according to the age of the incoming oceanic plate (Fig. 1): one is a subduction zone characterized by old oceanic plates (older than ~50 million years (m.y.); Fig. 1(a)) and the other is characterized by young oceanic plates (younger than ~50 m.y. in age; Fig. 1(b)). The where the water depth exceeds the carbonate compensation depth (CCD; ~4000–5000 m). The threshold of ~50 m.y. is derived from the age when the water depth exceeds the carbonate compensation depth (CCD; ~4000–5000 m), based on thermal modeling (Parsons and Sclater, 1977; Stein and Stein, 1992). The age of the subducting oceanic crust affects the thermal structures of the subduction zones and thus their seismogenic

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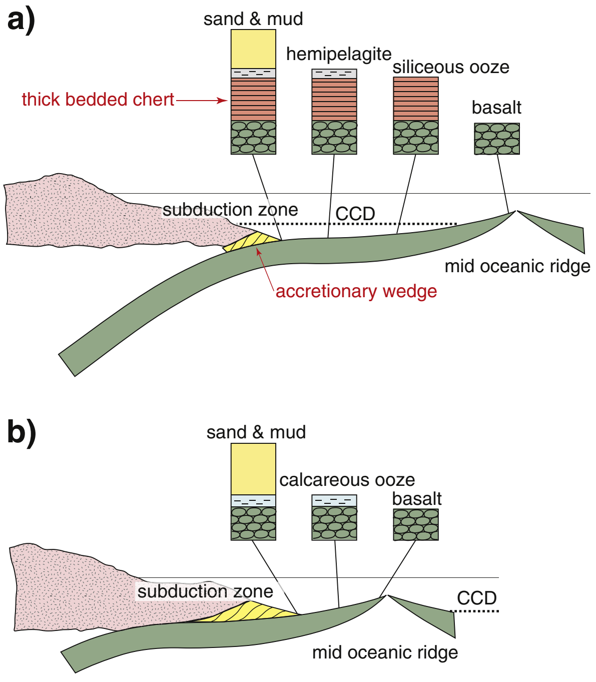

Fig. 1. Schematic diagram showing the differences between subduction zones where (a) old and (b) young oceanic plate underthrusting occurs. A thick accumulation of bedded radiolarian chert is only achieved after long exposure of the ocean floor at a depth below the carbonate compensation depth (CCD).

depths, because young oceanic plates are relatively warm, while old oceanic plates are relatively cold. Sediments upon the oceanic crust also differ depending on the age of the subducting plates. In the case of young oceanic plates, sediments are composed mainly of trench-filling terrigenous sediments, mostly sandstone and mudstone, because there are no time intervals in which pelagic sediments are deposited. On the other hand, in the case of old oceanic plates, pelagic sediments may be thick and abundant (Fig. 1(a)), owing to long-period exposure to the ocean far from the continents (Matsuda and Isozaki, 1991). Pelagic sediments composed mainly of diatomaceous and/or radiolarian ooze with slight volcanic ash and pelagic clay are accumulated on the ocean floor. Those pelagic sediments under the CCD are mostly composed of siliceous substance (SiO_2) originating from diatoms and radiolarians. The siliceous sediments are initially amorphous (opal-A) when they are deposited, and then convert to crystal (quartz) via diagenesis. As a result, the siliceous sediments become a chert, which is a hard siliceous rock.

The Nankai Trough off southwest Japan is a typical example of subduction of a young oceanic plate, and many studies have been conducted on dehydration and deformation processes in the Nankai Trough (e.g. Moore and Saffer, 2001; Spinelli et al., 2007; Saffer et al., 2008). These studies have had close relationships to the development of ocean drilling projects in the Nankai Trough (such as the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) since 2007 (Kinoshita et al., 2009)) and to investigations of the Shimanto Belt, a Cretaceous-to-Miocene accretionary complex formed during the subduction of relatively warm oceanic plates (Taira et al., 1988; Kimura et al., 2012b). In contrast to such settings, the dehydration and deformation mechanisms at subduction zones characterized by old and cold oceanic plates are less well understood. However, recent progress in the Integrated Ocean Drilling Program (IODP) Expedition 343 has brought new insights into coseismic deformation at the shallow plate boundary megathrust of the Japan Trench, a typical subduction zone where an old oceanic plate subducts (Chester et al., 2013a,b; Fulton et al., 2013; Ujiie et al., 2013). For a better understanding of deformation and fluid flow systems in much deeper portions, an on-land analog study of subduction zones where old and cold oceanic plates subduct would be efficient.

The Mino Belt (or the Mino–Tamba/Tanba Belt) in central Japan is an example of an on-land accretionary complex at a subduction zone where old oceanic plate underthrusting occurs. In this study, we investigated the meso- and microscopic features of a pelagic bedded chert in the Mino Belt in the Inuyama area in order to investigate the dehydration and deformation processes of siliceous sediments. In particular, we focus on mass and fluid transfer related to cherts on the basis of detailed microchemistry and chemical mapping of the cherts. Then, we discuss the source and sink of fluids and their relationship with seismo-tsunamigenesis in cold subduction zones.

2. Geological features of cherts in the Mino Belt in the Inuyama area

The Mino Belt in central Japan (Fig. 2(a)) comprises a Jurassic accretionary complex, which contains coherent units (chert–clastic sequences) and mélanges, including blocks of sandstones, mudstones, cherts, limestones, and basalts in shale matrices (Matsuda and Isozaki, 1991; Kimura and Hori, 1993). An excellent exposure of a coherent chert–clastic sequence (Fig. 2(b)) is observed in the Inuyama area along the Kiso River (Aichi and Gifu Prefectures). Fig. 2(c) shows a schematic of a columnar section of the Inuyama area.

Many detailed tectonostratigraphic studies based on radiolarian biostratigraphy have revealed the depositional ages of each stratum (Yao et al., 1980; Matsuda and Isozaki, 1991): i.e., Middle Triassic to Early Jurassic for pelagic cherts; Early to Middle Jurassic for hemipelagic siliceous mudstones; and Middle Jurassic for terrigenous sandstones and mudstones (Fig. 2c). From these age data, the age of the subducted oceanic plate is estimated to have been greater than ~80 million years old on the basis of the depositional age gap between the top of the terrigeneous sediments and the bottom of the pelagic sediments. Thus, Triassic–Jurassic thick red-colored bedded cherts (~100 m in thickness) can be investigated as an analog of pelagic siliceous sediments in subduction zones characterized by old oceanic plates, such as the Japan Trench, as pointed by Kameda et al. (2012). These ocean floor stratigraphy sequences are repeated by thrust stacking and duplexing, thereafter folded to represent large-scale west-plunging synforms (Matsuda and Isozaki, 1991; Kimura and Hori, 1993; Kimura, 1997).

2.1. Two-stages of deformation in bedded cherts

Kameda et al. (2012) indicated that the bedded cherts in the Inuyama area were deformed in two stages. First was a ductile deformation stage when siliceous sediments were not yet consolidated, and the second was a brittle deformation stage after the siliceous sediments had lithified to be hard cherts. Early ductile deformation is characterized by systematic intra-folial asymmetric folds indicating layer-parallel, top-to-south shear and shortening. The orientations of fold axis are well-aligned, but different in each thrust sheet. This observation suggests that the folds were tectonically formed before the formation of thrust sheets, which is equivalent to an underthrusting stage (Kimura and Hori, 1993). Radiolarian fossils were not broken in the axial parts of the folds, suggesting that independent particulate flow is the dominant deformation mechanism. Some layers of bedded cherts, especially the white cherts (see details in the following section), have been selectively folded at an outcrop scale (Fig. 3b) (Tsukamoto, 1989; Kameda et al., 2012). This occurrence suggests that the white chert was formed prior to the ductile deformation, and deformed as a competent layer in relatively incompetent red chert layers (Kameda et al., 2012). Later brittle deformation includes thrust stacking of chert–clastic sequences and outcrop-scale minor NE–SW left-lateral faulting (Kimura and Hori, 1993; Kameda et al., 2012).