

Earthquakes produce carbon dioxide in crustal faults

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Abstract

Fourier transform infrared (FTIR) microanalysis of pseudotachylytes (i.e. friction-induced melts produced by seismic slip) from the Nojima fault (Japan) reveals that earthquakes almost instantaneously expel 99 wt.% of the wall rock CO₂ content. Carbon is exsolved because it is supersaturated in the friction melts. By extrapolation to a crustal-scale fault rupture, large events such as the M7.2 Kobe earthquake (1995) may yield a total production of 1.8 to 3.4 × 10³ tons CO₂ within a few seconds. This extraordinary release of CO₂ can cause a flash fluid pressure increase in the fault plane, and therefore enhance earthquake slip or trigger aftershocks; it may also explain the anomalous discharge of carbon monitored in nearby fault springs after large earthquakes. Because carbon saturation in silicate melts is pressure-dependent, FTIR can be used as a new tool to constrain the maximum depth of pseudotachylyte formation in exhumed faults.

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1. Introduction

An earthquake occurs because the shear resistance of a slipping fault becomes weaker with increasing slip (Kanamori and Brodsky, 2004). The fault rocks are crushed by friction and may even melt if the heat

generated is large enough (Spray, 1995). Knowing how much energy is released as frictional heat, or converted into fractures and elastic waves, is essential for assessing how tectonic stress relaxation generates near-fault acceleration and surface damage, and how much stress is left for future rupture of the Earth's crust. However, the production of heat is poorly constrained in the energy budget of earthquakes because the magnitude of fault weakening and its mechanism are not well known. In most theoretical or experimental mechanisms proposed to explain slip weakening, the lubricating agent is

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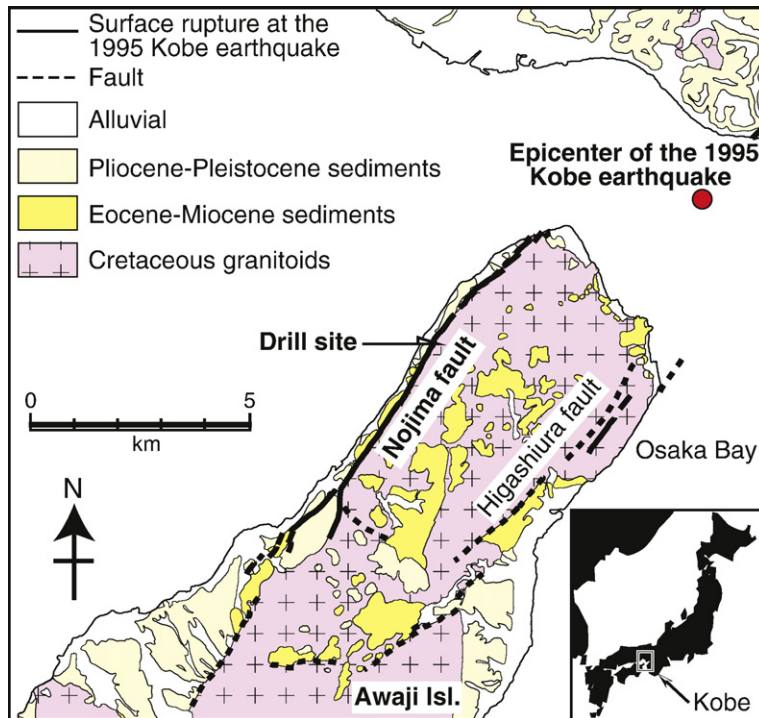


Fig. 1. Simplified geological map of Awaji Island, modified from Ohtani et al. (2000).

a fluid medium (either aqueous, melt or slurry) trapped within the fault plane and put under pressure by thermal or dynamic effects (McKenzie and Brune, 1972; Lachenbruch, 1980; Melosh, 1996; Brodsky and Kanamori, 2001; Andrews, 2002; Wibberley, 2005). The efficiency of these slip-weakening mechanisms depends largely on the quantity of fluid involved and the pressurization achieved, which are difficult to assess. Therefore, determining the magnitude of co-seismic shear stress reduction and the energy balance of earthquakes is still a major issue in seismology.

To constrain the fluid budget of a slipping fault and improve our understanding of weakening processes, we have analyzed the water and carbon dioxide content of pseudotachylytes (i.e. melts produced by friction during earthquakes) using a Fourier transform infrared micro-spectrometer (micro-FTIR). FTIR is a conventional tool for the study of volatile species in magmatic melts (Ihinger et al., 1994), albeit never applied to friction melts so far. We show that pseudotachylytes may be used to infer the fluid concentration in fault rocks at the time of seismic slip, providing new insights on earthquake mechanics.

The studied example is the Nojima fault (Fig. 1) that was activated on a dextral, 10.5 km-long surface rupture

(Awata et al., 1996) by the Kobe (Hyogo-ken Nanbu) earthquake ($M_{JMA}=7.2$, $M_W=6.9$, focal depth=16 km, January 17th, 1995), killing more than 6400 people. Immediately after the shake, the HCO_3^- concentration increased by 30 wt.% in nearby springs (Sato and Takahashi, 1997). This unexplained carbon discharge, together with other co-seismic geochemical anomalies, decreased gradually to normal values in the following ten months (King et al., 1995; Tsunogai and Wakita, 1995; Sato et al., 2000; Sugisaki et al., 1996). One year after the earthquake, the Geological Survey of Japan drilled a borehole (Fig. 1) that reached the upper boundary of the 83° dipping fault at 623.1 m depth within Cretaceous granodiorites (Ohtani et al., 2000). The fault core consists in a 30 cm-thick cataclasite composed of quartz, albite and K-feldspar clasts derived from the granodiorite protolith, crushed together with secondary clays, zeolites and carbonates (Ohtani et al., 2000; Tanaka et al., 2001). The carbonates have a biogenic isotopic signature as well as present-day pore fluids in the fault, which suggests a superficial or sedimentary source for the alteration fluids in general and the carbon in particular (Arai et al., 2001; Lin et al., 2003; Ueda et al., 1999). Because of hydrothermal alteration, the cataclasite is enriched in SiO_2 , CaO and

depleted in MgO, Fe₂O₃, Na₂O, K₂O relative to the granodiorite protolith. The cataclasite also contains 3.5 to 10 wt.% equivalent CO₂ with an average at 7.6 wt.%, and 1 to 5 wt.% H₂O with an average at 2.7 wt.% (mean of 5 measurements taken from Fig. 7 in (Tanaka et al., 2001)). This study focuses on two millimetre-thick pseudotachylytes (Fig. 2a) embedded in the cataclasite layers at 624.59 m within the Nojima fault core (Tanaka et al., 2001). The texture of these pseudotachylytes has

already been investigated in detail (Fujimoto et al., 1999; Boullier et al., 2001) and is only summarized briefly. The dark layer of pseudotachylyte (PT1) contains fragments of cataclasite (isolated or aggregated quartz, albite and calcite clasts with molten rims) in a brown matrix. These fragments, and the fresh PT1 — cataclasite interface devoid of shear localization structures, indicate that the cataclasite is the precursory of PT1. A second, clearer pseudotachylyte (PT2), containing plastically deformed fragments of PT1 and fewer mineral remnants in a transparent matrix (Fig. 2a), re-melted the dark layer. The random occurrence of fluid-filled vesicles in the two matrixes, and the homogeneous aspect of these matrixes under the SEM (Fujimoto et al., 1999) suggest that the two pseudotachylytes are made of undevitrified glass (Boullier et al., 2001). The composition of the vesicles (84 mol% H₂O; 15.3 mol% CO₂; 0.7 mol% NaCl) attests to the supersaturation of H₂O and CO₂ in the melts (Boullier et al., 2001). In addition, the molten rims of clasts in the two pseudotachylytes indicate that melting reached a minimum temperature of 1200 °C (Boullier et al., 2001), which is consistent with melting temperatures estimated from other pseudotachylyte samples in the Nojima fault (Otsuki et al., 2003). The two matrixes have a dacite composition (~68 wt.% SiO₂, 3 wt.% Na₂O+K₂O) similar to the bulk composition of the cataclasite. Calcite fragments in the melts, and the fact that both matrixes contain up to twice the CaO content of the granodiorite protolith (4.06 wt.%), imply that the precursory cataclasite was already carbonate-rich before melting. Carbonate precipitation continued between and after the melting events (Boullier et al., 2004a,b). Pseudotachylytes were quenched at ambient temperatures of 150–350 °C and a depth range of 4–15 km (Boullier et al., 2001; Fujimoto et al., 2001; Boullier et al., 2004a,b). These pseudotachylytes formed well after the cooling of the granodiorite basement (74 Ma (Murakami and Tagami, 2004)), and were then uplifted with the basement by a left-lateral thrust motion of the fault, mostly before the Eocene (Boullier et al., 2004a,b). Exhumation is still occurring in the present even though the fault has shifted to a right-lateral thrust movement since the Plio-Pleistocene (Murata et al., 2001). It is therefore likely that these exhumed pseudotachylytes represent slipping processes similar to those occurring today between the Kobe earthquake hypocenter and the surface. The multiple occurrence of pseudotachylytes within carbonate-bearing cataclasites on surface exposures of the Nojima fault (Otsuki et al., 2003), and on other faults along the Median Tectonic Line running through Japan, suggests that the lateral extent of melts is large, and/or

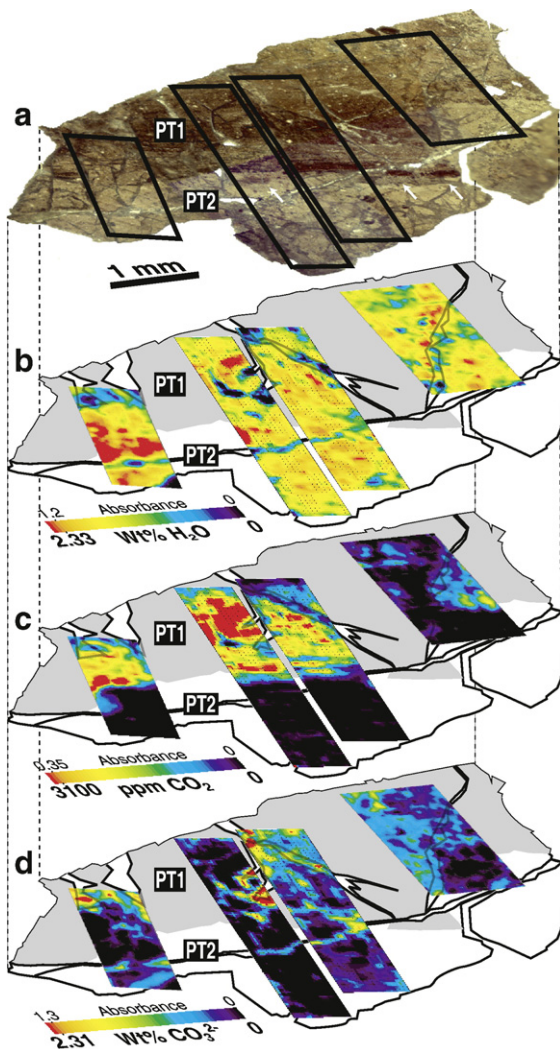


Fig. 2. FTIR mapping in pseudotachylytes from the Nojima fault. a) Optical microphotograph showing the older dark pseudotachylyte (PT1) re-molten into a younger clear pseudotachylyte (PT2). PT2 contains plastically deformed fragments of PT1 (white arrows) and fewer mineral remnants than PT1. Carbonate veins crosscut the two generations of friction melts. b–d) Peak height (absorbance) mapping of molecular H₂O (1630 cm⁻¹), molecular CO₂ (2340 cm⁻¹) and CO₃²⁻ (1460 cm⁻¹) converted into concentrations (wt.%).

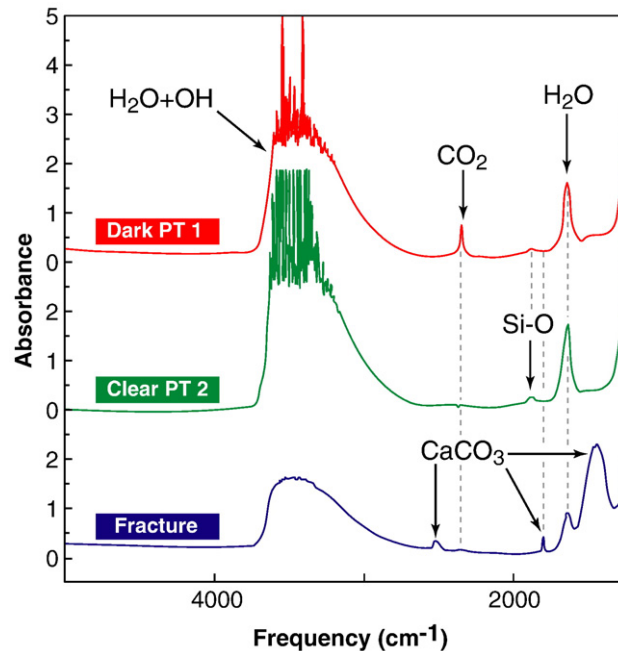


Fig. 3. Typical FTIR spectra of pseudotachylytes from the sample cored in the Nojima fault. Upper (red) spectrum: dark older pseudotachylyte (PT1). Middle (green) spectrum: clear younger pseudotachylyte (PT2). Lower (blue) spectrum: fracture. There is virtually no dissolved hydroxyl in the glass (the absorption peak of bound OH is at 4500 cm^{-1}). The absorption peak of total OH (corresponding to the O–H stretching vibration at 3450 cm^{-1} in hydroxyl and water molecules) is saturated (and useless) in the glass due to the high water concentration, but not in the fractured areas. The absorption peak of molecular CO_2 (recognized by its stretching vibration at 2340 cm^{-1}) is observed in the dark pseudotachylyte, but not in the clear one. Molecular H_2O (recognized by its bending vibration at 1630 cm^{-1}) displays a higher absorption peak and is therefore more abundant in the pure glasses than in the fractures. The three absorption bands of calcite (at 2510 , 1790 and 1460 cm^{-1}) are observed in fractured zones. A combination of Si–O vibrations (at 1870 cm^{-1}) is detected in pure glass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that friction melting is a widespread phenomenon along those faults.

2. Analytical methods and results

Infrared spectra were measured on a JASCO, FTIR 620plus, IRT 30 apparatus, equipped with an automatic XY mapping stage moving the sample at $50\text{ }\mu\text{m}$ steps on X and Y under the microscope. Spectra were acquired by collecting 50 scans in the range $6000\text{--}700\text{ cm}^{-1}$ with a 4 cm^{-1} resolution and a $50\times 50\text{ }\mu\text{m}$ aperture. Every ten spectra during the mapping, the automatic stage moved to a position beyond the sample in order to take a background air spectrum. All the spectra were automatically corrected from background by the JASCO Spectra Manager software, and then corrected using the same linear baseline in the range $5000\text{--}1300\text{ cm}^{-1}$. The thickness of the wafer was measured using a laser scanning confocal microscope (KEYENCE VK-8500) at the centre and corners of each of the mapped areas,

and was found to be $63\pm 3\text{ }\mu\text{m}$. Absorbance peaks were converted into volatile concentrations following the conventional procedure for SiO_2 -rich melts (Ihinger et al., 1994), assuming a glass density of 2.7 g cm^{-3} . The total error on concentration estimates is 5 to 10% (Ihinger et al., 1994). Concentration maps were built using the JASCO Spectra Manager software.

Four areas were analyzed by FTIR in the sample (Fig. 2). Each $50\times 50\text{ }\mu\text{m}$ pixel corresponds to an infrared spectrum, and hence to a couple of H_2O and CO_2 concentrations (typical FTIR spectra provided in Fig. 3). The measured concentrations include the fraction of H_2O and CO_2 dissolved in the glass and the fraction trapped in fluid inclusions. Water is observed entirely as molecular H_2O (no dissolved OH). The two pseudotachylytes display a similar water content of about 2 wt.% H_2O (Fig. 2b), except in cracks. There is, however, an extremely sharp contrast of molecular CO_2 concentration between the dark older PT1 containing up to 5000 ppm CO_2 , and the clear younger PT2 nearly devoid of CO_2

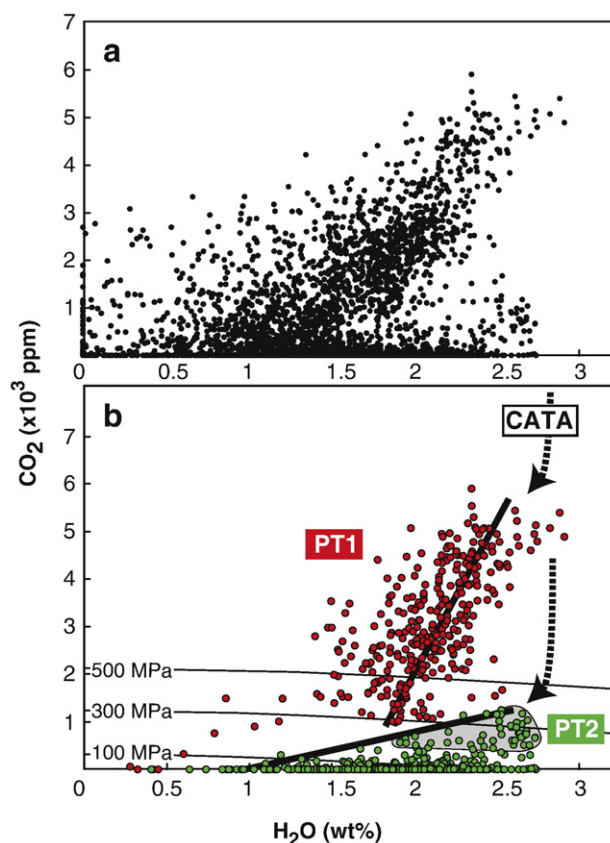


Fig. 4. H₂O versus CO₂ concentrations measured by FTIR in the pseudotachylytes. a) Complete dataset from the 3420 spectra. b) Dataset after filtering: spectra showing carbonate peaks (2510, 1790 and 1460 cm⁻¹) were removed in order to consider only pure glass without calcite. The isobars have been calculated using the VolatileCalc software (Newman and Lowenstern, 2002). Pseudotachylytes first degas as an open system (thick dashed arrows). Because of melt cooling, the pseudotachylytes eventually enter into a second step of closed-system degassing (solid lines). The degassing trend of PT1 (red dots) is consistent with an exsolved fluid phase at 80 mol% H₂O, 20 mol% CO₂ (upper solid line drawn by linear regression). PT2 (green dots) degassed a more water-rich mixture (≥97 mol% H₂O; ≤3 mol% CO₂, domain delimited by the lower solid line). The shaded area corresponds to the border of PT1, which is affected by incomplete re-melting and has a transitional CO₂ content between fresh PT1 and final PT2 (Fig. 2c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 2c). The presence of water and carbon dioxide dissolved as molecular species, not as ionic species, is typical of dacite type, silica-rich melts (Ihinger et al., 1999). In addition, CO₃²⁻ is detected as secondary carbonate minerals (mostly calcite) precipitated in microcracks or as mineral fragments in the glass (Fig. 2d). PT1 contains 1 wt.% CO₃²⁻ or 0.7 wt.% equivalent CO₂ (average of all the spectra measured on PT1). Because PT2 is younger and less fractured than PT1, it contains only 0.3 wt.% CO₃²⁻ or 0.2 wt.% equivalent CO₂ in average.

FTIR data are also reported in an H₂O–CO₂ diagram before (Fig. 4a) and after filtering (Fig. 4b) in order to consider only pure matrix glass without carbonates. PT1 contains 1.5–2.8 wt.% H₂O and 1000–5000 ppm CO₂, whereas PT2 contains 1–2.8 wt.% H₂O and 0–500 ppm CO₂ away from its contact with PT1.

3. Discussion and conclusion

3.1. Budget of volatile exsolution by friction melting

Our results show that friction melting causes carbon devolatilization of the fault rocks. Because PT1 contains up to 0.7 wt.% equivalent CO₂ as crystallized carbonates (i.e. 1 wt.% CO₃²⁻, Fig. 2d), some carbonates may postdate the first melting event such that the cataclasite possibly contained less carbon before PT1 formation than it does now, i.e. only 2.8–6.9–9.3 wt.% equivalent CO₂ (minimum–average–maximum of Tanaka's et al. measurements (Tanaka et al., 2001), minus 0.7 wt.%). In order to set a lower bound to our quantification of CO₂ loss, we therefore assume the precursory cataclasite to have contained no more than

2.5–3.5 wt.% equivalent CO₂ before PT1. Even though, PT1 (1.5–2.8 wt.% H₂O, 1000–5000 ppm CO₂) contains as much H₂O as the parent cataclasite, but about ten times less CO₂. Likewise, PT2 (at 1–2.8 wt.% H₂O, 0–500 ppm CO₂ away from its contact with PT1) contains as much H₂O as PT1 from which it melted, but ten times less CO₂ (for a minimum estimate of the CO₂ loss, we neglect the carbonates precipitated after PT1 and before PT2). Therefore, each fusion expels at least 90 wt.% of the CO₂ dissolved or trapped as carbonates in the protolith, because carbon is supersaturated in the molten phase. Only 1 wt.% of the initial CO₂ content is kept in the fault plane after the two melting events, while the remaining 99% are exsolved as fluid CO₂.

Assuming a rock density of 2.7 g cm⁻³, the fusion of 10⁻³ m³ (i.e. 1 mm thickness × 1 m² of fault plane) of cataclasite (at 2.5–3.5 wt.% CO₂) into PT1 (at 1000–5000 ppm CO₂) yields 56 to 95 g CO₂. Likewise, the refusion of 10⁻³ m³ of PT1 into PT2 (at 0–500 ppm CO₂) releases 1.4 to 14 g CO₂ in 1 m² of fault plane. Friction melting is therefore an unexpected and significant source of CO₂ in the Nojima fault.

3.2. Degassing behaviour of friction melts

FTIR data yield constraints on the ambient pressure during friction melting, because H₂O and CO₂ saturation in silicate melts is pressure-dependent. Spectra measured in PT1 define a trend in the high CO₂ field, whose slope indicates that the supersaturated melts were quenched

while degassing an 80 mol% H₂O and 20 mol% CO₂ fluid mixture (Fig. 4b), consistent with the measured composition of fluid inclusions (Boullier et al., 2001). The lower end of the degassing trend (2 wt.% H₂O, 1000 ppm CO₂) is the closer to the composition of the pure matrix glass without fluid inclusions. Considering the ~1200 °C temperature of melting, a maximum pressure of 300 MPa may then be estimated for the formation of the PT1 glass using the VolatileCalc software (Newman and Lowenstern, 2002), or a 11 km depth assuming a 2.7 g cm⁻³ rock density. Spectra acquired in PT2 lie in the low CO₂ range (Fig. 4b). The low slope of PT2 degassing path suggests that the glass exsolved a much higher proportion of H₂O relative to CO₂ than PT1 (≥97 mol% H₂O, ≤3 mol% CO₂). If PT2 ever reached equilibrium saturation, it is again in the lower end of the degassing path at less than 2 wt.% H₂O and 200 ppm CO₂, or a 130 MPa maximum pressure (5 km). The consistency of these depths with independent depth estimates (Fujimoto et al., 2001; Boullier et al., 2004a,b) implies that PT1 and PT2 nearly reached equilibrium volatile saturation. Our results suggest that the two melting events occurred at different depths, and therefore were separated by a large time span. FTIR mapping is a new method that provides depth constraints on the formation of individual layers of glassy pseudotachylyte in exhumed faults, without any assumption on the geotherm.

In addition, the solubility laws of volatiles in silicate melts may be used to explain the degassing pattern

Table 1

Abbreviations and parameter values used in the calculation of the fluid pressure

i	The subscripts $i=0$ and $i=f$ refer to quantities before and after CO ₂ exsolution, respectively
P_i	Fluid pressure (Pa)
P_{rock}	Lithostatic load (Pa)
T	Temperature (K)
R	Gas constant = 8.314472 J mol ⁻¹ K ⁻¹
Z_i	Compressibility factor of CO ₂ given by the Saxena and Fei EOS (Saxena and Fei, 1987)
T^c	Temperature of the critical point of CO ₂ = 304.14 K (Lemmon et al., 2005)
P^c	Pressure of the critical point of CO ₂ = 73.8 × 10 ⁵ Pa (Lemmon et al., 2005)
M^{CO_2}	Molar mass of CO ₂ = 44 g mol ⁻¹
m_i	Mass of fluid CO ₂ contained in a fault zone of thickness w , i.e. in the porosity of $1 \times 1 \times w$ m ³ of fault rock (g)
ϕ_i	Porosity of the fault zone
w	Maximum distance of CO ₂ outflow in the direction perpendicular to the fault plane, within the time span of friction melting (m)
L_f	Hydraulic diffusion length scale of CO ₂ (m)
D_f	Hydraulic diffusivity after exsolution (m ² s ⁻¹)
ψ	Characteristic timescale of frictional exsolution set at 5 s (the time lapse for glass melting and quenching does not exceed a few seconds (Swanson, 1992))
k_i	Permeability of the fault zone (m ²)
η_i	Viscosity (Pa s) of CO ₂ in the supercritical state (data from Lemmon et al. (2005))
β_i	Storage capacity of the fault zone (Pa ⁻¹)
β_i^b	Compressibility of the bulk fault core (Pa ⁻¹)
β^s	Compressibility of the mineral grains assumed to be constant at 1.2 × 10 ⁻¹¹ Pa ⁻¹
$\beta_i^{\text{CO}_2}$	Compressibility of CO ₂ (Pa ⁻¹)

during friction melting. In doing so, we assume that H₂O and CO₂ exsolution in pseudotachylytes is ruled by local liquid–gas equilibrium as a first approximation, keeping in mind that true equilibrium was probably not achieved within the short time lapse of heating and quenching. Under this assumption, CO₂ exsolves faster than H₂O due to the low solubility of carbon compared to H₂O. Consequently, a silicate melt degassing in an open system (i.e. the exsolved fluid mixture is removed from the melt) follows a steep path in the H₂O–CO₂ space, because CO₂ is almost entirely lost before H₂O supersaturation begins. On the other hand, a magma degassing in a closed system (in which the exsolved fluid stays in contact with the melt) follows a gently sloping path in the H₂O–CO₂ space, because the partial pressure of CO₂ gradually increases in the exsolved phase and hampers further CO₂ degassing. Accordingly, FTIR data reveal that each pseudotachylyte degassing proceeds in two stages: 1) Loss of 90 wt.% CO₂ without significant H₂O loss from the cataclasite to PT1, and from PT1 to PT2 (dashed arrows in Fig. 4b). This degassing path is consistent with an open system that prevails as long as the melt viscosity is low enough for CO₂-rich bubbles to escape the pseudotachylytes. Because it is an open system, this stage is not recorded in H₂O–CO₂ concentrations, yet is evidenced by comparing volatile concentrations before and after melting. 2) Loss of water-rich mixtures (80 mol% H₂O, 20 mol% CO₂ for PT1; ≥ 97 mol% H₂O, ≤ 3 mol% CO₂ for PT2) is consistent with melts degassing in closed system (solid lines in Fig. 4b). This second stage of closed system degassing occurs because the viscosity of the cooling melts becomes too large to let the bubbles

escape, resulting in the entrapment of fluid inclusions. To summarize, pseudotachylytes in the Nojima fault behave as open systems at the beginning of flash friction melting, and then as closed systems during the last stage of melt cooling.

3.3. Implication for fault mechanics

The first essential implication of our findings is that CO₂ degassing may increase the fluid pressure (P) in the fault zone during and/or after an earthquake, depending on the rate of exsolution, the permeability of the fault core, the carbonate content of the precursory fault rocks and the depth considered. To estimate the fluid pressure increase solely caused by frictional exsolution, we consider the effect of CO₂ emission at constant temperature (~200 °C at 5 km and ~400 °C at 11 km), and neglect elastohydrodynamic or thermal pressurization (Lachenbruch, 1980; Brodsky and Kanamori, 2001; Andrews, 2002; Wibberley, 2005), keeping in mind that these effects may be considerable if combined with CO₂ exsolution. Moreover, the ~15 volume% increase caused by the transformation of cataclasite into pseudotachylyte is neglected, although it may contribute to increasing the fluid pressure and reducing the shear stress on the fault plane. For the sake of simplicity, we also consider the porosity of the fault zone to be entirely filled with pure CO₂, even though other fluids such as H₂O may be dominant before an earthquake. This assumption does not yield significant error in the calculation because the compressibility factors and viscosities of H₂O and CO₂ are nearly equal in the supercritical state within the pressure and temperature ranges considered here.

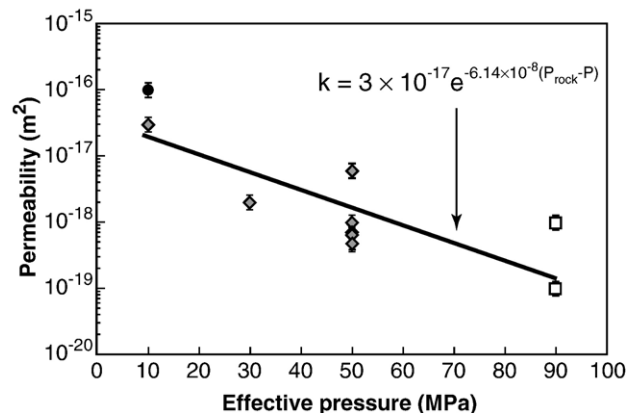


Fig. 5. Best fit log-linear equation for permeability in the Nojima fault core with increasing effective pressure. Black dots compiled from Moore et al. (2001), grey diamonds from Lockner et al. (1999), and empty squares from Mizoguchi et al. (2000).

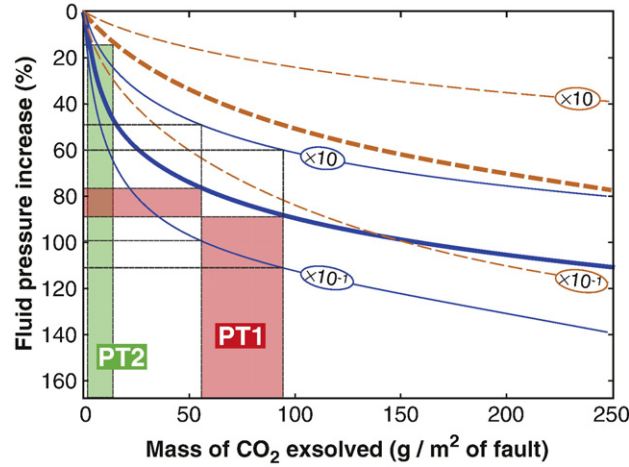


Fig. 6. Fluid pressure increase (P_f/P_0) caused by CO_2 exsolution at two different depths, assuming a hydrostatic initial fluid pressure, and without considering thermal pressurization. Plain (blue) curves: 11 km, 400 °C. Dashed (orange) curves: 5 km, 200 °C. Each color set includes three curves: One curve calculated using the permeability law defined by Eq. (4) (Fig. 5), one curve using a permeability ten times larger ($\times 10$), and one curve using a permeability ten times smaller ($\times 10^{-1}$). The red and green areas correspond to the CO_2 production caused by PT1 (56–95 g/m^2) and PT2 (1.4–14 g/m^2), respectively, on 1 m^2 of fault plane. Calculation detailed in the text.

Accordingly, the fluid pressure increase (P_f/P_0) is computed from the equation of state (EOS) of pure CO_2 :

$$P = \frac{mZRT}{M^{\text{CO}_2} \phi w}, \quad (1)$$

which yields

$$\frac{P_f}{P_0} = \frac{\phi_0 Z_f m_f}{\phi_f Z_0 m_0}. \quad (2)$$

Parameter values, units and definitions are given in Table 1. The subscripts 0 and f refer to quantities before and after exsolution, respectively. R , T , ϕ and M^{CO_2} denote the gas constant, the temperature, the porosity of the fault zone and the molar mass of CO_2 , respectively. Z , the compressibility factor of pure CO_2 , is calculated using the Saxena and Fei EOS (Saxena and Fei, 1987):

$$Z = (1 - 0.5917) \left(\frac{T^c}{T} \right)^2 + 0.09122 \left(\frac{T^c P}{TP^c} \right) + \left[1.4164 \times 10^{-4} \left(\frac{T^c}{T} \right)^2 - 2.8349 \times 10^{-6} \ln \frac{T}{T^c} \right] \left(\frac{P}{P^c} \right) \quad (3)$$

where P^c and T^c represent the pressure and temperature at the critical point of CO_2 . m_0 and m_f are the masses of CO_2 present before and after friction melting in a volume of fault zone equal to $1 \times 1 \times w \text{ m}^3$. m_0 is calculated assuming hydrostatic pressure in Eq. (1). m_f is equal to $(m_0 + m_e)$, where m_e is the mass of CO_2

exsolved by a 1 mm thick pseudotachylyte. w is the maximum distance of co-seismic CO_2 outflow in the direction perpendicular to the fault plane, taken as the half width of the pseudotachylyte (0.5 mm) plus twice the hydraulic diffusion length scale of CO_2 (L_f). L_f is given by $L_f = \sqrt{D_f \psi}$ (Wibberley, 2005), ψ being the characteristic timescale of frictional exsolution, set at 5 s (the time lapse for glass melting and quenching does not exceed a few seconds (Swanson, 1992)). D_f is the hydraulic diffusivity after exsolution, given by $D_f = k_f / \eta \beta_f$, where k_f denotes the final permeability of the fault zone, β_f its storage capacity, and η the P – T dependent viscosity of supercritical CO_2 . β_f is computed from $\beta_f = \beta^b - \beta^s + \phi_f (\beta_f^{\text{CO}_2} - \beta^s)$, β^s being the compressibility of mineral grains, β^b the bulk rock compressibility, and $\beta_f^{\text{CO}_2} = -\frac{P_f}{Z_f} \left(\frac{\partial Z/P}{\partial P} \right)_f^{T=c/e}$ the compressibility of supercritical CO_2 .

To calculate the pressure-dependent permeability of the slipping fault (k_f), we use an empirical law (Fig. 5) derived from the available data at different effective pressures ($P_{\text{rock}} - P$):

$$k = 3 \times 10^{-17} e^{-6.14 \times 10^{-8} (P_{\text{rock}} - P)}. \quad (4)$$

Note that permeability in the Nojima fault is at least two orders of magnitude larger than the permeability of some other crustal faults (at similar effective pressures) investigated so far (Wibberley, 2005; Lockner et al., 2005; Morrow and Lockner, 2005; Morrow and Byerlee, 1992; Chu et al., 1981). In the absence of specific laws of pressure

dependence for ϕ and β^b on the Nojima fault core, we are left to adapt to our case the empirical relations determined on the Median Tectonic Line (Wibberley, 2005):

$$\phi = \varphi e^{-2.97 \times 10^{-8} (P_{\text{rock}} - P)} \quad (5)$$

$$\beta^b = 2.5 \times 10^{-10} e^{-1.38 \times 10^{-13} (P_{\text{rock}} - P)} \quad (6)$$

using $\varphi = 0.03$, which is the mean porosity measured on samples from the Nojima fault core at room pressure (Surma et al., 2003).

The fluid pressure increase (P_f/P_0) due to frictional exsolution is depicted in Fig. 6. At 11 km depth, a flash release of 56–95 g CO₂ per m² of fault plane raises the pore fluid pressure of 78 to 90% above the hydrostatic pressure, or an 80–100 MPa increase, even without considering thermal pressurization. At 5 km, the release of 1.4–14 g CO₂ raises the fluid pressure by 5–15% above the hydrostatic pressure. Note that the magnitude of fluid pressure increase strongly depends on the permeability of the fault core (Fig. 6), as do other mechanisms of pore pressurization. For example, at 11 km depth the fluid pressure increases by 100–110% if the permeability is ten times smaller than the selected permeability law (Fig. 5), and is still of 50–60% if the permeability is ten times larger. Frictional CO₂ exsolution can therefore be a significant pressurization mechanism in fault zones, even at relatively high permeability, and even at hydrostatic starting fluid pressure. Slip-weakening by frictional exsolution should be taken into account when considering earthquake processes at slip velocities large enough to produce friction melts. In addition, the low velocity of seismic waves from the Kobe earthquake aftershocks suggests the presence of high pore fluid pressures in the fault zone after the main shock (Zhao et al., 1996). Since the co-seismic exsolution of CO₂ may sustain such fluid pressurization, it could also enhance later ruptures and trigger aftershock sequences in the Nojima fault, in a same way than mantle CO₂ degassing triggers aftershock trees in thrust faults from Northern Italy (Miller et al., 2004).

4. Implication for fault degassing

The second major consequence of our findings is that co-seismic carbon discharge in near-fault springs might result from friction melting. The relative abundance of pseudotachylytes in carbonate-rich cataclases on different cores and outcrops of the Nojima fault suggests that coseismic CO₂ loss might be the rule rather than an exception. In addition, core sample

studies conclude that magnitude 6–7 earthquakes are responsible for the formation of millimetre-thick pseudotachylytes (Boullier et al., 2001). In the following discussion, we assume that an earthquake such as the M7.2 1995 Kobe earthquake produces pseudotachylytes at least as wide as those observed in cores (Boullier et al., 2001) and outcrops (Otsuki et al., 2003) of the Nojima fault. Under this assumption, the friction melts caused by a single earthquake at 11 km and 5 km along the fault plane should be similar to the pseudotachylytes (PT1 and PT2) caused by two separate slip events in the sample. To calculate the minimum CO₂ production of a Kobe-like earthquake, we hence consider a very idealistic model in which the rupture produces PT1 from 11 km to 8 km and PT2 from 8 km to 5 km. The production of CO₂ beneath 11 km and above 5 km is unknown and therefore not considered, even though it might be significant. Accordingly, a minimum range of 170 to 330 kg CO₂ is released per meter of fault trace, or a total emission of 1.8–3.4 10³ tons CO₂ for a 10.5 km surface rupture of the Nojima fault such as in the Kobe earthquake. Note that thermal decomposition of carbonates in cataclases could also contribute to release carbon in the Nojima fault, and hence increase the proposed budget. However, a large part of this CO₂ likely re-precipitates as new carbonate minerals soon after the earthquake. Yet a fraction of CO₂ may be evacuated through the ground waters that leach the fault. Indeed, an excess of ~20 tons equivalent CO₂ was emitted by the Awaji Island springs within the ten months of the Kobe earthquake (Sato and Takahashi, 1997; Sato et al., 2000), i.e. about 1 wt.% of the CO₂ possibly produced by friction melting. As the carbon isotopic signature in past and present ground waters from the Nojima fault is biogenic and not consistent with a deep degassing source (Arai et al., 2001; Lin et al., 2003), the coseismic carbon discharge in springs might well have come from frictional exsolution. This possibility opens promising applications for soil and spring gas monitoring in active faults, such as in the San Andreas fault that is also degassing biogenic carbon (Lewicki and Brantley, 2000). In the absence of a deep contribution, post-seismic CO₂ discharge might be taken as an evidence of frictional exsolution. The amount of CO₂ released should be proportional to the amount of heated carbon-bearing fault rock, and to the heat generated by shear friction. In deep wells probing those faults, measuring the CO₂ flux could therefore provide an additional tool to constrain the frictional strength of the fault, and the physical processes that govern seismic slip.

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