Permeability structure of young ocean crust from poroelastically triggered earthquakes

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[1] Permeability is a primary control on fluid flow within mid-ocean ridge hydrothermal systems and strongly influences the transfer of energy and mass between the ocean and the lithosphere. Little is known about how this parameter might vary in zero-age crust even though such variations may determine the locations and areal extents of upflow and downflow zones. Typically, estimates of permeability in seafloor environments are given as a single value (or range of values) for entire systems. Here we model crustal stresses inferred from poroelastically triggered earthquake patterns to estimate the two-dimensional permeability structure within a hydrothermal system on the East Pacific Rise at 9°50′N. We show that permeability in young ocean crust may vary by several orders of magnitude over horizontal scales of hundreds of meters with values ranging from \(10^{-13.4}\) to \(10^{-9.4}\) m². Such values are consistent with other estimates of permeability in ocean crust. These variations may prescribe the geometry of hydrothermal convection and should be considered in future models of these systems. Citation: Crone, T. J., M. Tolstoy, and D. F. Stroup (2011), Permeability structure of young ocean crust from poroelastically triggered earthquakes, Geophys. Res. Lett., 38, L05305, doi:10.1029/2011GL046820.

[2] The permeability of the lithosphere strongly controls fluid flow within mid-ocean ridge hydrothermal systems [Fisher, 1998, 2004]. This property helps determine the intensity of hydrothermal convection and the geometry of subsurface flow, and it helps control the transfer of heat and chemicals between the crust and the ocean. For these reasons, permeability plays a key role in mediating the activity of chemoorganizing microorganisms that support the diverse deep sea ecosystems often found in mid-ocean ridge settings [Kelley et al., 2002].

[3] Despite its importance, permeability is the most poorly constrained of the hydrological parameters, with little known about its spatial variation on the scales of vent fields or hydrothermal convection cells [Fisher, 2004]. Direct measurements of permeability have not been made because drilling into zero-age crust is extremely difficult. Models of these systems, ranging from analytical analyses [Wilcock and McNabb, 1996; Wilcock and Fisher, 2004; Lowell and Germanovich, 2004] to sophisticated three-dimensional simulations [Coumou et al., 2008, 2009], have provided substantial insights into crustal permeability, but most models assume uniform or nearly-uniform permeability distributions and have not explored the effects of abrupt permeability variations.

[4] Because mid-ocean ridges are active spreading margins with extensive tectonism and magmatism, and hydrothermal flow helps drive the precipitation and dissolution of minerals, heterogeneous permeability distributions are expected. Characterizing the spatial variations of crustal permeability on the scales relevant to hydrothermal circulation will be a critical step toward understanding the plumbing of these systems and their influence on the chemical, geological, and biological processes within the deep ocean and Earth’s youngest lithosphere. In this paper we use a two-dimensional poroelastic model of tidally induced stress perturbations, constrained by observations of tidal triggering patterns [Stroup et al., 2009], to map the permeability structure within a hydrothermal system on the East Pacific Rise (EPR).

[5] During a seven month period in 2003–2004 a micro-earthquake survey was conducted near a hydrothermal vent field on the EPR at 9°50′N [Tolstoy et al., 2008]. Using relative relocation techniques [Waldhauser and Ellsworth, 2000] 6,050 earthquakes were located along this section of ridge with a hypocentral accuracy of 50 m or less [Tolstoy et al., 2008] (Figure 1). The majority of these events were located within 500 m of the ridge’s spreading axis and extended from very near the seafloor to a depth of about 1500 m, or to just above the axial magma chamber [Kent et al., 1993]. As previously observed at mid-ocean ridges [Wilcock, 2001; Tolstoy et al., 2002], earthquakes in this catalog tended to occur near times of peak predicted extensional stress [Stroup et al., 2007]. However, a detailed spatial analysis of these events [Stroup et al., 2009] revealed a more complex triggering pattern. Averaged over time, these earthquakes tended to occur in a “wave-like” pattern along axis, with events near the southern and central part of the study area tending to occur as much as four hours before those in the intervening sections of crust (Figures 1 and 2). The events occurring before maximal predicted extension are situated within the inferred downflow and upflow zones of a hydrothermal convection cell [Tolstoy et al., 2008].

[6] In continental systems, earthquake swarms can migrate through the lithosphere ostensibly triggered by aqueous fluid pressure perturbations [e.g., Ingebritsen and Manning, 2010]. As a potential explanation for the pattern observed at the EPR, we hypothesize that pore pressure perturbations generated by ocean tidal loading and Earth tides propagate laterally along axis from the inferred upflow and downflow zones into the intervening section of crust. As this pressure transient propagates through the crust, it raises the potential for fault rupture by lowering the normal stresses on fault planes. The effects of pore pressure on the mechanics of

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density and bulk modulus of 3.2 wt% NaCl signed a viscosity of pure water \cite{2009}. The model is isothermal (0°C) with the fluid as-
porosity of 5% \cite{1500}. The model medium is assigned elastic properties
to simulate ocean tidal loading. It is forced with a time-
the value predicted by global tide models for this area \cite{2005}. The model domain (Figure 3) represents a 3200-
Earth tides and ocean tidal loading \cite{2005}‐
dimension of crust from the seafloor to a depth of
zone is presumed to exist beneath the hydrothermal vents.
that minimized the difference (i.e. the sum of the
minimization process proceeded in four stages: it started with a
corresponds to the triggering pattern (Figure 2). The mini-
finer grid and used to seed the populations of subsequent stages. This approach
range between $10^{-16}$–$10^{-8}$ m$^2$. Resulting populations
resultantly flat near the minimum, we repeated this proce-
the sides of
Figure 1. Map showing the epicenters of the 6,050 double
difference relocated earthquakes used in this study and the
locations of the ocean bottom seismometers. Each dot mark-
ing each event epicenter has been colored according to the
average phase (relative to predicted maximal extension) of
all events within a 100-m radius in plan view. The colors
thus represent a vertically averaged phase.

faulting is well studied \cite{2000, 2002, 2003}, and although the process is complex,
increases in pore pressure generally favor induced seismicity
regardless of fracture orientation \cite{2002}. Pore pressure
gradients that drive the diffusion of along‐axis pressure
perturbations can be generated by variations in crustal perme-
ability that allow pressure changes at the seafloor to enter
the lithosphere at different rates and travel to different depths
over a tidal cycle.

\cite{1}. To test this hypothesis and estimate the required perme-
ability structure, we developed a two‐dimensional por-
elastic model to predict the relative phases of extensional
stress maxima within a fluid saturated crust subjected to
Earth tides and ocean tidal loading \cite{2005}. The model domain (Figure 3) represents a 3200‐m
along‐axis section of crust from the seafloor to a depth of
1500 m. The model medium is assigned elastic properties
of zero‐age seismic layer 2B lithosphere and a porosity of 5% \cite{2005, 2009}. The model is isothermal (0°C) with the fluid as-
signed a viscosity of pure water \cite{1998} and a
density and bulk modulus of 3.2 wt% NaCl‐H$_2$O solution
\cite{1993, 1984}. The model is forced with a time‐dependent fluid load on the top boundary
to simulate ocean tidal loading. It is forced with a time‐
dependent solid load on one side boundary to simulate Earth
tides, as these forces generate strains that are predominantly
horizontal near the seafloor. We allow the ocean tidal
loading stress to lag the Earth tide stress by 158 degrees,
the value predicted by global tide models for this area
\cite{2000, 2007}. The sides of
the domain are symmetry boundaries and the bottom is
closed to flow because a melt lens located just below
1500 m likely defines the base of the hydrothermal sys-
tem along this section of the ridge \cite{1993}. Because strong horizontal pressure gradients are not
generated near the side boundaries, the choice of closed
side boundaries does not significantly affect our results.

\cite{8} We used forward modeling and a genetic algorithm
technique \cite{1989} to find the permeability distrib-
ution that minimized the difference (i.e. the sum of the
residuals where model and data overlap) between the
modeled extensional stresses and the extensional stresses
inferred from the triggering pattern (Figure 2). The mini-
mization process proceeded in four stages: it started with a
course grid of eight 400‐m wide vertical permeability zones,
and progressed to a finer grid of 64 50‐m wide zones by
doubling the number and halving the width of zones after
each stage. The permeability within each zone was allowed
to range between $10^{-16}$–$10^{-8}$ m$^2$. Resulting populations
from each stage were interpolated onto a finer grid and used
to seed the populations of subsequent stages. This approach
allowed us to compute solutions with large numbers of individuals in the early stages to adequately sample the
solution domain, and focus on solution refinement in the
later stages as the computational cost of obtaining solutions increased. Because the residual sum function was
relatively flat near the minimum, we repeated this proce-

Figure 2. (a) Colored contours of the mean phase of the
closest 100 earthquakes to each grid cell using a three-
dimensional search radius \cite{2009}, and (b) the
data projected onto the along‐axis dimension. Areas with
low earthquake density in Figure 2a are colored white,
grey dots indicate the locations of the 6,050 microearth-
quakes projected onto this plane, and red stars mark the
locations of high temperature hydrothermal vents when
these data were collected. (Vent locations are available
through the Ridge 2000 Data Portal at http://www.marine-
geo.org/portals/ridge2000.) A downflow zone (marked by
arrows) is inferred near 9°49.3’N where earthquakes occur
very near the seafloor \cite{2008}, and an upflow
zone is presumed to exist beneath the hydrothermal vents.
The wave‐like pattern suggests that pore pressure perturba-
tions travel along axis on each tidal cycle leading to enhanced
triggering in different parts of the crust at different phases of the tide.
dure 32 times to obtain a rough estimate of the uncertainty of our permeability solution.

Figure 4 shows the results from this modeling procedure. Here we plot the average of the 32 best permeability distributions, contours of the resulting phases of maximal extensional stress, and horizontal cross-sections of the phases projected onto the along-axis dimension for comparison with the data from Figure 2. Error bars on the permeability distribution indicate the standard deviation of the permeability at each node from the 32 minimization runs. About two-thirds of the values in the permeability distribution are near $10^{-12}$ m$^2$. However two sections have significantly higher permeability values. One section located about 400–700 m along axis has values that are near $10^{-11.5}$ m$^2$, and another located about 2100–2500 m has values near $10^{-10}$ m$^2$. Another section near the right-hand side boundary has values that are lower, with a minimum of about $10^{-13.5}$ m$^2$. The baseline permeability of about $10^{-12}$ m$^2$ is similar to (and bracketed by) values that have been predicted for hydrothermal systems using analytical models constrained by heat flow data [Wilcock and Fisher, 2004; Lowell and Germanovich, 2004], models of flow rate perturbations generated by earthquake swarms [Crone et al., 2010], and measurements and models in ridge flank systems [Becker and Fisher, 2008; Fisher et al., 2008; Hutnak et al., 2006]. Permeabilities in off-axis basement measured over very large spatial scales have been estimated to be as high as $1.7 \times 10^{-10}$ m$^2$ [Davis et al., 2000], a value similar to the highest permeability predicted by our model.

In our model, this pattern in the timing of maximal extensional stress is generated by the Earth and ocean tidal

Figure 3. Model geometry and boundary conditions used in this study. The poroelastic model domain is closed to fluid flow on the bottom and side boundaries, and open to flow across the top boundary, which represents the seafloor. The right-hand side boundary is forced with a sinusoidal solid stress with a period of 12 hours to simulate the effects of the solid Earth tide. The top boundary is forced with a sinusoidal fluid stress function with a similar period (lagging the Earth tide by 158 degrees) to simulate the effects of ocean tides. No boundary sustains any shear stresses. The elastic properties of the medium are assigned values that are typical of seismic layer 2B [Crone and Wilcock, 2005; Stroup et al., 2009]. For the finest resolution model runs, the poroelastic medium is divided into 64 vertical slices (gray lines), each of which can be assigned a different permeability value. We use a genetic algorithm minimization scheme to find the permeability distribution that minimizes the difference between the modeled extensional stress phases (Figure 4) and the inferred stresses from earthquake triggering (Figure 2).

Figure 4. (a) Colored contours of the relative phases of modeled extensional stress maxima, (b) several horizontal cross sections of the data from the lower two-thirds of the model domain projected onto the along-axis dimension (blue dots) along with the earthquake triggering phases from Figure 2b (gray dots), and (c) the along-axis permeability distribution that generated the best fit between the model and the data. The standard deviation of the residuals (where model and data overlap) is 15 degrees.
forces through an interplay between the loading stresses and the fluid pressures which are strongly influenced by the permeability structure. At the beginning of each tidal cycle, as the ocean tide rises and compresses the poroelastic medium, fluid flows into the model from the top boundary, with more fluid flowing into the domain where the permeability is elevated. At nearly the same time, Earth tide stresses are acting to bring the system into extension. Where fluid pressures are greatest (i.e. within the high permeability zones), maximal extension is reached first. As fluids flow into lower permeability crust, maximal extension is achieved later in the cycle. With the permeability distribution shown in Figure 4c, the resulting stress pattern is similar to the inferred stresses from the triggering pattern in Figure 2.

This model can only generate large differential phase lags to match the earthquake data when the ocean tidal loading and Earth tide stress functions (Figure 3) have similar magnitudes (i.e. within about 25% of one another). The global tide model we use [Matsumoto et al., 2000] provides estimates of both phase and magnitude of these forcing functions, and because the EPR at 9°50’N is near an amphidromic point where ocean tides are small, the magnitude of the Earth tide stresses are predicted to be nearly twice that of the ocean loading stresses. However, although we have high confidence in the tide model’s predictions of phase, we have lower confidence in its predictions of amplitude. The tide model’s predictions are based on a radially-symmetric reference Earth model, which is a reasonable approximation for many locations on and within the Earth. It is probably not a good approximation for the lithosphere at a fast spreading mid-ocean ridge with a relatively shallow axial magma chamber and the presence of off-axis magma bodies [Kent et al., 1993; Canales et al., 2008]. Our results suggest that near 9°50’N on the EPR, the relative magnitude of Earth tide stresses may be smaller than predicted by a radially-symmetric reference Earth model, which is consistent with tilt measurements conducted in other ridge environments [Tolstoy et al., 1998]. A comprehensive geodetic survey of this section of the ridge using tilt meters and bottom pressure recorders may help resolve this issue.

Our results illustrate how horizontal variations in permeability could contribute to the pattern of earthquake triggering observed at 9°50’N on the EPR. The predicted permeability variations are large and occur over relatively small distances, but they are within the range of modeled values from other studies as well as values measured in off-axis environments. Such large permeability variations may be generated by tectonic stresses associated with the fourth-order ridge crest discontinuity near 9°49.3’N [Haymon, 1996], and the geochemically and seismically defined discontinuity at 9°50.3’N [Tolstoy et al., 2008; Von Damm and Lilley, 2004]. That these high permeability zones appear to coincide with areas of inferred downflow and upflow suggests that the permeability structure may strongly affect the geometry of hydrothermal flow along this section of the ridge. Future modeling studies of hydrothermal processes at mid-ocean ridges should consider the potential effects of large horizontal permeability variations in the lithosphere. These structural variations may ultimately control heat transport, chemical processes, and biological productivity in the subseafloor.


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