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Key Points:

- In situ chert sample was recovered from an active subduction margin
- The chert is dominated by opal-CT and may be deformable via pressure solution creep
- Chert diagenesis may be related to physical transition of subduction zone plate boundary

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Opal-CT in chert beneath the toe of the Tohoku margin and its influence on the seismic aseismic transition in subduction zones

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Abstract Thick accumulation of chert is a ubiquitous feature of old oceanic plates at convergent margins. In this study, we investigate chert fragments recovered by the Integrated Ocean Drilling Program expedition 343 at the Japan Trench where the 2011 Tohoku-Oki earthquake (M_w 9.0) occurred. This sample provides a unique opportunity to investigate in situ chert diagenesis at an active subduction margin and its influence on the kinematics of megathrust faulting. Our mineralogical analyses revealed that the chert is characterized by hydrous opal-CT and may therefore be highly deformable via pressure solution creep and readily accommodate shear strain between the converging plates at driving stresses of kilopascal order. As chert diagenesis advances, any further deformation requires stresses of >100 MPa, given the increasing transport distances for solutes as represented in cherts on land. The chert diagenesis is thus related to the mechanical transition from a weakly to strongly coupled plate interface at this margin.

1. Introduction

The 2011 Tohoku-Oki earthquake (M_w 9.0) is the largest seismic event ever observed in Japan. A pronounced feature of this earthquake is that the coseismic rupture propagated to the trench and caused more than 50 m of displacement of the frontal prism [*Fujii et al.*, 2011; *Fujiwara et al.*, 2011; *Kodaira et al.*, 2012]. This displacement resulted in a destructive tsunami along the northeast coast of Honshu, Japan. The Japan Trench is a typical subduction margin where an old (~100 Ma) oceanic plate is subducting. Chert on the plate is >100 m thick [*Shipboard Scientific party*, 1980] and is a major constituent of the material entering the subduction zone.

Pelagic chert is derived from biogenic marine deposits (ooze) of the siliceous tests of radiolaria and diatoms that accumulate far from continents [*Karl*, 1984; *Knauth*, 1994]. Thick accumulations of siliceous ooze on the abyssal seafloor form hard chert over long geologic timescales. Bedded chert is ubiquitous in orogenic belts and is commonly intensely folded [*Ramberg and Johnson*, 1976; *Yao et al.*, 1980], as a result of tectonic stress at convergent margins [*Brueckner and Snyder*, 1985; *Kimura and Hori*, 1993; *Kameda et al.*, 2012], thereby indicating that chert deforms ductilely after being subducted. However, given the lack of in situ samples collected for analysis, it remains unclear how chert fundamentally behaves during underthrusting and how it affects processes associated with megathrust faulting. To solve this issue, knowledge of the diagenetic state of chert (e.g., mineralogy and microtexture) within an active subduction zone is of particular importance, because such features are fundamental controls on deformation style of chert rocks [*Snyder et al.*, 1983; *Brueckner et al.*, 1987].

Integrated Ocean Drilling Program Expedition 343 Japan Trench Fast Drilling Project (JFAST) collected rock samples from the active slip zone on which the coseismic displacement of the Tohoku-Oki earthquake may have occurred, as well as from the footwall sedimentary sequence, which included chert deposits on the subducting oceanic plate [*Chester et al.*, 2012]. As a result of this sampling, a 5 m thick plate boundary fault zone has been identified and characterized as a very weak shear zone due to large amounts of pelagic smectite [*Chester et al.*, 2013; *Ujiie et al.*, 2013; *Kameda et al.*, 2015]. However, it is uncertain whether such a thin clay-rich horizon extends over the whole rupture area of the great earthquake or occurs locally. Recent seismic imaging suggested the possibility that chert deposits on horst structures may be in direct contact with the

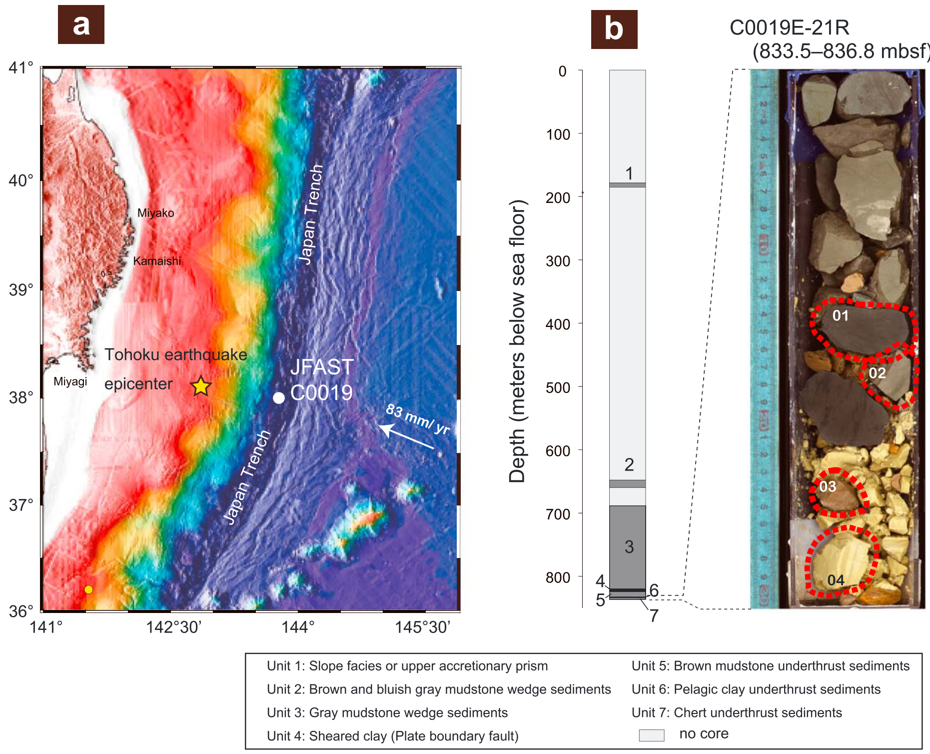

Figure 1. (a) Locations of the drill sites for JFAST (site C0019). The hypocenter of the Tohoku-Oki earthquake is shown by yellow star. (b) Lithologic units of Site C0019. The plate boundary fault was identified for the interval of 821.5–822.5 mbsf (unit 4). Photos of Core 21 (chert unit) showing analyzed fragments (01–04).

overriding fore-arc prism [*Nakamura et al*., 2013]. This opens the possibility that chert may have played an important role in megathrust faulting. From the JFAST borehole, chert fragments were recovered approximately 15 m below the slip zone [*Chester et al*., 2012], which provide a unique opportunity to investigate chert that is currently being subjected to diagenesis within an active subduction margin.

In this study, we performed a mineralogical investigation of in situ chert samples collected from beneath the Tohoku frontal fore arc. Based on our results, we discuss the mechanical properties of chert and its possible influence on the kinematics of the megathrust faulting.

2. Samples and Experimental Procedures

The samples analyzed in this work were recovered from the JFAST borehole (C0019E), which is located 5 km landward from the Japan trench axis where the largest coseismic slip of the 2011 Tohoku-Oki earthquake was observed (Figure 1a) [*Chester et al*., 2012]. In this borehole, a 1 m thick plate boundary fault zone (maximum thickness of ~5 m, if intervals with no core recovery are included) was identified at 821.5–822.5 m below the seafloor (mbsf) (Figure 1b). Mudstone and pelagic clays make up the uppermost sedimentary section of the footwall (824–833.5 mbsf) just below the plate boundary fault [*Chester et al*., 2012]. The deepest section of the borehole (833.5–836.8 mbsf) yielded lithified fragments, described as chert [*Expedition 343/343T Scientists*, 2013], with variable colors from pale gray (21R: 0–12 cm and 16–18 cm), dark gray (21R: 13–22 cm), and pale yellow (21R: 21–30 cm). The pale yellow fragments are sporadically accompanied with dark brown fragments (21R: 23–25 cm and 30–30.5 cm) (Figure 1b).

We selected four representative samples from these fragments (01–04; Figure 1b) and analyzed bulk-rock mineralogy with X-ray diffraction (XRD). XRD patterns were obtained using a MAC Science MX-Labo with monochromatized CuKα radiation at 40 kV and 30 mA, with 1° divergence and antiscattering slits, and a 0.15 mm receiving slit in continuous scan mode at a rate of 1° 2θ min^{-1}.

Water content of the sample was measured by Thermogravimetry (TG; Rigaku Thermo Plus EVOII TG8120). In the TG analyses, temperatures were raised from room temperature to 1300°C at a rate of 10°C min^{-1}.

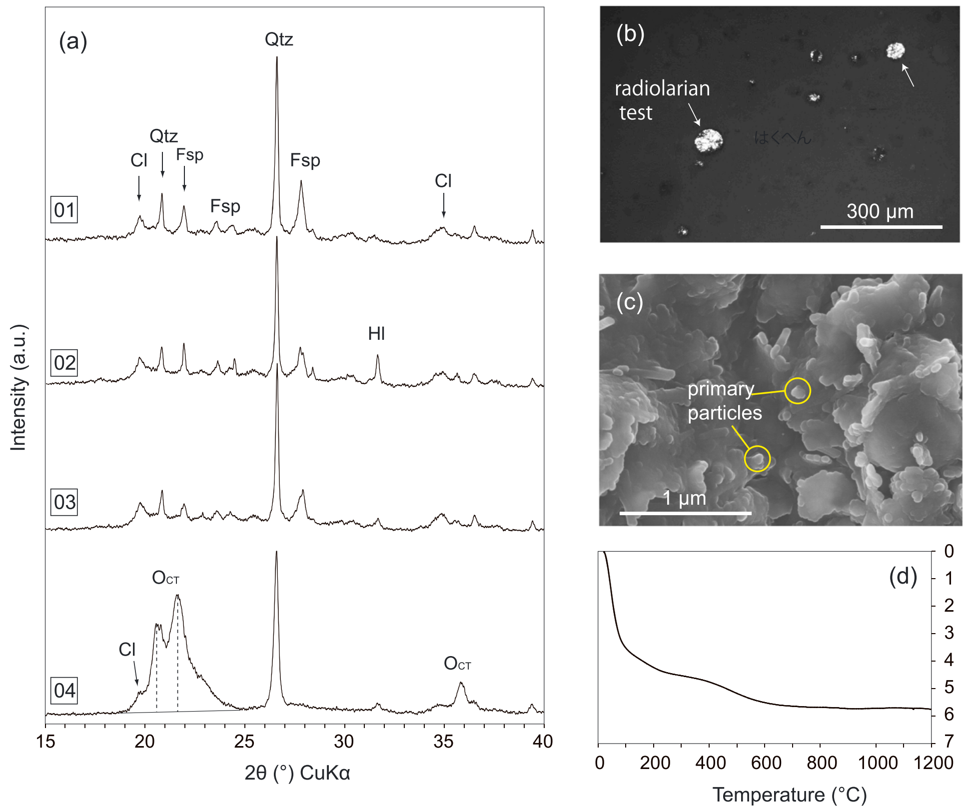

Figure 2. (a) XRD patterns for the analyzed samples. Sample 04 shows completely different patterns represented by peaks of opal-CT. Cl = clay minerals; Qtz = quartz; Fsp = feldspar; Hl = halite; O_{CT} = opal-CT. Two reflections marked by the dotted lines (*d* = 4.27 and 4.13 Å) are characteristic peaks of opal-CT. (b) Typical appearance of the sample under polarized light. The sample is largely composed of opaque materials with sporadic distribution of radiolarian tests filled by chalcedony. (c) Microtextures of the analyzed chert under SEM. Fine-grain elemental particles (~100 nm) are assembled to form second-order larger grains. (d) Weight loss curve during TG analysis showing 6 wt % of water content.

3. Results

The XRD analyses confirmed that three of the samples (01–03) are consolidated clay-rich deposits including quartz and feldspar (Figure 2a). However, the 04 sample from the bottom of this interval exhibits a completely different XRD pattern from the other samples, with peaks ascribed to quartz and opal-CT [*Graetsch*, 1994]. The opal-CT is an typical intermediate reaction product of chert diagenesis from opal-A to quartz. The pattern also shows a trace peak from clay minerals (Figure 2a). The opal-bearing pale yellow fragments constitute > ~70 vol % of the lower interval of the core 21R (21–30 cm). Considering the result of the seismic imaging around the JFAST drill site [*Nakamura et al*., 2013], this may correspond to the topmost part of the underthrusting chert layer at the Tohoku margin.

Under the optical microscope, the 04 sample is composed mainly of a matrix of opaque materials with sporadic radiolarian test molds filled with fine-grained chalcedony (Figure 2b). Scanning electron microscope (SEM; Hitachi SU8000) images show that the opaque materials are composed of very fine primary particles (~100 nm) that become aggregated to form larger (>1 μm) second-order particles with variable morphological features, ranging from spherical to plate-like shapes (Figure 2c). TG analysis indicates that the sample contains ~6 wt % water (Figure 2d), which is typical of opal-CT [*Day and Jones*, 2008].

4. Discussion

The deformation mechanism of chert is thought to depend on its diagenetic state. The occurrence of opal-CT, rather than other polymorphs such as opal-A or quartz, may be favorable for the folding of chert via intergranular flow and fracturing [*Snyder et al*., 1983; *Brueckner et al*., 1987]. The present work has shown that the

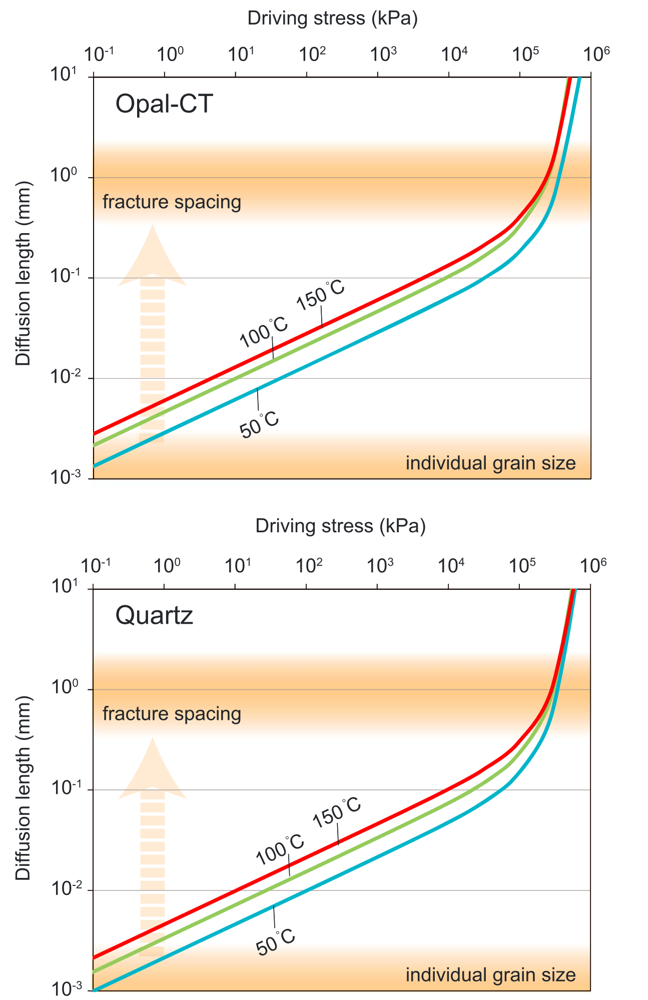

Figure 3. d - $\Delta\sigma_n$ relation for opal-CT and quartz as a function of temperature under the strain rate of 2.6×10^{-11} s^{-1}. Possible extension of the solute diffusion length (thick arrows) from the individual grain size (~μm) to fracture spacing along the solution cleavages (~mm), resulting in significant hardening of chert.

sampled chert rock is dominated by opal-CT beneath the frontal fore arc, suggesting that the rock should be deformable in a similar way to folded cherts within on-land accretionary complexes.

Here we examine the possibility of ductile deformation of chert using a law for steady state pressure solution creep. Pressure solution creep is a common deformation mechanism that operates at shallow crustal levels and allows rocks to deform in a ductile manner [*Rutter*, 1976; *Spiers and Schutjens*, 1990; *Wheeler*, 1992; *Gratier et al.*, 2013]. The rate and extent of such deformation is governed by the overall rate of dissolution-transport-reprecipitation processes of minerals from stressed grain contacts to interstitial spaces [e.g., *Gratier et al.*, 2013]. In general, the pressure solution of quartz at low temperatures is governed by dissolution rather than diffusion [*Gratier et al.*, 2013]. However, we here adopt a diffusion-limited creep law, because the surface reaction kinetics of opal is several orders of magnitudes faster than quartz [e.g., *Rickert et al.*, 2002], and the irregular grain surfaces as seen in SEM (Figure 2c) may significantly enhance such reaction. However, it is noted that the estimated stress based on this assumption represents lower bounds if the rate-limiting process is the surface reactions, which is more probable in the case of quartz. A laboratory indentation test has established the following relationship [*Gratier et al.*, 2009]:

$$\dot{\varepsilon} = \frac{8D\delta c v_s \left(\exp\left(\frac{3\Delta\sigma_n v_s}{RT}\right) - 1\right)}{d^3} \quad (1)$$

where $\dot{\varepsilon}$: strain rate (s^{-1}), d: mean diffusion distance (m), D: diffusion constant along the stressed interface (m^2 s^{-1}), δ: thickness of the trapped fluid along which diffusion occurs (m), c: solubility of the diffusing solid (mol/m^3), v_s: molar volume of the stressed solid (2.2×10^{-5} m^3/mol), $\Delta\sigma_n$: driving stress (= difference between normal stress on a dissolution surface and fluid pressure), R: gas constant (8.31 J mol^{-1} K^{-1}), and T: temperature (K). We assume that shear strain of chert is regulated by diffusion-accommodated grain boundary sliding [*Ashby and Verrall*, 1973]. In such a case, d corresponds to the size of individual particles [*Gratier et al.*, 2013]. The equilibrium constants K for the quartz and cristobalite (α) water systems [*Rimstidt and Barnes*, 1980] were adopted to estimate the solubility of quartz and opal-CT, respectively, at relevant temperature conditions (log $K = 1.881–2.028 \times 10^{-3}T - 1560/T$ for quartz and log $K = -0.0321–988.2/T$ for α-cristobalite). We used 10^{-19} m^3 s^{-1} for the product $D\delta$ as a representative value for conditions of the upper crust [*Gratier et al.*, 2013].

Figure 3 shows the d-$\Delta\sigma_n$ relationship for opal-CT and quartz as a function of temperature under a strain rate of 2.6×10^{-11} s^{-1}, which is calculated by dividing the rate of plate convergence at the Japan Trench

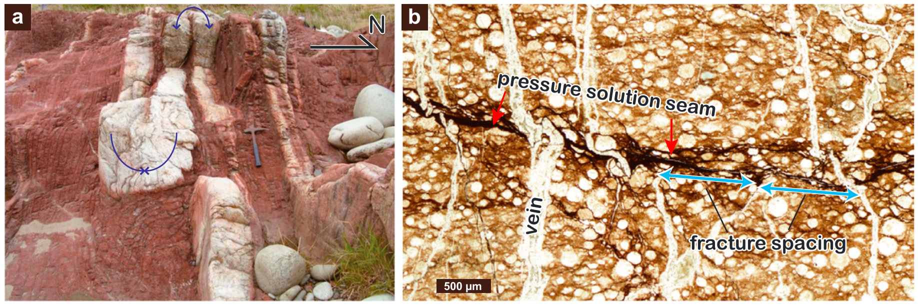

Figure 4. (a) On-land exposure of a pelagic chert in the Mino-Tamba belt, a Jurassic accretionary complex in central Japan. The asymmetric folding of bedded chert indicates the bulk shear direction (top to south) consistent with the ancient plate convergence [*Kameda et al*., 2012; *Yamaguchi et al*., 2016]. (b) The *d* value in equation (1) for crystalline chert is estimated from the spacing of fractures (mineralized veins) crosscut the pressure solution cleavage (blue double-headed arrows).

(83 mm/yr) by the chert thickness (~100 m) inferred from the seismic reflection survey [*Nakamura et al*., 2013]. It is noted that this assumption overestimates the driving stress if a certain amount of the total convergence is accommodated by other frictionally weak horizons such as the smectite-rich slip zone at the JFAST site. The result indicates that shear displacement between the overriding and subducting plates is easily accommodated by a driving stress on the order of kilopascals when micron-scale diffusion-accommodated grain boundary sliding is operating and the strain is equally distributed over the whole chert unit. In this case chert is never a rigid rock, but rather highly deformable with a much weaker shear strength than the slip zone materials [*Ikari et al*., 2015]. A consequence of this result is that plate coupling may be weak along the megathrust due to steady creep of the chert unit, and this calls into question the existence of a strong asperity near the trench that is proposed to have caused the shallow and large slip during the Tohoku earthquake [e.g., *Kato and Yoshida*, 2011; *Yoshida and Kato*, 2011].

However, the diagenetic process of chert promoted by pressure solution deformation itself could markedly modify the mechanical property of chert at depth along the megathrust by altering the mineralogy, driving grain growth of silica minerals, and reducing pore space by reprecipitation. The lower solubility of quartz than opal-CT acts to reduce the dissolution rate of stressed grain contacts, whereas increasing temperature acts to enhance the dissolution rate. Most importantly, however, grain growth and especially pore cementation reduces the trapped fluid phase along the grain boundary and increases the distance of mass transfer from the scale of an individual grain up to the spacing of rock fractures along solution cleavages [*Gratier et al*., 2013]. This transition can be observed in a pelagic chert exposed in the Mino-Tamba belt, a Jurassic accretionary complex in central Japan. In this exposure, the thick bedded chert of ~150 m is intensely folded with a top-to-south asymmetric geometry consistent with accommodation of shear strain between the converging plates, so the geological record preserved is thought as an on land analogue for the Tohoku margin [*Kameda et al*., 2012; *Yamaguchi et al*., 2016] (Figure 4a). In microscopic scale, radiolarian fossils were completely filled with crystals of quartz and chalcedony, and quartz veins formed at later stage of diagenetic process crosscut the pressure solution seam within chert (Figure 4b). Thus, the *d* value in equation (1) for this crystalline chert is estimated from the spacing of fractures (mineralized veins) along the pressure solution cleavage (blue double-headed arrows). As a consequence, these factors act to progressively harden the chert rock. Previous models of silica diagenesis within the Tohoku subduction zone suggest that opal-CT to quartz transition quickly occurs at temperatures of ~100–130°C along the megathrust [*Kimura et al*., 2012; *Kameda et al*., 2012]. In equation (1), if we assume *d* is on the order of several hundreds of microns to millimeters, which is similar to the estimated values of *d* from the chert in subduction complex, the driving stress needed to achieve the above strain rate is estimated to be 100 MPa or higher (Figure 3). Although the presence of clays could activate the pressure solution process (the chert on land contains ~20 wt % of clays [*Kameda et al*., 2014]), brittle deformation is more likely prevailing at this stage of compressional deformation [*Kameda et al*., 2012], implying that chert will effectively behave like a rigid medium. If this chert rock is exposed directly on the overriding plate at a topographic undulation on the plate interface and comprises a part of the megathrust, it may contribute to the loading of elastic energy by locking the plates and may form a strong asperity zone on the megathrust.

In summary, the occurrence of opal-CT in chert and its diagenesis as described in this study may be related to the mechanical transition from a weakly to strongly coupled plate interface at this margin. However, it seems oversimplified to claim that chert is a fully ductile or fully brittle material. In fact, folds in cherts are commonly accompanied with a brittle component of deformation, whereas the pressure solution deformation may be also operative where the brittle deformation of crystalline chert is prevailing [*Kameda et al*., 2012]. Future drilling with additional recovery of chert samples could provide more insights into the depth-variable chert behaviors along the megathrust.

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