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Evidence for water-filled cracks in earthquake source regions

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[1] We identify lowered Vp/Vs ratios near earthquake source regions in southern California using observations from a seismic tomography model and high-resolution local Vp/Vs estimates using waveform cross-correlation data from within similar event clusters. The median tomographic Vp/Vs ratio is 1.716 ± 0.008 at all the relocated crustal earthquake locations, compared to the background median value of 1.729 ± 0.007 for the tomography model, although the error estimates overlap slightly. The median in situ Vp/Vs ratio of 1.673 ± 0.022 within the similar event clusters suggests that tomographic studies are overestimating Vp/Vs at source regions. Interpretation of Vp/Vs anomalies is complicated by the scatter in values obtained for individual clusters and in comparisons to absolute Vp and Vs velocities in the tomography model. However, the low Vp/Vs ratios measured for the seismicity clusters are hard to explain with known rocks and suggest the presence of water-filled cracks with several percent porosity in earthquake source regions in southern California, which likely has an effect on faulting and earthquake activity.
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1. Introduction

[2] Fluids in subsurface cracks and pores may play a major role in fault mechanics and earthquake rupture. Under some conditions, they can promote fault slip at lower levels of shear stress than are required in dry rock, and they are a likely driving mechanism for many earthquake swarms [*Vidale and Shearer*, 2006]. However, because crustal earthquakes typically occur at 5 to 15 km depth, in situ fluid properties can only be studied indirectly, using seismic or electrical resistivity data [e.g., *Eberhart-Phillips et al.*, 1995]. In seismology, crack and fluid properties are very sensitive to the compressional- to shear-velocity ratio (Vp/Vs).

[3] Crustal Vp/Vs ratios are typically obtained by seismic tomographic inversions using arrival time data. Previous studies have obtained varied results concerning the relationship between seismicity and Vp/Vs. Association of seismicity with moderate to slightly low Vp/Vs was found at Arthur's Pass [*Bannister et al.*, 2006] and the Taupo Volcanic Zone [*Reyners et al.*, 2006, 2007] of New Zealand, in the seismic zone of New Madrid [*Powell et al.*, 2005], and in active volcanoes of northeast Japan [*Nakajima et al.*, 2001a, 2001b]. However, in the Central Appenines, Italy, it was found that aftershock seismicity mainly occurs within a high Vp/Vs region [*Monna et al.*, 2003]. In addition, *Mishra and Zhao* [2003] identified a high Vp/Vs region in the vicinity of the 2001 Bhuj, India, earthquake hypocenter, and on the Korean peninsula, *Kim and Bae* [2006] found high Vp/Vs ratios near earthquakes. The differences in these studies may be partly due to the resolution of local near-source region Vp/Vs ratios from tomography, which is usually limited due to the ray coverage and finite frequency of the waves.

[4] The high-resolution Vp/Vs estimate method of *Lin and Shearer* [2007] provides a way to obtain details in the near-source region that cannot easily be resolved by tomographic methods. In this study, we show an association of seismically active regions with low Vp/Vs ratios in southern California using observations from both a seismic tomography model and high-resolution local Vp/Vs estimates from within similar earthquake clusters. The high resolution Vp/Vs estimates suggest the presence of water-filled cracks of relatively large aspect ratio and porosities of several percent in earthquake source regions in southern California, although this interpretation must be tempered by the lack of direct evidence for lowered P velocities in the tomography model.

2. Method

[5] We apply the new technique of *Lin and Shearer* [2007], which uses P- and S-wave differential times from waveform cross-correlation to estimate in situ Vp/Vs ratios within similar earthquake clusters. Equation (1) shows the basic idea of this method for a single pair of events in a cluster recorded by a common station *i*.

$$\left(\delta t_s^i - \bar{\delta t_s}\right) = \left(\frac{V_p}{V_s}\right)\left(\delta t_p^i - \bar{\delta t_p}\right) \quad (1)$$

where δt_p^i and δt_s^i are the differential P and S times, and $\bar{\delta t_p}$ and $\bar{\delta t_s}$ are the mean values of the differential times from all the stations. In this way we can estimate the local Vp/Vs ratio using the demeaned differential times from all event pairs in the cluster. In principle, this provides a local measure of the average Vp/Vs within the clusters, which are typically only a few kilometers across. The most accurate Vp/Vs results will be obtained for clusters with a three-dimensional distribution of events because they are less biased by possible differences in the P and S ray paths (refer to *Lin and Shearer* [2007] for more details). In order to estimate the spatial distribution of events in each cluster, we use the method of principal component analysis [e.g., *Kirschvink*, 1980] to compute eigenvalues (λ_i, where $\lambda_1 \geq$

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$\lambda_2 \geq \lambda_3$) for the covariance matrix of the earthquake locations within each similar event cluster. This approach has been applied to analyze seismicity clusters in previous earthquake location studies [e.g., *Michelini and Bolt*, 1986; *Shearer et al.*, 2003]. In this study, we consider the cluster to have an adequate distribution if $\lambda_1/\lambda_3 \leq 5$. We select the 142 event clusters that satisfy this condition, have more than 50 events and 1000 differential times, and have estimated standard errors in Vp/Vs of less than 0.01. These errors are computed using a bootstrap approach [*Efron and Gong*, 1983; *Efron and Tibshirani*, 1991], in which the pairs of differential P and S times in the same cluster are randomly resampled 1000 times. We also analyze the Vp/Vs ratios from the seismic tomographic model of *Lin et al.* [2007b]. Figure 1 shows the locations of the 142 clusters with the tomography model at 10 km depth as background. The clusters are not confined to any particular source region and are widely distributed within the areas of high seismic activity.

3. Results

[6] In Figure 2, we show a histogram of our local Vp/Vs measurements within the similar earthquake clusters (shown by the red curve), together with seismic tomographic Vp/Vs ratios for: (1) all of the southern California crust that is well-resolved in the tomographic model (black curve), (2) at all earthquake locations between 4 and 18 km depth in the LSH catalog (blue curve), the southern California earthquake catalog by Lin, Shearer and Hauksson [*Lin et al.*, 2007a], and (3) at the centroids of the 142 similar event cluster locations (pink curve). For the cluster centroids and the high resolution estimates, the standard errors at the 95% confidence level are computed using a bootstrap approach, in which we randomly resample the Vp/Vs ratios 1000 times. For the southern California crust, we randomly resampled the cells in the resolved part of the tomographic model between 4 and 18 km depth. For the LSH location catalog, we first counted the number of earthquakes in each well-resolved tomographic cell and resampled these cells, and then we computed the median Vp/Vs using all the earthquakes in resampled tomographic cells. The crustal median Vp/Vs ratio is 1.729 ± 0.007, a typical value for rocks in the upper crust. The median Vp/Vs is reduced at the locations of both the crustal seismicity (1.716 ± 0.008) and the similar event clusters (1.715 ± 0.012), with the agreement indicating that the clusters are representative of the overall seismicity. These values are less than the crustal median Vp/Vs (between 1.722 and 1.736), although the error estimates overlap slightly. Notably, the median Vp/Vs ratio for the in situ measurements of 1.673 ± 0.022 is much less than the tomographic-inverted Vp/Vs ratios, suggesting that the tomography results are underestimating the magnitude of the true Vp/Vs anomalies at the cluster locations.

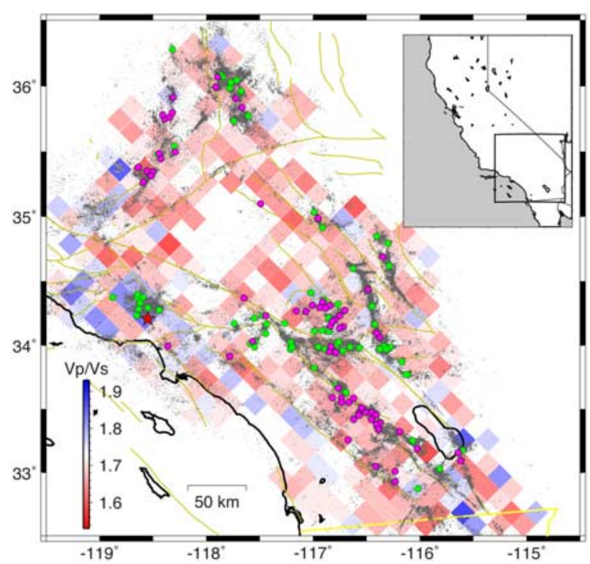

Figure 1. Locations of 142 similar earthquake clusters in our study (big dots), compared to general seismicity (gray dots), and Vp/Vs ratios at 10 km depth estimated from a tomography model (red/blue colors) for southern California. Green dots: clusters with tomographic Vp/Vs ≥ 1.716; pink dots: clusters with Vp/Vs < 1.716. Black lines denote the coast line and lakes, yellow lines are rivers and surface traces of mapped faults. The red star shows the 1994 Northridge mainshock. The square in the inset shows our study area.

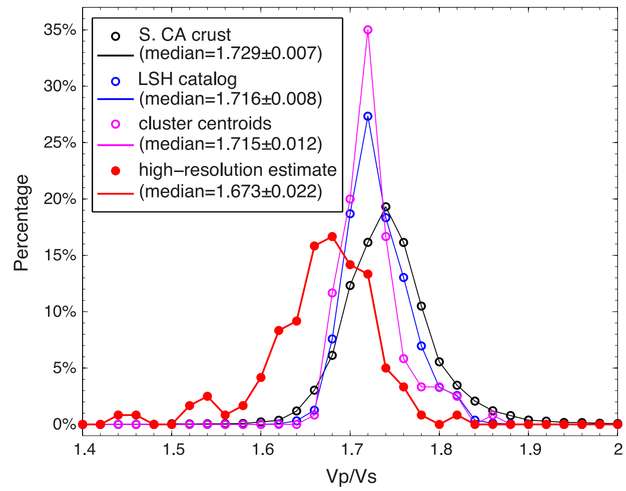

Figure 2. Distribution of Vp/Vs ratios at the cluster and earthquake locations, compared to tomography results for the entire crust.

4. Discussion

[7] In order to determine whether our Vp/Vs observations are affected by any cluster properties, we analyzed their possible dependence on cluster size, depth, duration, median stress-drop and focal mechanism, but we did not find any clear correlations (see auxiliary material for more details).[1] Although there is considerable scatter in the individual Vp/Vs values, which may reflect random measurement errors, the anomalously low median value of 1.673 is a robust result given the criteria of our cluster selection. The corresponding Poisson's ratio is 0.222, which is substantially less than values measured for most common crustal rocks, which typically range from 0.24 to 0.29 [*Christensen*,

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039098.

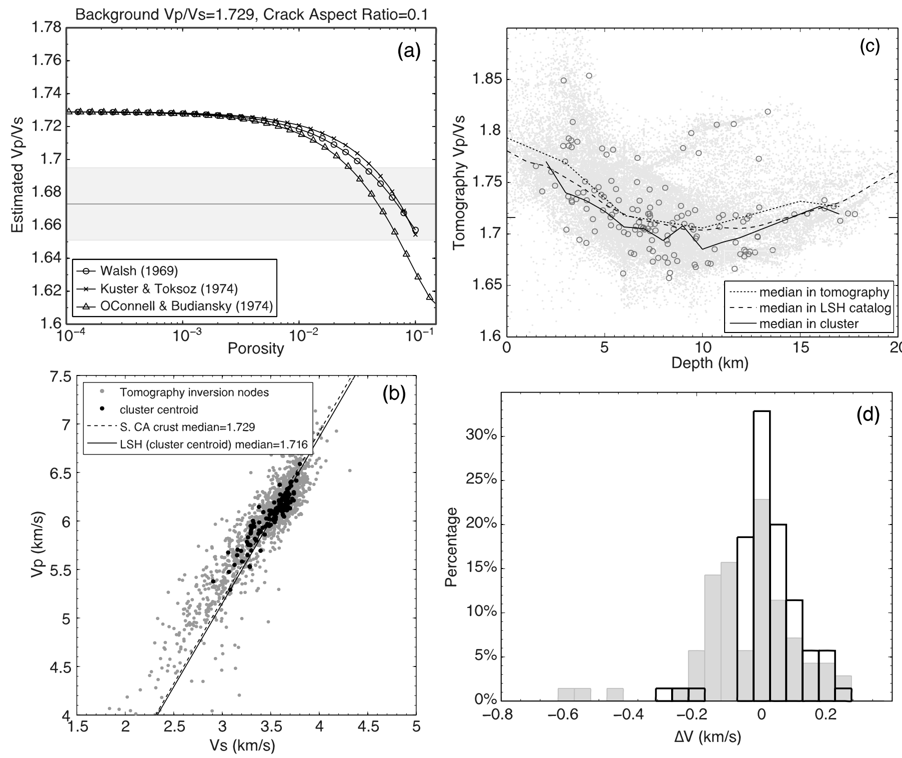

Figure 3. (a) Vp/Vs ratios as a function of porosity according to theoretical crack models. The gray area shows the range of our estimated in situ Vp/Vs ratios between 1.651 and 1.695 with the center at 1.673 shown by the horizontal line. (b) P velocity versus S velocity from the 3D seismic velocity model by *Lin et al.* [2007b]. Gray dots: velocity values at the well-resolved tomographic inversion nodes; black dots: velocities at the similar event cluster centroids. (c) Tomographic Vp/Vs ratio versus depth at the LSH catalog event locations (gray dots) and similar event cluster centroids (black dots). The dotted, dashed and solid lines indicate the median Vp/Vs for the well-resolved tomography model, the LSH catalog and the clusters, respectively. (d) Histograms of S and P velocity perturbations at the centroids of the clusters relative to the mean velocity at the same depth (gray for P perturbations, bin width = 0.05 km/s).

1996]. Pure quartz has a Vp/Vs ratio of about 1.5 and the Poisson's ratio of rocks containing more than about 55% quartz generally decreases for increasing quartz content [*Christensen*, 1996], but our observed value of 0.222 is less than that measured for any likely (uncracked) rock type in the southern California crust, including quartz-rich geisses and schists [*McCaffree and Christensen*, 1998]. Cracks and fractures affect seismic velocities, but only water-filled cracks of large aspect ratio can lower the Vp/Vs ratio of the host rock to the extent that we observe [e.g., *Shearer*, 1988; *Takei*, 2002; *Kurashimo and Hirata*, 2004].

[8] Because this interpretation depends critically upon the reliability of our Vp/Vs measurements, it is important to consider possible sources of bias in our method for estimating local Vp/Vs ratios within similar event clusters using waveform cross-correlation times. This is discussed by *Lin and Shearer* [2007], who performed synthetic tests to assess the accuracy of the technique. The largest potential source of bias occurs when the P and S ray paths are not coincident because of Vp/Vs variations outside of the source region. However, this bias can be minimized by using a dispersed set of stations and selecting clusters with a three-dimensional distribution of seismicity. As discussed above, we characterized the spatial distribution of each cluster using principal component analysis and selected only clusters with $\lambda_1/\lambda_3 \leq 5$. To test whether this affect could nonetheless be biasing our results, we sorted our 142 similar event clusters by their λ_1/λ_3 values. The 71 clusters with the smallest values should be less subject to bias and have a median Vp/Vs value of 1.655, close to the median value obtained for the complete group. We performed a similar test using our individual estimates of standard error in Vp/Vs. The group of 71 events with the smallest standard errors have a median Vp/Vs value of 1.679, again very close to the median value for the entire group. Thus, we conclude that our result is likely a reliable estimate of the true median Vp/Vs ratio within the similar event clusters.

[9] To determine the porosity and crack density that are necessary to lower the Vp/Vs ratio to the observed median value of 1.673 ± 0.022, we apply the theoretical crack models discussed by *Shearer* [1988]. We use crustal median Vp/Vs ratios ranging from 1.722 to 1.736 as the background for the host rock and assume the cracks are ellipsoidal and water-filled (α = 1.5 km s^{-1} and ρ = 1.0 Mg m^3) with crack aspect ratios (d = crack height divided by crack radius) from 0.01 to 0.5. Changes in the background Vp/Vs ratio produce changes in the composite Vp/Vs ratio of similar magnitude, and we find that only thick-crack material with $0.05 \leq d \leq 0.1$ (when $d \ll 1$, material is considered thin-crack) can produce Vp/Vs ratios as low as 1.695 (the upper boundary of our estimated in situ Vp/Vs), even when the background Vp/Vs is set to the lower value of our range. In Figure 3a, we show Vp/Vs ratios as a function of porosity according to these theoretical crack models using a background Vp/Vs of

1.729 and crack aspect ratio of 0.1. The theories of *Walsh* [1969], *Kuster and Toksöz* [1974], and *O'Connell and Budiansky* [1974] all yield fairly similar results, with porosities of 5 to 7% and crack densities of 0.11 to 0.17 required to explain our observed ~3% drop in Vp/Vs. These results are also roughly consistent with the analysis of *Nakajima et al.* [2001a] who applied the method of *Yamamoto et al.* [1981] to model a ~2% drop in Vp/Vs seen beneath active volcanoes in northeast Japan, and obtained porosities of a few percent for water filled cracks of 0.1 aspect ratio. These relatively large porosities suggest an open, connected, crack system, which is likely to have high electrical conductivity.

[10] Because our high-resolution Vp/Vs measurements are only possible within similar event clusters, these results alone cannot establish that these low Vp/Vs values are confined to earthquake source regions. However, receiver function and tomography studies [*Zhu and Kanamori*, 2000; *Lin et al.*, 2007b] have shown that the average crustal Vp/Vs ratio in southern California is 1.73 to 1.78. In addition, the tomography results indicate an association of seismicity with lower Vp/Vs values (see Figures 1 and 2). In principle, tomography results can provide additional constraints by providing absolute P and S velocities. Ideally these velocities would be estimated completely independently of each other, however in practice many tomography codes perform joint inversions for P and S velocities and generally use regularization to enforce at least some correlation between the velocity anomalies. The SIMULPS program [*Thurber*, 1983, 1993; *Eberhart-Phillips*, 1990; *Evans et al.*, 1994] used to generate the tomography model of *Lin et al.* [2007b] solves for both a Vp and a Vp/Vs model; we obtained the velocity values at each similar event cluster centroid by interpolating the model between grid points and computing Vs values by dividing Vp by Vp/Vs. Figure 3b plots P versus S velocity at each cluster centroid (black dots) and the well-resolved (i.e., the resolution diagonal element greater than 0.1) inversion nodes of the seismic velocity model (gray dots); Figure 3c plots the corresponding Vp/Vs ratios versus depth. The clearest trend is that Vp/Vs decreases with depth and this is seen in both the background model and at the locations of the seismicity clusters. The lower average Vp/Vs values for the event clusters compared to the background velocities is a more subtle feature, which only becomes clear in the histogram plot of Figure 2. The high Vp/Vs values for the clusters at shallow depths (Figure 3c) are specific to the tomography model—the high-resolution Vp/Vs estimates exhibit no depth dependence (see auxiliary material). This difference likely reflects the high Vp/Vs values in many of the sedimentary basins and the limited resolution of the tomography model.

[11] To assess whether low Vp/Vs values at the cluster locations in the tomography model are caused more by anomalously low Vp or anomalously high Vs, we computed velocity perturbations at each cluster centroid relative to the average velocity at the centroid depth from the well-resolved tomography inversion nodes. The histograms of these perturbations are shown in Figure 3d. The majority of S velocity perturbations are positive, i.e., greater than the average velocity at the same depth, while P velocity perturbations are almost evenly distributed in both negative and positive directions. This indicates that the decreased average Vp/Vs ratio in the tomography model in earthquake source regions may be more due to higher than average Vs instead of lower than average Vp. This result is inconsistent with our models of fluid-filled cracks specific to earthquake source regions, which would lower both the P and S velocities. However, the resolution of the tomography model is very limited and it remains difficult to explain the median high-resolution Vp/Vs value of 1.673 with any expected rock type in the southern California crust without the presence of thick fluid-filled cracks.

[12] Theoretical results suggest that fluids will have different effects on normal and reverse faulting regimes, depending upon the permeability of the system [*Sibson*, 1991]. We were not able to document a clear difference in Vp/Vs between normal, strike-slip, reverse faulting earthquakes (see auxiliary material), but our analysis is limited by the relatively small number of normal and reverse events in our data set. Anomalously low Vp/Vs ratios have been widely observed in volcanic and geothermal areas [e.g., *Chatterjee et al.*, 1985; *Nakajima et al.*, 2001a, 2001b; *Reyners et al.*, 2007]. Our results suggest that low Vp/Vs anomalies may also be characteristic of active areas of microseismicity, at least in southern California, and thus a more general property of earthquake source regions.

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