Hydrothermal temperature changes at the southern Juan de Fuca Ridge associated with M_W 6.2 Blanco Transform earthquake

Robert P. Dziak
William W. Chadwick Jr. — Cooperative Institute for Marine Resources Studies, Oregon State University, Hatfield Marine Science Center, Newport, Oregon 97365, USA
Christopher G. Fox
Robert W. Embley — National Oceanographic and Atmospheric Administration, Pacific Marine Environmental Laboratory, Hatfield Marine Science Center, Newport, Oregon 93765, USA

ABSTRACT

The regional impact of transform seismicity on ridge-crest hydrothermal venting and ridge-transform dynamics is investigated using a June 1–7, 2000, Blanco Transform earthquake sequence. The mainshock (M_w 6.2) and 170 foreshocks and aftershocks were located using *T* waves recorded on U.S. Navy hydrophones, and indicate that the active transform fault may be farther south than in previous tectonic models. During the earthquake sequence, two temperature probes were deployed in black smoker chimneys at the Vent1 and Plume hydrothermal fields along the southern Juan de Fuca Ridge. These two hydrothermal systems are ~39 km northwest of the mainshock's acoustic location. Both probes show significant (>5 °C) temperature declines following the mainshock, the Vent1 temperature changes occurring over days to weeks while the Plume changes were coseismic. The Vent1 and Plume fluid temperature decreases are consistent with earthquake-induced changes to permeability in the upper ocean crust. The evidence suggests that deep-ocean hydrothermal systems can be altered by large earthquakes even at a distance and across tectonic provinces, and ridge-crest seismic and magmatic activity are not the only causes of change to hydrothermal systems.

Keywords: hydrothermal vents, earthquakes, fluid temperature, Juan de Fuca Ridge, transform fault.

INTRODUCTION

Earthquake-related changes to fluid levels and pressure at subaerial wells and geothermal sites following large (M > 6) earthquakes have been well documented (Roeloffs, 1996; Bjornsson et al., 2001). Rapid changes in crustal permeability induced by either the earthquake's static strain field (Quilty and Roeloffs, 1997) or ground motion from surface waves have been invoked to cause the observed pressure and water-level changes (Hill et al., 1993; Brodsky et al., 2001), even though in many cases the geothermal sites are hundreds of kilometers from the mainshock epicenter (Roeloffs, 1998). Mid-ocean-ridge hydrothermal vents have also been observed to change temperature, fluid chemistry, and flow rate following on-axis earthquake swarms located directly below the vents (Sohn et al., 1998; Baker et al., 1999) and also following ridge-flank earthquake swarms at local to regional distances (10–50 km) from the vents (Johnson et al., 2000, 2001). The seafloor hydrothermal changes observed to date are likely a result of either permeability and/or vent conduit changes induced by nearby tectonic faulting, or direct magmatic input into the hydrothermal system.

We present evidence that a large transform earthquake altered temperatures at hydrothermal vent sites ~39 km away along an adjacent spreading center. During June 1–7, 2000, a tectonic sequence of 170 earthquakes was detected from the western Blanco Transform fault (Fig. 1). The sequence mainshock (M_w 6.2) was the largest earthquake to occur along the western Blanco Transform fault in the past four decades (National Earthquake Information Center, 2001). The acoustic earthquake locations indicate that the entire West Blanco segment ruptured during the sequence, and that the southern wall of the segment basin is the location of the active transform trace. During the earthquake sequence, in situ probes recorded temperature from black smoker chimneys at two hydrothermal sites on the Cleft segment of the Juan de Fuca Ridge. Both vent sites show sudden, although temporally different, decreases in fluid temperature associated with the earthquake sequence. This is the first evidence of a link between thermomechanical changes at a mid-ocean-ridge hydrothermal vent and seismicity on the adjacent transform.

TECTONIC SETTING

The Cleft segment is the southernmost spreading-center segment of the Juan de Fuca Ridge (2.75 cm yr^{-1} half-spreading rate) adjacent to the western Blanco Transform fault. The Cleft segment is ~50 km long and exhibits several high-temperature (to 340 °C) hydrothermal vent sites located within the axial valley at the northern and southern ends of the segment (Normark et al., 1986). The Blanco Transform is a 350-km-long right-lateral strike-slip fault that links the Juan de Fuca and Gorda Ridges (Fig. 1), and comprises five major right-stepping strike-slip fault segments offset by deep extensional (pull apart) basins (Embley and Wilson, 1992). The western section of the Blanco Transform is dominated by the West Blanco Trough, a 4860-m-deep, 44-km-long basin (Fig. 1) that extends from the southern tip of the Juan de Fuca Ridge to the pseudofault trace of the most recent propagator wake (Juteau et al., 1995). The northern wall of the West Blanco Trough has been interpreted as the location of the active transform trace due to its steepness (Embley and Wilson, 1992), and from submersible observations of deformation features consistent with right-lateral strike-slip motion (Juteau et al., 1995). The southern wall of the West Blanco Trough is also steep, but was observed to have a benched morphology interpreted as multiple normal faults (Juteau et al., 1995). Dauteil (1995) suggested a northward transform jump at 2 Ma placing the present active transform zone along the southern wall of the West Blanco Trough near the ridge-transform intersection and along the northern trough wall east of 130°10′W (Fig. 1).

JUNE 2000 EARTHQUAKE SEQUENCE

On June 1, 2000, at 1917Z a sequence of 170 earthquakes began along the southern wall of the West Blanco Trough (Fig. 1). The earthquakes were detected and located using U.S. Navy SOSUS (sound surveillance system) hydrophones located in the sound channel throughout the North Pacific Ocean (Fox et al., 1994). Earthquake locations are estimated by selecting *T* wave arrival times at each of nine hydrophones, then minimizing the difference between observed and predicted traveltime to derive an event's latitude, longitude, and origin time (Slack et al., 1999). Good azimuthal distribution of the hydrophones and availability of accurate sound-speed models allow for well-defined locations (Fig. 1). Earthquakes from the Blanco Transform are within the region of lowest error attainable for the SOSUS array configuration (Dziak, 2001), although error estimates are based on a point-source model, whereas *T* waves are generated over a finite seafloor area. The aftershock time distribution of this sequence is well described by Omori's Law (Bohnenstiehl et al., 2002), indicating that the events were tectonic in origin with no obvious magmatic component.

The sequence began with 79 foreshocks located in a cluster centered at ~44°21′N; 130°15′W. On June 2 at 1113Z, the M_w 6.2 mainshock occurred on the east side of the foreshock cluster. The National Earthquake Information Center location for the mainshock

Geology; February 2003; v. 31; no. 2; p. 119–122; 4 figures.

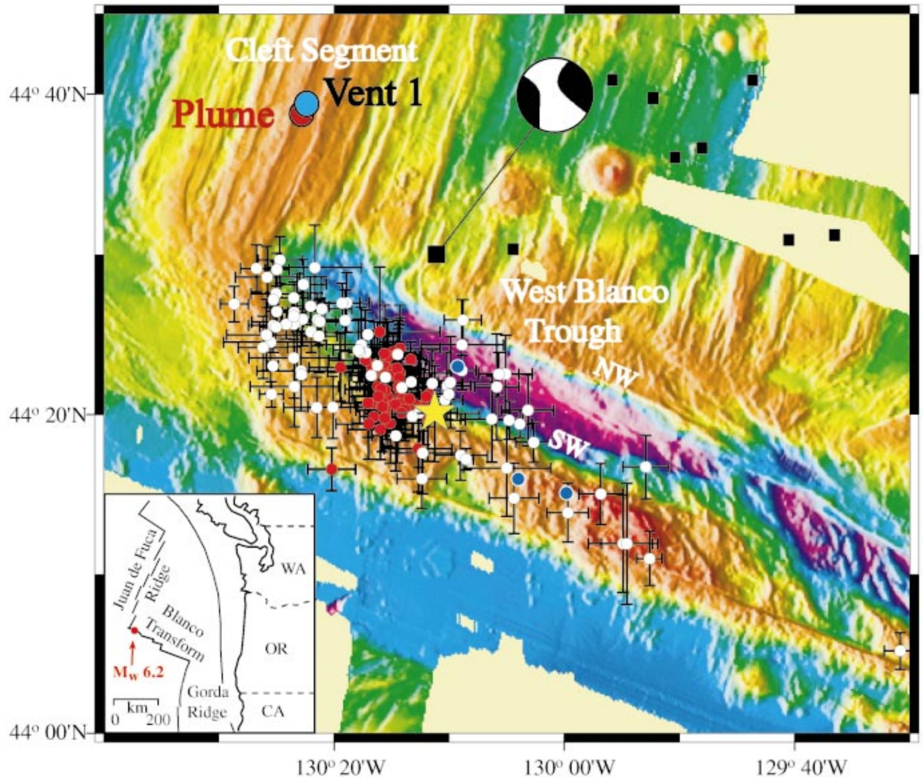

Figure 1. Map showing acoustically derived locations of foreshocks (red dots), mainshock (yellow star), and aftershocks (white dots) of June 1–7, 2000, earthquake sequence on bathymetry of western Blanco Transform. Foreshocks and aftershocks refer to earthquakes that occurred 16 h before and 33 h after M_w 6.2 mainshock. Error bars on earthquake locations represent one standard error. NW and SW stand for north wall and south wall of West Blanco Trough, respectively. Locations of Vent1 and Plume hydrothermal vent sites along southern Juan de Fuca Ridge are also shown. Black squares are locations of all foreshocks and aftershocks detected by land seismic networks (National Earthquake Information Center, NEIC). Mainshock moment-tensor solution (NEIC) is also shown. Mainshock acoustic location is along West Blanco Trough southern wall, in contrast to seismic location (large black square). Blue dots show acoustic locations of NEIC detected earthquakes that correlated with other temperature changes at Plume vent (Fig. 3).

is north of the transform and $\sim$18 km north of the hydroacoustic location (Fig. 1). A northward bias in seismically derived earthquake locations in the North Pacific Ocean is attributed to inaccurate crustal velocities and a lack of seismic stations to the south and west (Johnson and Jones, 1978). The National Earthquake Information Center derived moment-tensor solution for the mainshock indicates that the event was 12 km deep, and predominantly right lateral (with a significant non-double couple component) on a high-angle (dip 73°) fault trending 128°, consistent with the general strike of the transform. Only three foreshocks and five aftershocks ($2.7 \le m_b \le 4.2$) were detected by land seismic networks (Fig. 1).

Although most of the 90 aftershocks (Fig. 1) were concentrated near the ridge-transform intersection, many were distributed along the entire southern wall. Based on the aftershock distribution, the mainshock appears to have ruptured the entire western transform strike-slip fault segment ($\sim$44 km). Moreover, the earthquake locations indicate that the southern wall is the location of the active transform trace. It seems doubtful that bathymetric steering played a role in biasing the hydroacoustic earthquake locations to the south, because the depth of the seafloor is the same on the north and south sides of the West Blanco Trough.

HYDROTHERMAL CHANGES

Regional hydrothermal perturbations seem to have been associated with the Blanco earthquake sequence. Two high-temperature probes (Fornari et al., 1996) were placed within black-smoker chimneys at the Vent1 hydrothermal site from September 1999 to July 2000, and from the Plume site from September 1999 to June 2001, recording temperatures every 40 min. The vents are $\sim$1.8 km apart and 39 km (1 source dimension) to the northwest of the Blanco mainshock's acoustic location (Fig. 1). After 7 months of relatively constant readings (272 ± 3 °C), the probe at Vent1 recorded a temperature decrease of 3.1 °C over 17 days before the mainshock from May 16 to June 2 (Fig. 2). This initial decrease was followed by a 3 °C decrease over the next 7 days (June 9), then by an 18 °C decrease over 10 days until June 19. Afterward, the temperatures at the vent were relatively steady (246.1 °C) until the probe was retrieved on July 3. Fluid at the Plume vent decreased 4.9 °C over 18 h immediately following the mainshock, beginning with the 1200Z temperature reading on June 2 (Fig. 3, right). The fluid temperature then increased 2.9 °C for 3 days, then again decreased 2.8 °C over the next 18 days (until June 23). The record then continues its overall temperature decrease until late May 2001, when the temperature began to gradually increase until the probe was recovered on July 18. Another notable observation from the 2-yr-long Plume record is that three of the other rapid decreases in temperature visible in the record occur from 2 h to 13 days following other small ($4.2 \le m_b \le 4.4$) earthquakes within the West Blanco Trough (Fig. 3, left). The Plume vent is at distances from 40–60 source dimensions from these small earthquakes (rupture lengths < 1 km), suggesting that the Plume vent is very sensitive to coseismic perturbations. There are, however, other temperature decreases at the Plume vent that are not obviously correlated with significant ($M > 4$) seismicity.

DISCUSSION

Pressure (flow rate) changes at geothermal sites have been observed several tens of kilometers away from the epicenters of large earthquakes in Iceland (Bjornsson et al., 2001). In June 2000, two M_s 6.6 south Iceland earthquakes produced pressure changes (from 10 to 1000 kPa) in geothermal reservoirs (from 1 to 75 km from the epicenters) that correlated with the focal mechanisms of the earthquakes, i.e., reservoir pressure increased in areas of rock compression and decreased in dilational quadrants. Pressure changes of 0.2–3.2 kPa were observed in four seafloor drill holes (25–101 km away) following an on-axis earthquake swarm along the northern Juan de Fuca Ridge (Davis et al., 2001). Therefore, a Coulomb failure function (CFF) model of the Blanco Transform fault mainshock was produced to (1) estimate the magnitude and polarity of regional stress changes induced by this earthquake, and (2) see if the earthquake mechanism and hydrothermal change relationship is consistent with the Iceland and Juan de Fuca Ridge observations. The ΔCFF model (Fig. 4) indicates that the June 2 mainshock likely caused a regional stress reduction of 20 kPa along the southern Juan de Fuca Ridge. The 20 kPa change is equivalent to the tidal stress from ocean loading, which has been shown to induce microseismicity to 4.5 km deep along the Juan de Fuca Ridge (Wilcock, 2001).

We propose that regional stress reduction along the Cleft Segment caused by the M_w 6.2 event might explain the observed declines in temperature, stress reduction in the crust leading to an increase in permeability and allowing an increase in the mass flow rate of the hydrothermal system. The thermal output of a

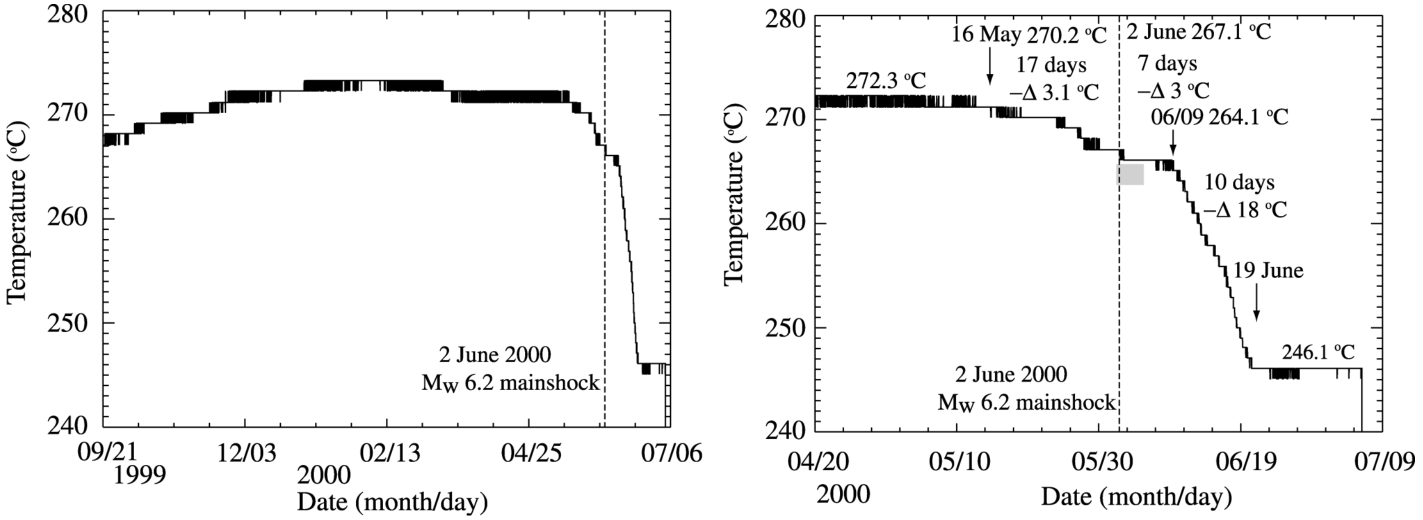

Figure 2. Left diagram shows entire 11 month temperature probe record at Vent1 hydrothermal site; right diagram shows temperature record several weeks before and after June 2000 Blanco mainshock (dashed line). Gray rectangle (right diagram) shows time duration (June 1–7) of entire foreshock and aftershock sequence. After 7 months of steady readings (272 ± 3 °C), probe recorded temperature decrease of 3.1 °C for 17 days from May 16 until June 2. This was followed by 3 °C decrease over next 7 days until June 9, then 18 °C decrease over 10 days until June 19.

vent system can be described as H = $Q \times T$, where H is the heat output, Q is the volume flux, and T is the fluid temperature. Assuming that the distant earthquake introduced no new heat sources into the hydrothermal system (H is constant), flux rate should increase as a result of a permeability increase, and therefore fluid temperature decreases (Germanovich et al., 2001). The decrease in the Vent1 fluid temperatures days to weeks after the mainshock is consistent with temperature-change delay times observed at hydrothermal systems on the northern Juan de Fuca Ridge (Johnson et al., 2000), and may reflect the time-dependent nature of the regional stress effects from the West Blanco Trough earthquake sequence.

Another method for inducing coseismic fluid-temperature changes is through removal of solid precipitate blocking the fluid-flow pathways by shaking (dynamic strain) from the mainshock (Hill et al., 1993). Shaking by seismic waves removes the obstruction and fluid flows rapidly to readjust pore pressure generating dramatic head changes (Brodsky et al., 2001). It is possible that ground motion at the vent sites played a significant role in altering recorded temperatures, because the mainshock could cause displacements of as much as a few centimeters at a distance of 39 km (Bullen and Bolt, 1985). The record at the Plume vent is consistent with this model because the temperature change was truly coseismic with the June 2 mainshock. The correlation of other rapid temperature decreases at the Plume vent with small West Blanco Trough earthquakes (Fig. 3, top) is also consistent with this hypothesis.

The M_w 6.2 Blanco mainshock in June 2000 apparently caused a reduction in hydrothermal fluid temperatures along the southern Juan de Fuca Ridge by changing permeability within the upper ocean crust. Despite the close proximity of the two sites (1.8 km), the Vent1 and Plume vents exhibited strikingly different responses to the mainshock. The Plume vent showed instantaneous changes following the mainshock and other significant west Blanco earthquakes. The Vent1 site showed small temperature decreases beginning two weeks

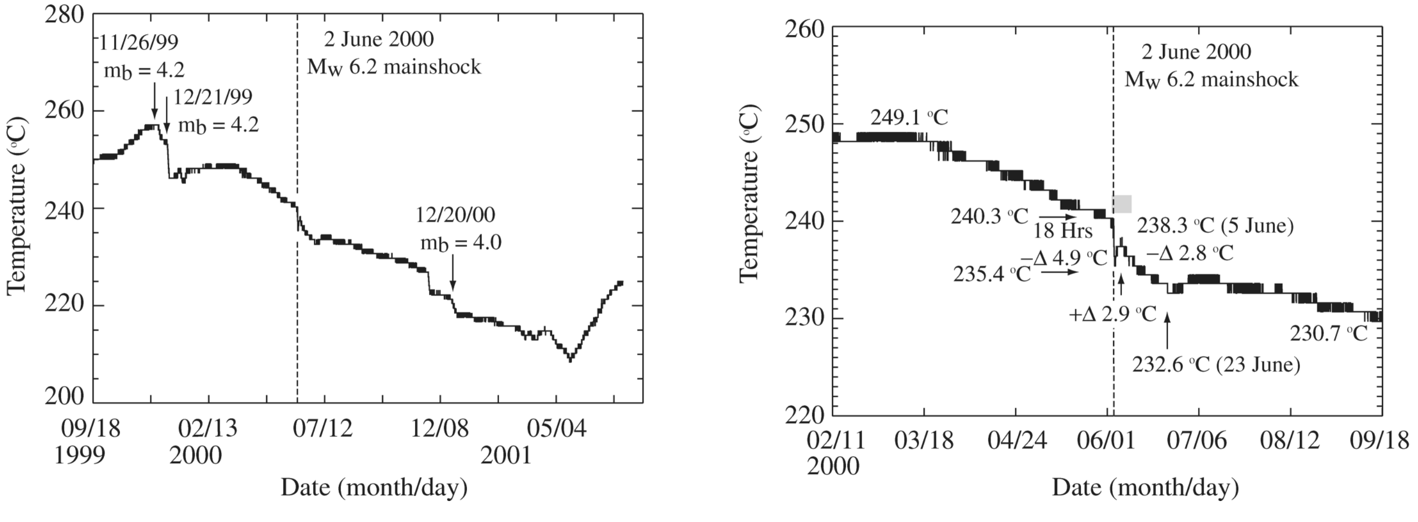

Figure 3. Left diagram shows entire 23 month temperature probe record at Plume hydrothermal site; right diagram shows temperature record several weeks before and after June 2000 Blanco mainshock (dashed line). Gray rectangle (right diagram) shows time duration of entire June 2000 earthquake sequence. Fluid at Plume vent decreased 4.9 °C over 18 h immediately following mainshock, beginning with June 2 (12:00Z) temperature. Fluid temperature then increased 2.9 °C for 3 days, then again decreased 2.8 °C over next 18 days (until June 23). Left diagram shows date of three other National Earthquake Information Center detected West Blanco Trough earthquakes that occurred from 2 h to 13 days prior to significant decreases in vent fluid temperature. Acoustic locations of these events are shown in Figure 1.

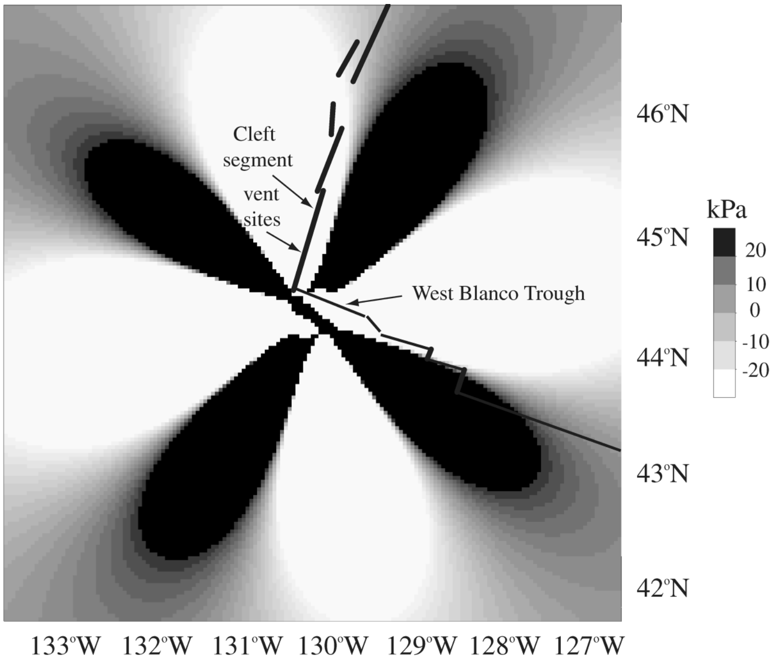

Figure 4. Coulomb failure model of June 2000 Blanco mainshock indicates regional stress (both normal and shear) reduction of 20 kPa along southern Juan de Fuca Ridge (JdFR). Model was produced using dislocation equations of Okada (1992) and assuming fault length of 44 km (from aftershocks), 12.6 km width (from moment-tensor dip and depth), slip of 0.6 m (from fault length-slip relationships; Scholz, 1982), and regional fault-plane orientations parallel to southern JdFR.

before and larger decreases after the Blanco mainshock. The disparate temporal responses of the Vent1 and Plume sites likely reflect differences in the subseafloor conduits of the two vents and possibly different mechanisms of induced permeability change. Unfortunately further interpretation is limited, because little is known about the subsurface structure of these vent systems.

The null hypothesis, that the vent temperature variations may be independent of the earthquake, does not seem a likely explanation for the observed data. The exact temporal correlation of the mainshock with fluid temperature changes at the Plume vent strongly argues for a cause and effect relationship. The delay times observed at the Vent1 site are consistent with temperature-earthquake delay times observed along other mid-ocean ridges (Johnson et al., 2001; Sohn et al., 1998). The Vent1 fluid temperature decrease before the Blanco mainshock is also consistent with observations at terrestrial geothermal systems where hydrologic changes have been shown to be precursors to seismic activity, occurring anywhere from hours to months before a large earthquake (Roeloffs, 1996). If the Vent1 fluid change was a precursor to the Blanco mainshock, this reduces the likelihood that the temperature changes were due to local mechanisms such as changes to the vent nozzle and/or conduits.

ACKNOWLEDGMENTS

We thank Paul Johnson and Del Bohnenstiehl for insightful reviews, Robert Simpson for the dislocation software, and Paul Will for processing the Blanco earthquake data. SOSUS research is supported by the National Oceanographic and Atmospheric Administration (NOAA) Vents Program, Pacific Marine Environmental Laboratory contribution 2458. The south Cleft temperature probes were deployed using the ROV *Jason* off the R/V *Thompson*, and were recovered by the ROV *ROPOS* off the NOAA ship *Ronald H. Brown.* ROV work was funded by the National Science Foundation RIDGE Program (grants OCE-9633261 and OCE-0099038 to Chadwick).

REFERENCES CITED

Baker, E.T., Fox, C.G., and Cowen, J.P., 1999, In situ observations of the onset of hydrothermal discharge during the 1998 submarine eruption of Axial volcano, Juan de Fuca Ridge: Geophysical Research Letters, v. 26, p. 3445–3448.

Bjornsson, G., Flovenz, O.G., Saemundsson, K., and Einarsson, E.M., 2001, Pressure changes in Icelandic geothermal reservoirs associated with two large earthquakes in June 2000, *in* Proceedings, 26th Workshop on Geothermal Reservoir Engineering, SGP-TR-168: Stanford, Stanford University, January 29–31, 2001, 122 p.

Bohnenstiehl, D.W., Tolstoy, M., Dziak, R.P., Fox, C.G., and Smith, D.K., 2002, Aftershock sequences in the mid-ocean ridge environment: An analysis using hydroacoustic data: Tectonophysics, v. 354, p. 49–70.

Brodsky, E.E., Roeloffs, E., Woodcock, D., Gall, I., and Manga, M., 2001, A new mechanism for pore pressure changes induced by distant earthquakes: Eos (Transactions, American Geophysical Union), v. 82, Fall meeting supplement, p. S12F-04.

Bullen, K.E., and Bolt, B.A., 1985, An introduction to the theory of seismology: Cambridge, UK, Cambridge University Press, 499 p.

Davis, E.E., Wang, K., Thomson, R.E., Becker, K., and Cassidy, J.F., 2001, An episode of seafloor spreading and associated plate deformation inferred from crustal fluid pressure transients: Journal of Geophysical Research, v. 106, p. 21,953–21,963.

Dauteuil, O., 1995, Fault pattern from SeaBeam processing: The western part of the Blanco Fracture Zone (NE Pacific): Marine Geophysical Research, v. 17, p. 17–35.

Dziak, R.P., 2001, Empirical relationship of T-wave energy and fault parameters of northeast Pacific Ocean earthquakes: Geophysical Research Letters, v. 28, p. 2537–2540.

Embley, R.W, and Wilson, D.S., 1992, Morphology of the Blanco Transform fault zone, northeast Pacific: Implications for its tectonic evolution: Marine Geophysical Research, v. 14, p. 25–45.

Fornari, D., Voegli, F., Olsson, M., 1996, Improved low-cost, time-lapse temperature loggers for deep ocean and seafloor observatory monitoring: RIDGE Events, February, p. 13–16.

Fox, C.G., Dziak, R.P., Matsumoto, H., and Schreiner, A.E., 1994, Potential for monitoring low-level seismicity on the Juan de Fuca Ridge using fixed hydrophone arrays: Marine Technology Society Journal, v. 27, p. 22–30.

Germanovich, L.N., Lowell, R.P., and Astakhov, D.K., 2001, Temperature dependent permeability and bifurcations in hydrothermal flow: Journal of Geophysical Research, v. 106, p. 473–495.

Hill, D.P., and 30 others, 1993, Seismicity remotely triggered by the magnitude 7.3 Landers, California, Earthquake: Science, v. 260, p. 1617–1623.

Johnson, H.P., Hutnak, M.A., Dziak, R.P., Fox, C.G., Urcuyo, I., Fisher, C., Cowen, J.P., and Nabelek, J., 2000, Earthquake-induced changes in a hydrothermal system at the Endeavour segment, Juan de Fuca Ridge: Nature, v. 407, p. 174–177.

Johnson, H.P., Dziak, R.P., Fisher, C.R., Fox, C.G., and Pruis, M.J., 2001, Earthquakes influence distant hydrothermal vents: The far-field effect and delayed response: Eos (Transactions, American Geophysical Union), v. 82, p. 233–236.

Johnson, S.H., and Jones, P.R., 1978, Microearthquakes located on the Blanco Fracture Zone with sonobuoy arrays: Journal of Geophysical Research, v. 83, p. 255–261.

Juteau, T., Bideau, D., Dauteuil, O., Manach, G., Naidoo, D.D., Nehlig, P., Ondreas, H., Tivey, M.A., Whipple, K.X., and Delaney, J.R., 1995, A submersible study in the western Blanco Fracture Zone: Structure and Evolution during the last 1.6 Ma: Marine Geophysical Research, v. 17, p. 399–430.

National Earthquake Information Center, 2001, Significant earthquakes of the world for 2000: http://wwwneic.cr.usgs.gov/neis/eqlists/sig_2000.html (March 2001).

Normark, W.R., Morton, J.L., Bischoff, J.L., Brett, R., Holcomb, R.T., Kappel, E.S., Koski, R.A., Ross, S.L., Shanks, W.C., III, Slack, J.F., Von Damm, K.L., and Zierenburg, R.A., 1986, Submarine fissure eruptions and hydrothermal vents on the southern Juan de Fuca Ridge: Preliminary observations from the submersible Alvin: Geology, v. 14, p. 823–827.

Okada, Y., Internal deformation due to shear and tensile faults in a half-space: Seismological Society of America Bulletin, v. 82, p. 1018–1040.

Quilty, E., and Roeloffs, E., 1997, Water level changes in response to the December 20, 1994 M4.7 earthquake near Parkfield, California: Seismological Society of America Bulletin, v. 87, p. 310–317.

Roeloffs, E.A., 1996, Poroelastic methods in the study of earthquake-related hydrologic phenomena, *in* Dmowska, R., ed., Advances in geophysics: San Diego, Academic Press, 203 p.

Roeloffs, E.A., 1998, Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes: Journal of Geophysical Research, v. 103, p. 869–889.

Scholz, C., 1982, Scaling laws for large earthquakes: Consequences for physical models: Seismological Society of America Bulletin, v. 72, p. 1–14.

Slack, P.D., Fox, C.G., and Dziak, R.P., 1999, P-wave detection thresholds, Pn velocity estimates, and T-wave location uncertainty from oceanic hydrophone arrays: Journal of Geophysical Research, v. 104, p. 13,061–13,072.

Sohn, R.A., Fornari, D.J., Von Damm, K.L., Hildebrand, J.A., and Webb, S.C., 1998, Seismic and hydrothermal evidence of a cracking event on the East Pacific Rise near 9°50′N: Nature, v. 396, p. 159–161.

Wilcock, W.S.D., 2001, Tidal triggering of microearthquakes on the Juan de Fuca Ridge: Geophyiscal Research Letters, v. 28, p. 3999–4002.

Manuscript received 26 June 2002
Revised manuscript received 15 October 2002
Manuscript accepted 17 October 2002

Printed in USA