High Resolution Surface Wave Tomography From Ambient Seismic Noise

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Submitted to *Science*: December 5, 2004. Accepted by *Science*: January 19, 2005.

Cross-correlating one month of ambient seismic noise recorded at USArray stations in California yields hundreds of short period surface-wave group-speed measurements on inter-station paths. We used these measurements to construct tomographic images of the principal geological units beneath California, with low-speed anomalies corresponding to the main sedimentary basins and high-speed anomalies corresponding to the igneous cores of the major mountain ranges. This method can improve the resolution and fidelity of crustal images obtained from surface wave analyses.

The aim of ambitious new deployments of seismic arrays, such as the PASSCAL and USArray programs (*1*), is to improve the resolution of images of Earth's interior by adding more instruments to regional- and continental-scale seismic networks. Traditional observational methods cannot fully exploit emerging array data because they are based on seismic waves emitted from earthquakes, which emanate from select source regions predominantly near plate boundaries and are observed at stations far from source regions, such as most locations within the United States. With such teleseismic observations, high frequency information is lost due to intrinsic attenuation and scattering and resolution is degraded by the spatial extent of the surface wave's sensitivity which expands with path length (*2–4*). Here we move beyond the limitations of methods based on earthquakes and recover surface wave dispersion data from ambient seismic noise (*5*).

The basic idea of the new method is that cross-correlation of a random, isotropic wavefield computed between a pair of receivers will result in a waveform that differs only by an amplitude factor from the Green function between the receivers (*6, 7*). This property is reminiscent of the fluctuation-dissipation theorem (*8*) which posits a relation between the random fluctuations of a linear system and the system's response to an external force. The relation is widely used in a variety of physical applications, finding its roots in early works on Brownian noise (*9, 10*). Recent results in helioseismology (*11*), acoustics (*12–16*), and seismology (*5, 17*) suggest that such a statistical treatment can be applied to non-thermal random wavefields, in particular to long series of ambient seismic noise because the distribution of the ambient sources randomizes when averaged over long times. Ambient seismic noise is additionally randomized by scattering from heterogeneities within Earth (*18*). Surface-waves are most easily extracted from the ambient noise (*5*) because they dominate the Green function between receivers located at the surface and also because ambient seismic noise is excited preferentially by superficial sources, such as oceanic microseisms and atmospheric disturbances (*19–22*). The seismic noise field is often not perfectly isotropic and may be dominated by waves arriving from a few principal directions. To reduce the contribution of the most energetic arrivals, we disregard the amplitude by correlating only one-bit signals (*15, 17*) before the computation of the cross-correlation.

Examples of cross-correlations between pairs of seismic stations in California appear in Fig. 1 (*23*). Cross-correlations between two station pairs (MLAC - PHL, SVD - MLAC) in two short period bands (5 s - 10 s, 10 s - 20 s) are presented using four different one month time series (January, April, July, October 2002). For each station-pair, results from different months are similar to one another and to the results using a whole year of data, but differ between the station-pairs. Thus, the emerging waveforms are stable over time and characterize earth structure between the stations. In addition, the cross-correlations of noise sequences are very similar to surface-waves emitted by earthquakes near one receiver observed at the other receiver. This confirms that the cross-correlations approximate Green functions of Rayleigh waves propagating between each pair of stations and that one month of data suffices to extract Rayleigh wave Green functions robustly in the period band of interest here (7 s - 20 s)

We selected 30 relatively quiescent days (during which no M>5.8 earthquakes occurred) of continuous 1 sample per second data from 62 USArray stations within California (*24*) from August and September 2004. Short period surface wave dispersion curves are estimated from the Green functions using frequency-time analysis (*25–27*) from the 1891 paths connecting these stations. We rejected waveforms with "signal-to-noise" ratios smaller than 4 and for paths shorter than two wavelengths, resulting in 678 and 891 group speed measurements at periods of 7.5 s and 15 s, respectively (Fig. S2). We then applied a tomographic inversion (*28*) to these two data sets to obtain group speed maps on a 28 km $\times$ 28 km grid across California (Fig. 2). The maps produced variance reductions of 93% and 76% at 7.5 s and 15 s, respectively, relative to the regional average speed at each period. To test the robustness of the inversion, we applied the same procedure to a second month of data and produced similar tomographic maps (Fig. S3) The resolution of the resulting images is about the average inter-station distance, between 60 and 100 km across most of each map (Fig. S4).

A variety of geological features (*29*) are recognizable in the estimated group-speed dispersion maps (Fig. 2). For the 7.5 s Rayleigh wave, which is most sensitive to shallow crustal structures no deeper than about 10 km, the dispersion map displays low group speeds for the principal sedimentary basins in California, including the basins in the Central Valley, the Salton Trough in the Imperial Valley, the Los-Angeles Basin, and the Ventura Basin. Regions consisting mainly of plutonic rocks (e.g., the Sierra Nevada, the Peninsular Ranges, the Great Basin, and the Mojave Desert region) are characterized predominantly by fast group speeds. Somewhat lower speeds are observed in the Mojave Shear Zone and along the Garlock fault. The Coast Ranges, the Transverse Ranges, and the Diablo Range which are mainly composed of sedimentary rocks are characterized by low group speeds, with the exception of the Salinian block located south of Monterey Bay.

For the 15 s Rayleigh wave, sensitive mainly to the middle crust down to depths of about 20 km, very fast group speeds corresponds to the remnants of the Mesozoic volcanic arc: the Sierra Nevada and the Peninsular Ranges composed principally of Cretaceous granitic batholiths. The map also reveals the contrast between the western and eastern parts of the Sierra Nevada (*30*). The group speeds are lower in the Great Basin and in the Mojave Desert, indicating that the middle crust in these areas is probably hotter and weaker than in the Sierra Nevada. In the Central Valley, slow group speeds are associated with two deep sedimentary basins, the San Joaquin Basin in the south and the Sacramento Basin in the north separated in the middle by the igneous dominated Stockton Arch (*31*). Group speeds are low in the sedimentary mountain ranges; e.g., the Transverse Ranges, the southern part of the Coast Ranges, and the Diablo Range. Neutral to fast wave speeds are observed for the Salinian block. In this area, the 15 s map shows a contrast between the high speed western wall of the San-Andreas fault, composed of plutonic rocks of the Salinian block, and its low-speed eastern wall composed of sedimentary rocks of the Franciscan formation.

These results establish that Rayleigh wave Green functions extracted by cross-correlating long sequences of ambient seismic noise, which are discarded as part of traditional seismic data processing, contain information about the structure of the shallow and middle crust. The use of ambient seismic noise as the source for seismic observations addresses several shortcomings of traditional surface wave methods. The method is particularly advantageous in the context of temporary seismic arrays such as the Transportable Array component of USArray or PASSCAL experiments because it can return useful information even if earthquakes do not occur. The short period dispersion maps produced by the method can provide homogeneously distributed information about shear wave speeds in the crust which are hard to acquire with traditional methods. The new method enhances resolution because measurements are made between regularly spaced receivers which may lie much closer to one another than to earthquakes.

It may seem initially surprisingly that deterministic information about the Earth's crust can result from correlations of ambient seismic noise. This result reminds us that random fluctuations can, in fact, yield the same information as provided by probing a system with an external force (*9*) and that not all noise is bad. In seismology, external probing through active seismic sources (e.g., explosions) may be prohibitively expensive and earthquakes are both infrequent and inhomogeneously distributed. In many instances, merely "listening" to ambient noise may be a more reliable and economical alternative.

Competing interests statement.

The authors declare that they have no competing financial interests.

References and Notes

1. USArray (www.iris.iris.edu/USArray) is one of the components of the new EarthScope (www.earthscope.org) initiative in the United States. PASSCAL is the Program for the Array Seismic Studies of the Continental Lithosphere (www.iris.edu/about/PASSCAL), a program of the Incorporated Research Institutions for Seismology (IRIS, www.iris.edu).

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system (www.trinet.org), 17 permanent stations of the Berkeley Digital Seismic Network (quake.geo.berkeley.edu/bdsn), 2 permanent stations of the Anza Seismic Network (eqinfo.ucsd.edu/deployments/anza.html), and 3 new USArray stations.

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33. The data used in this work were obtained from the IRIS Data Management Center. We are also particularly grateful to Mikhail Barmin for help with the tomographic code and to Peter Goldstein for clarifications about the SAC program. We thank Craig Jones for a tutorial on the geology of California and Eric Larose, Oleg Lobkis, Ludovic Margerin, Roger Maynard, Anne Paul, Bart van Tiggelen, and Richard Weaver for helpful discussions. We acknowledge the support from CNRS/INSU (program DyETI) and CEA (France).

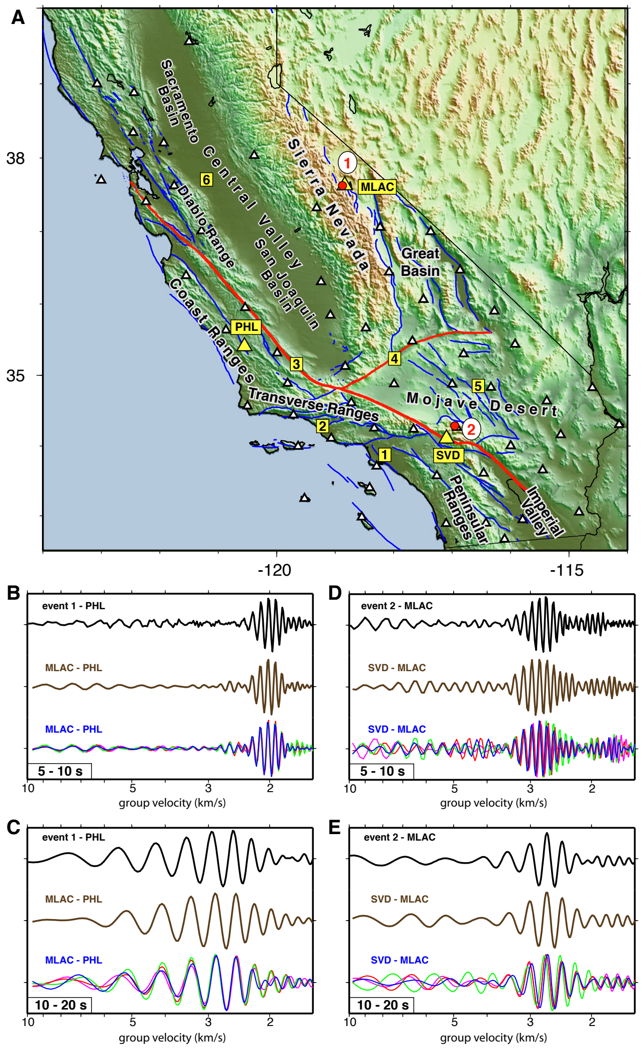

Figure 1: Waveforms emerging from cross-correlations of ambient seismic noise compared with Rayleigh waves excited by earthquakes. (A) Reference map showing the locations of the principal geographical and geological features discussed in the test. White triangles show the locations of the USArray stations used in this study (5 of the 62 stations are located north of 40°N). Blue and red solid lines are locations of known active faults. Yellow rectangles with digits indicate the following features: (1) Los Angeles Basin; (2) Ventura Basin; (3) San Andreas fault; (4) Garlock fault; (5) Mojave shear zone; and (6) Stockton Arch. (B) Comparison of waves propagating between stations MLAC and PHL (yellow triangles), bandpassed between 5 and 10 s period. The upper trace (black) is the signal emitted by earthquake 1 (red circle in A) near MLAC observed at PHL, the middle trace (gold) is the cross-correlation from one year of ambient seismic noise observed at stations MLAC and PHL, and the lower traces are cross-correlations from four separate months of noise observed at the two stations in 2002 (magenta – January, red – April, green – July, blue – October). The earthquake-emitted signal was normalized to the spectrum of the cross-correlated ambient noise. (C) Similar to (B), but with the bandpass filter between 10 s and 20 s period. (D) Similar to (B), but between stations SVD and MLAC (yellow triangles). Earthquake 2 is near station SVD observed at station MLAC. (E) Similar to (D), but with the bandpass filter between 10 s and 20 s period.

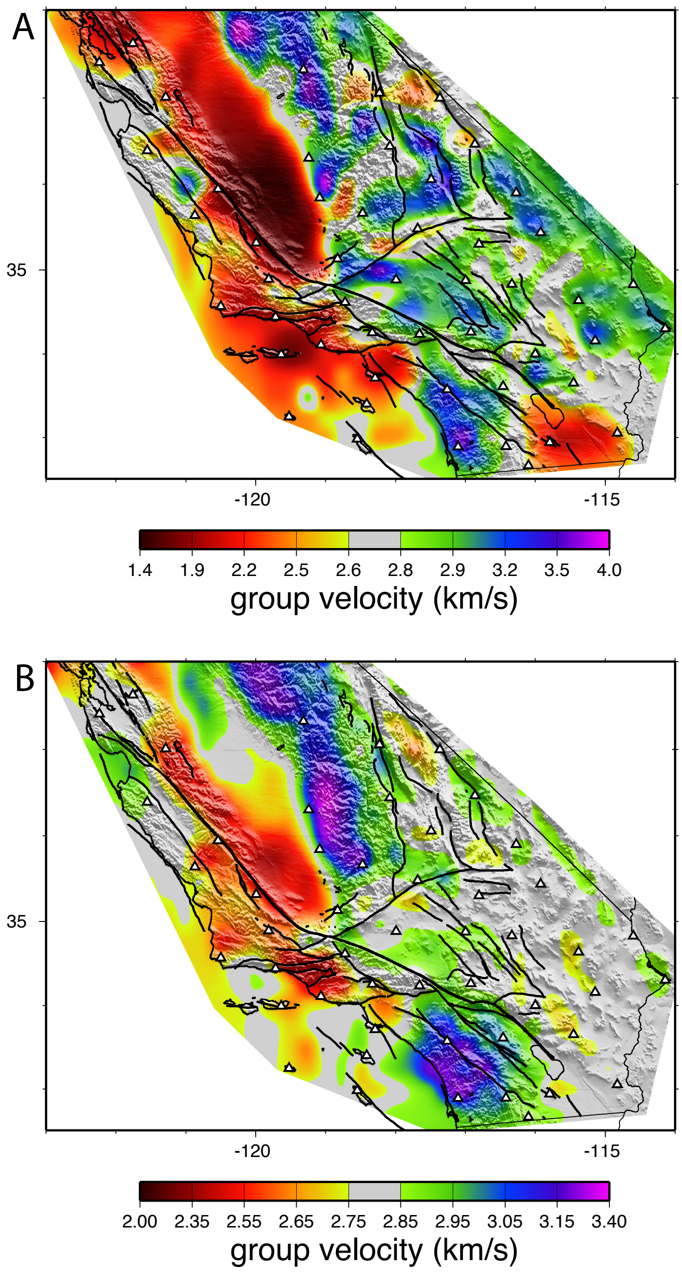

Figure 2: Group speed maps constructed by cross-correlating 30 days of ambient noise between USArray stations. (A) 7.5 s period Rayleigh waves. (B) 15 s period Rayleigh waves. Black solid lines show known active faults. White triangles show locations of USArray stations used in this study. Similar maps from a different 1 month of data are shown in the Supplementary Materials.