**In situ** observations of earthquake-driven fluid pulses within the Japan Trench plate boundary fault zone

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**ABSTRACT**

Transient fluid flow within faults is suspected to be an important component of the earthquake cycle and subduction zone evolution. However, an understanding of the mechanisms and time scales involved has been limited due to a paucity of direct measurements. Here we report on **in situ** observations that appear to capture the thermal signature of earthquake-driven fluid pulses within the damage zone of the Japan Trench plate boundary fault. The data are from a sub-seafloor temperature observatory installed through the fault following the March 2011 Mw 9.0 Tohoku-oki earthquake as part of the Integrated Ocean Drilling Program’s Japan Trench Fast Drilling Project (JFAST). High-resolution temperature time series data reveal spatially correlated transients in response to earthquakes that are indicative of advection by transient fluid flow. We interpret the observed phenomenon as reflecting pressure redistribution in a fault zone and a potential mechanism for earthquake triggering and episodic heat and chemical transport.

**INTRODUCTION**

Hydrogeology plays an important role in the strength and behavior of faults. Pore fluid pressures reduce rock and fault strength, and the hydrogeologic structure around faults affects how pressures are distributed (Hubbert and Rubey, 1959; Neuzil, 1995). Hydrologic properties and conditions are not necessarily static quantities (Kitagawa et al., 2002; Elkhoury et al., 2006; Xue et al., 2013; Saffer, 2014). Transient fluid flow is suspected to be an important driver of heat and chemical transport and pore pressure redistribution within active fault zones on the basis of geochemical and thermal anomalies and fluid budget constraints (e.g., Fisher and Hounslow, 1990; Le Pichon et al., 1990; Blanc et al., 1991; Bekins et al., 1995; Sample, 1996; Carson and Screaton, 1998; Solomon et al., 2009; Saffer and Tobin, 2011). However, the time scale and causes of transient fluid flow, particularly within subduction zone faults, are not well understood (Saffer, 2014).

A major candidate for fluid flow in subduction zones is earthquake-driven flow. Earthquake-driven hydrologic transients have been observed in wells, streams, and springs both on land and occasionally in the ocean crust (e.g., Muir-Wood and King, 1993; Wang and Manga, 2009, and references therein; Davis et al., 2004; Tsuji et al., 2013). It is thought that such transients may be particularly prevalent in the conduits provided by major fault zones (Saffer and Bekins, 1998; Saffer, 2014). However, due to the difficulty of monitoring in situ, few direct observations of such transients within the subduction channel have been made (e.g., Solomon et al., 2009).

Here we report on **in situ** observations that appear to be the effects of transient fluid flow within an active fault zone. Using borehole temperature measurements, we observe the thermal signature of what we infer are transient pulses of fluid flow from the damage zone of the Japan Trench plate boundary fault in response to numerous earthquakes.

**JFAST TEMPERATURE OBSERVATORY**

Our observations come from a sub-seafloor observatory installed across the plate boundary fault as part of the Integrated Ocean Drilling Program’s (IODP) Japan Trench Fast Drilling Project (JFAST). The temperature observatory was installed within the shallow subduction zone where the fault slipped ~50 m during the March 2011 Mw 9.0 Tohoku-oki earthquake (Fig. 1; Fulton et al., 2013; Fujiiwara et al., 2011). The observatory consists of 55 temperature-sensing data loggers with an accuracy of ~10⁻³ °C and crosses the main plate boundary fault ~820 m below the seafloor (mbsf) in a water depth of 6900 m. Geophysical logs and core samples were collected in two separate boreholes ~30 m away and provide additional characterization of the fault zone and its surroundings (Chester et al., 2013a, 2013b).

The primary purpose of the observatory was to record the frictional heat signal from the Tohoku-oki earthquake in order to constrain the dissipated energy during slip and the fault’s coseismic frictional stress. In addition to revealing a 0.31 °C frictional heat temperature anomaly, which was interpreted to imply that the fault had very little resistance during slip, the high-resolution data record the thermal recovery of drilling-related disturbances and advection by subsurface fluid flow (Fulton et al., 2013). Together, different aspects of the data provide insight into conductive processes such as the diffusion of frictional heat and the geothermal heat flux, as well as information regarding the fault zone hydrogeologic structure and the movement of water within the subsurface over space and time.

**SPATIALLY CORRELATED TEMPERATURE TRANSIENTS**

The temperature sensors recorded data during a 9 mo deployment from 15 July 2012 through 26 April 2013. During this time, a Mw 7.3 intraslab doublet on 7 December 2012 occurred very close to the observatory, involving slip on a normal fault within the downgoing Pacific plate (Lay et al., 2013; Inazu and Saito, 2014). This earthquake resulted in an easily observable change in the temperature pattern. Within the damage zone above the plate boundary fault, temperature decreased at 784 mbsf while increasing at ~763 and 810 mbsf (Fig. 2). We previously speculated that the 2012 intraslab...
doublet drove the changes by forcing fluid flow through permeable fracture zones within the fault damage zone (Fulton et al., 2013).

Here we develop a new analysis of the data to uncover multiple thermal events. We use these results to map when and where fluid advection occurred in the subsurface. We first filter out long-wavelength signals that record diffusive processes with a characteristic diffusion time >20 d (see the GSA Data Repository¹ for methods). The remaining high-pass filtered data reveal temperature fluctuations indicative of the effects of transient fluid flow, whereas the steady-state thermal structure and the long-period conductive signal of diffusion of frictional heat from the 2011 megathrust earthquake are removed.

In the filtered data, it is apparent that much of the temperature variability is similar on adjacent sensors (Fig. 3A). This suggests that these depths are similarly being affected by advection. Large changes are seen in response to the 7 December 2012 event, as well as smaller changes at other times. Short-lived increases occur at several adjacent depths at the same time as short-lived decreases at deeper depths, while other depths record no change at all (Fig. 3A).

These patterns are consistent with transient fluid flow from permeable pathways within the rock into the borehole annulus as illustrated schematically in Figure 3A. Because the background geotherm increases with depth (Fig. DR1 in the Data Repository), when fluids flow into the borehole, they are typically warmer than the surroundings when they flow up the borehole wall and cooler than the surroundings when they flow down. The resulting thermal effect of transient fluid flow is also evident in the results of modeling simulations, discussed below. Patterns indicative of this phenomenon are seen at multiple times within the data (Figs. 3A and 4).

To better identify temperature transients suspected to result from fluid advection, we compute the maximum normalized cross-correlation between neighboring sensors within given overlapping time windows (see methods in the Data Repository). The high-pass filtered data from adjacent sensors are expected to be uncorrelated unless they are similarly affected by advection. The resulting space-time map of correlation coefficient reveals where and when active advection occurred (Fig. 3C).

The results reveal discrete pulses of advection consistently around the same locations. These depths correspond with regions independently inferred to have higher permeability based on the characteristic diffusion time of the drilling disturbance recovery (Fig. 2; Fulton et al., 2013); more permeable zones allow for greater infiltration of cool drilling fluids, are more greatly thermally disturbed, and take longer to recover.

Through our cross-correlation analysis, we discern several clearly identifiable fluid pulses (Table DR1). As with the response to the 2012 intraslab doublet, the onset times of these pulses coincide with earthquakes and aftershocks of the 7 December 2012 Mw 7.3 intraslab event, including a Mw 4.7 on 9 December 2012, a Mw 4.3 on 14 December 2012, and a Mw 4.5 on 20 December 2012 (Fig. 3; Fig. DR2).

During the deployment, an ocean bottom pressure (OBP) sensor located ~600 m away in a water depth of 6482 m recorded pressure spikes in response to earthquake ground motions. Of the 71 identifiable earthquakes with an absolute pressure spike >100 Pa, we find signatures suggestive of advection by fluid pulses in response to 28 of them.

INTERPRETATION AS TRANSIENT FLUID FLOW

The temperature changes were sufficiently rapid that they must have been due to advection of heat by fluid flow. There are two candidate classes of flows that must be considered: either fluid flow between the formation and the borehole or a flow entirely confined to the borehole. Several observations suggest that the temperature transients resulted from an influx of fluid from the formation rather than by the dynamics of water within the borehole.

First of all, if fluid movement in the borehole were the cause independent of any flow from the formation, then the effects should be observed over all depths. Instead signals are repeatedly seen centered around the same depths over time. Borehole convection could achieve spatial consistency, however the aspect ratio of fluid movement implied by the observations is inconsistent with convection. Disturbances consistently occurred in similar patterns over tens of meters. If a convection cell were the cause, fluids would have to overturn over tens of meters within a borehole annulus or internal diameter on the order of several centimeters, which is difficult. Second, if water movement in the borehole due to ground motions were the cause, then the transients should likely correspond with the magnitude of the OBP spike. Instead, we see the sensitivity to OBP spikes change over time, with what appears to be greater sensitivity to cause a transient after a prior large event (Fig. DR3). Suspected fluid pulses occurred in response to earthquakes with a wide range of OBP spikes immediately after the 7 December 2012 event, but did not respond to earthquakes with similar-magnitude spikes at other times. Thirdly, water movement solely within the borehole would have been greatest immediately after an earthquake, whereas the transients observed commonly took ~0.1 d to build.

¹GSA Data Repository item 2016281, supplementary methods, Figures DR1–DR5, and Table DR1, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.
In summary, Figure 4 shows examples of temperature transients suspected to have resulted from fluid pulses that appear isolated in time and largely affected by only one earthquake. We cannot conceive of a realistic model to explain these observations with just the movement of borehole fluids alone. We prefer the interpretation of an influx of fluids along the borehole annulus pushing fluids both up and down the borehole wall.

To further investigate whether these signatures can be explained by transient fluid flow into a borehole, we compare distinct transients centered around 792.5 mbsf to numerical modeling simulations (Fig. 4). Figure 4A shows results of a model where excess pore pressure within a several-meter-wide permeable zone in the formation drives fluid flow into the borehole annulus at a rate of \(10^{-4}\) m/s before quickly decreasing (see the Data Repository; Figs. DR4 and DR5). The resultant temperature effect is similar to observations. Although more sophisticated models are clearly possible, this demonstrates that the observations are consistent with realistic localized transient fluid flow from the formation into the borehole.

**POTENTIAL DRIVING MECHANISMS**

We interpret the observations of spatially correlated temperature transients in the JFAST observatory to result from earthquake-driven fluid pulses out of permeable zones and into the borehole annulus. The depths where advection signals are observed occur where the borehole intersects the fault damage zone, an \(-100\)-m-wide region identified in geophysical logging data and core samples with open faults and fractures within lithified mudstone above the <4.87-m-thick clay-rich uppermost candidate plate boundary fault, and other mudstones, siliceous clays, chert, and basalt within the downgoing Pacific plate (Chester et al., 2013a; Rabinowitz et al., 2015; Keren and Kirkpatrick, 2016). Depths near the bottom of the observatory array, around the main plate boundary fault and where the largest part of the frictional heat signal is observed, are largely unaffected by advection, which is consistent with the previous inference that the plate boundary fault has much lower permeability than the damage zone due to its composition of low-porosity scaly clay (Fulton et al., 2013; Chester et al., 2013b; Tanikawa et al., 2013). The location and relatively small magnitude of borehole transients are consistent with the interpretation of the broad long-lasting 0.3 °C signal at \(-819\) mbsf as conductive frictional heat.

A mechanism for fluid pulses may include changes in fluid flow rate through permeable zones driven by persistently high pore pressures and transient changes in permeability associated with damage and healing (Claesson et al., 2004; Elkhoury et al., 2006; Xue et al., 2013; Wästeby et al., 2014). Evidence of large background pore pressures was not observed during monitoring of pressure while drilling, and both the measurements during drilling and observatory temperature data suggest that background flow rates are generally small (Fulton et al., 2013; Chester et al., 2013b). Thermal anomalies of \(-0.1\) °C at 763 and 784 mbsf (Fig. 2) that appear or disappear, respectively, in response to the 7 December 2012 doublet suggest time-averaged background fluid flow rates locally on the order of \(10^{-4}\) m/s (see the Data Repository). Peak transient flow rates in simulations with temperature transients similar to observations are roughly three orders of magnitude greater over a relatively short time and seem plausible (Fig. 4). The effects of changes in hydrologic properties associated with fresh earthquake damage may combine with poroelastic pore pressure responses to drive transient fluid flow (e.g., Cocco and Rice, 2002; Brodsky and Prejean, 2005).

Prior work has associated other types of hydrologic responses with either the dynamic or static stresses imposed by earthquakes (e.g., Muir-Wood and King, 1993; Wang and Manga, 2009). To evaluate the static effects of each earthquake at the JFAST site, we utilize earthquake focal mechanisms from the Japan National Research Institute for Earth Science and Disaster Resilience—Full Range Seismograph Network of Japan (NIED F-NET) Earthquake Mechanism catalog (www.fnet.bosai.go.jp) for the majority of the earthquakes identified in the OBP data and estimate the direction of expected static strain changes at the JFAST site following the model of Okada (1985). We find no systematic relationship between either the polarity or the amplitude of the static volumetric strain and the occurrence or absence of fluid pulses (Table DR1). This suggests that static effects are unlikely to have been the primary driver.

We also compare the magnitude and distance of each earthquake, the magnitude of the coseismic OBP response, and whether or not the earthquake resulted in a suspected fluid pulse (Figs. DR3 and DR4). The results support the potential importance of dynamic stresses, although the sensitivity appears to change over time, suggestive of a damage/healing process. Several earthquakes of comparable size, distance, and OBP response to those that drove fluid pulses did not result in a suspected fluid pulse. This may reflect uncertainty in earthquake location and ground motion at the JFAST site or in detecting advection signals. Alternatively, because most of the suspected fluid pulses occurred in response to aftershocks of the large 7 December 2012 doublet, perhaps it suggests that the system was more susceptible after having already been disturbed and required time to adequately heal from the effects of a prior event. Previous studies have noted similar regional or temporal variations in susceptibility to earthquake-induced disturbances based on a variety of geochemical and hydrologic observations with healing rates operating over multiple time scales (Claesson et al., 2004; Elkhoury et al., 2006; Xue et al., 2013; Wästeby et al., 2014).

**CONCLUSIONS**

Our high-resolution temperature observations within an active plate boundary fault zone provide insight into fault zone hydrogeology during a major aftershock sequence. The JFAST observatory data capture short-lived temperature transients interpreted to have resulted from fluid pulses within the damage zone above the Japan Trench plate boundary fault. The observations likely reflect permeability changes, pore pressure changes, or a combination of both within discrete permeable zones in response to earthquakes. This earthquake-driven hydrologic response is perhaps a direct manifestation of one of the drivers of transient fluid flow long suspected and required to explain many geochemical and thermal observations within...
subduction zones (e.g., Fisher and Hounslow, 1990; Le Pichon et al., 1990; Blanc et al., 1991; Bekins et al., 1995; Sample, 1996; Carson and Scretanton, 1998; Solomon et al., 2009; Saffer and Tobin, 2011). The transient redistribution of fluid pressures within fault zones inferred here in response to earthquakes is a potential mechanism that can affect fault stability and may be involved in earthquake triggering.

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