Ambient noise seismic imaging

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Abstract:	A recent innovation in seismic imaging based on using long time sequences of ambient seismic noise moves beyond some of the limitations imposed on earthquake-based methods to reveal higher resolution information about the crust and uppermost mantle. This method is called Ambient Noise Tomography (ANT), and has been applied predominantly to seismic surface waves. With the application of ANT to data from ambitious new deployments of seismic arrays, such as the EarthScope USArray in the United States, improved seismic models of the earthâ□□s crust and uppermost mantle at unprecedented resolution are rapidly emerging.

Ambient Noise Seismic Imaging

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Introduction

Traditional seismic imaging of large-scale structures within Earth's interior is based on observations of surface displacements following earthquakes or human-caused explosions. These methods measure body and surface wave travel times as well as whole waveforms typically following earthquakes, because of the expense and environmental impact of explosive sources. Such measurements are unraveled (inverted) to reveal the isotropic and anisotropic variation of compressional (Vp) and shear (Vs) wave speeds in Earth's crust, mantle, and core that are then interpreted in terms of temperature, composition, and fluid content. The ability of earthquake-based methods to resolve structural features within the Earth degrades during the propagation of the wave over long (teleseismic) distances. For seismic surface waves (Rayleigh and Love waves), teleseismic transmission results in the loss of the high frequencies needed to infer information about Earth's crust and uppermost mantle. A recent innovation in seismic imaging based on using long time sequences of ambient seismic noise moves beyond some of the limitations imposed on earthquake-based methods to reveal higher resolution information about the crust and uppermost mantle. This method is called Ambient Noise Tomography (ANT), and has been applied predominantly to seismic surface waves. With the application of ANT to data from ambitious new deployments of seismic arrays, such as the EarthScope USArray in the United States, improved seismic models of the earth's crust and uppermost mantle at unprecedented resolution are rapidly emerging.

The idea of ambient noise tomography

Between earthquakes, seismometers continuously record surface displacements with a wide range of causes; e.g., wind, atmospheric pressure variations, fluid flows beneath and on the surface, human and animal motions, and ocean waves. Seismic waves produced by ocean waves, called microseisms, are particularly well studied and are observed to propagate deep into continental interiors. Microseismic amplitudes peak near 8 sec and 16 sec period, but extend to longer periods merging into the somewhat more enigmatic, but increasingly well studied, "earth hum" at periods above 20 sec. Debate continues into whether earth hum is generated predominantly in shallow waters like microseisms, or in deep waters. Recent evidence presented by B. Romanowicz and collaborators and others indicates that it is predominantly a shallow water phenomenon, but this does not preclude a deep water component.

Any mechanism that produces waves that propagate coherently between a pair of seismometers can be used as a basis for seismic tomography. This idea has a long history in seismology, but was resurrected by R. Weaver and O. Lobkis and other researchers in a series of papers beginning in 2001 that showed in the laboratory and theoretically that cross-correlations between recordings of diffuse waves at two receiver locations yield the "Green's function" between these positions. The Green's function is a seismic waveform that contains all of the information about wave propagation in the medium between the two stations. Once estimated, traditional seismic methods of tomography then can be applied to the Green's function to recover information about the medium of transport.

The relevance of these results to large-scale earth imaging was not immediately clear, because the Earth's ambient noise field, containing as it does energetic microseismic energy, is not diffuse, is probably not homogeneously distributed in azimuth, and its frequency content was poorly understood. In 2004, N. Shapiro and M. Campillo showed that coherent Rayleigh surface waves can be extracted from the Earth's ambient noise field and that the primary frequency content of the waves lies in the microseismic and earth hum bands from about 6 sec to 100 sec period with the highest amplitudes in the microseismic band. Subsequent studies have confirmed that the full Green's function does not emerge from cross-correlating seismic data because the cross-correlations are

dominantly surface waves, with Love waves also being observable. Nevertheless, the ability to constrain surface wave speeds at periods from 6 to 20 sec, which are sensitive to crustal depths but difficult to measure from teleseismic earthquakes, provided much of the early interest in the method.

Observations of broad-band surface waves

Seismic surface waves, in contrast with body waves, are waves that propagate in a waveguide near Earth's surface. The depth extent of the waveguide depends on wavelength; with a fair approximation being about a third of a wavelength. Thus, surface waves with periods below about 20 sec are sensitive to the crust and waves between 20 and 100 sec period are sensitive predominantly to the uppermost mantle to a depth of about 150 km. Both Rayleigh (vertically polarized waves) and Love (horizontally polarized waves transverse to the direction of motion) waves are dispersive; their speeds depend on frequency with lower frequencies typically traveling faster than higher frequencies.

Surface waves appear strongly on cross-correlations of ambient noise and their dispersion characteristics are readily identifiable (Figure 1). G. Bensen and collaborators presented a primer on ambient noise data processing in 2007. They provide methods for removing earthquakes and instrumental irregularities from seismograms prior to cross-correlation and show that longer time series (a year or more) homogenize the azimuthal content of ambient noise, that reliable measurements require a station separation of at least two wavelengths, and that uncertainties can be estimated from the temporal repeatability of the measurements.

The production of maps of the speed of Rayleigh or Love waves as a function of frequency is called surface wave tomography. What has come to be known as ambient wave tomography (ANT) is the generation of such maps from inter-station ambient noise cross-correlations. The first ambient noise tomographic images of Rayleigh wave group speeds in the micrsoseismic band were presented simultaneously by N. Shapiro and collaborators and K. Sabra and collaborators in 2005 based on one to several months of data from stations in southern California. These studies were followed by a multiplicity

of applications around the world including studies in Europe, New Zealand, South Africa, Korea, Japan, Iceland, Canada, Australia, and China in addition to the US. Both Rayleigh and Love wave dispersion maps are now commonly obtained at periods from 6 sec to 100 sec with the spatial extent of the study ranging up to the continental scale and time series lengths of more than 4 years used in some cases. ANT is most powerfully applied to large deployments of seismometers, such as the Transportable Array (TA) component of EarthScope/USArray (Figure 2), which includes more than 400 broad-band seismometers deployed concurrently with a station separation of about 70 km and is presently sweeping across the US. F. Lin and collaborators show that the resolution of ANT applied to EarthScope TA data is better than the inter-station spacing, which is unprecedented over an area the size of the western US. The construction of similar large-scale deployments of seismometers is occurring or planned in China and Europe.

There has remained pockets of concern among seismologists that ambient noise in the Earth does not meet the theoretical conditions on which ANT rests. In particular, the worry has been that the azimuthal inhomogeneity of ambient noise may, at worst, vitiate the method and, at best, generate biased measurements. Studies of the directionality of ambient noise published in 2006 and 2008 by L. Stehly and Y. Yang and their respective collaborators demonstrate that with the use of time series of a year or more in length, ambient noise propagates across a wide range of azimuths although there maybe some preferred directions. Simulations of the observed azimuthal content of ambient noise establish that measurement bias is small relative to other sources of measurement error.

3D images of Earth's interior

The purpose of ANT is not just to reveal the speed of surface waves at different periods (Figure 2), but to use this information to unveil the three-dimensional (3-D) variation of seismic waves in Earth's interior in order to advance knowledge of temperature, composition, and fluid content which hold the key to the understanding of Earth processes. Recent studies, such as that by Y. Yang and collaborators in 2008 for the western US, which inverted ambient noise and earthquake derived information simultaneously, are now providing 3-D images of the crust and uppermost mantle over large areas in unprecedented detail (Figure 3). ANT provides not only better lateral

resolution over traditional surface wave methods in regions with good station coverage, but its broad frequency content, which extends to periods below 10 sec, also gives the vertical resolution needed to resolve crustal from mantle structures clearly.

Applications other than earth imaging

Ambient noise can be exploited constructively in other contexts than Earth imaging. Other bodies in the solar system, for example, have been targets for the method. T. Duvall and collaborators in 1993 established time-distance seismology on the Sun (helioseismology) based on cross-correlating intensity fluctuations observed on the solar surface. In 2005, E. Larose and collaborators correlated seismic noise on the Moon's surface taken from the Apollo 17 Lunar Seismic Profiling Experiment, estimated Rayleigh wave group speeds between frequencies of 4 and 11 Hz, and inverted them to provide new information about the lunar regolith. They also established that the Sun actively generates the lunar seismic noise because of strong thermal gradients induced during the lunar day. These results suggest the extension of ambient noise tomography to planetary exploration where the origin of the noise may be quite different than on Earth. Back on Earth, variations in cross-correlations between stations can provide information about the changing state of the shallow crust that may, for example, precede volcanic activity or possibly earthquakes. In 2008, for example, F. Brenguier and collaborators showed how seismic wave speeds determined from ambient noise decreased before eruptions of the Piton de Fournaise volcano, presumably attributable to pre-eruptive inflation caused by increased magma pressure.

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Related Web Sites

EarthScope: http://www.earthscope.org or http://www.iris.edu

Ambient noise tomography in the US: http://ciei.colorado.edu/ambient_noise

Figure Captions

Figure 1. Cross-correlation between two years of ambient noise recorded on the vertical components of two seismic stations in the western US. The stations are EarthScope/USArray Transportable Array stations M03 (McCloud, CA) and Y14A (Wickenburg, AZ) separated by a distance of 1144 km. Arrivals at positive and negative times are for waves traveling in opposite directions between the stations. Rayleigh waves arrive at times between 200 sec and 500 sec. (a) The broad-band cross-correlation is shown. (b) – (d) Band-pass filters are applied to the broad-band cross-correlation centered on 10 sec, 20 sec, and 50 sec period, respectively. The longer periods are seen to travel faster, indicative of the dispersive nature of the Rayleigh wave. (Figure courtesy of Morgan Moschetti.)

Figure 2. Rayleigh wave group speed map at 8 sec period across the western US determined by ambient noise tomography applied to more than two years of data from the EarthScope/USArray Transportable Array. Slow wave speeds are shown in white and faster speeds are indicated with darker shades of grey. Black lines delineate geological provinces. The 8 sec Rayleigh wave is sensitive to about the top 10 km of the crust beneath the surface. Slow speeds are associated with sedimentary basins (e.g., Central Valley in CA, Salton Trough in CA, Green River Basin in WY), deformed regions (e.g.,

CA coastal ranges, Olympic Peninsula in northwest WA; Yakima Fold Belt in central WA), and very hot areas (e.g., Yellowstone in WY). Faster regions are correlated with mountain belts (e.g., Sierra Nevada in CA; Cascade Range in CA, OR, WA; Peninsular Range in southern CA and Baja Mexico), massive flood basalts in OR and WA, and the Colorado Plateau near the Four-Corners region. (Figure courtesy of Morgan Moschetti.)

Figure 3. Images of the 3-D variation of shear wave speed (Vs) in the crust and uppermost mantle determined from ambient noise and earthquake information. (a) Horizontal slice at 100 km depth. (b) Vertical profile underlying the white line in (a). Vertically exaggerated surface topography is presented at top and the black line indicates the Mohorovicic discontinuity, separating the crust from the mantle. In both panels, Vs is presented as the perturbation in percent from the average at each depth across the model. Numerous features are imaged in the crust and mantle. For example, in the mantle the subducting Juan de Fuca and Gorda plates are seen as high Vs beneath N. CA, OR, and WA in both (a) and (b). In (b), the high Vs subducting plate is overlain by low Vs speeds (high temperature and volatile content) beneath active volcanoes in the Cascade Range. (Figure courtesy of Yingjie Yang.)

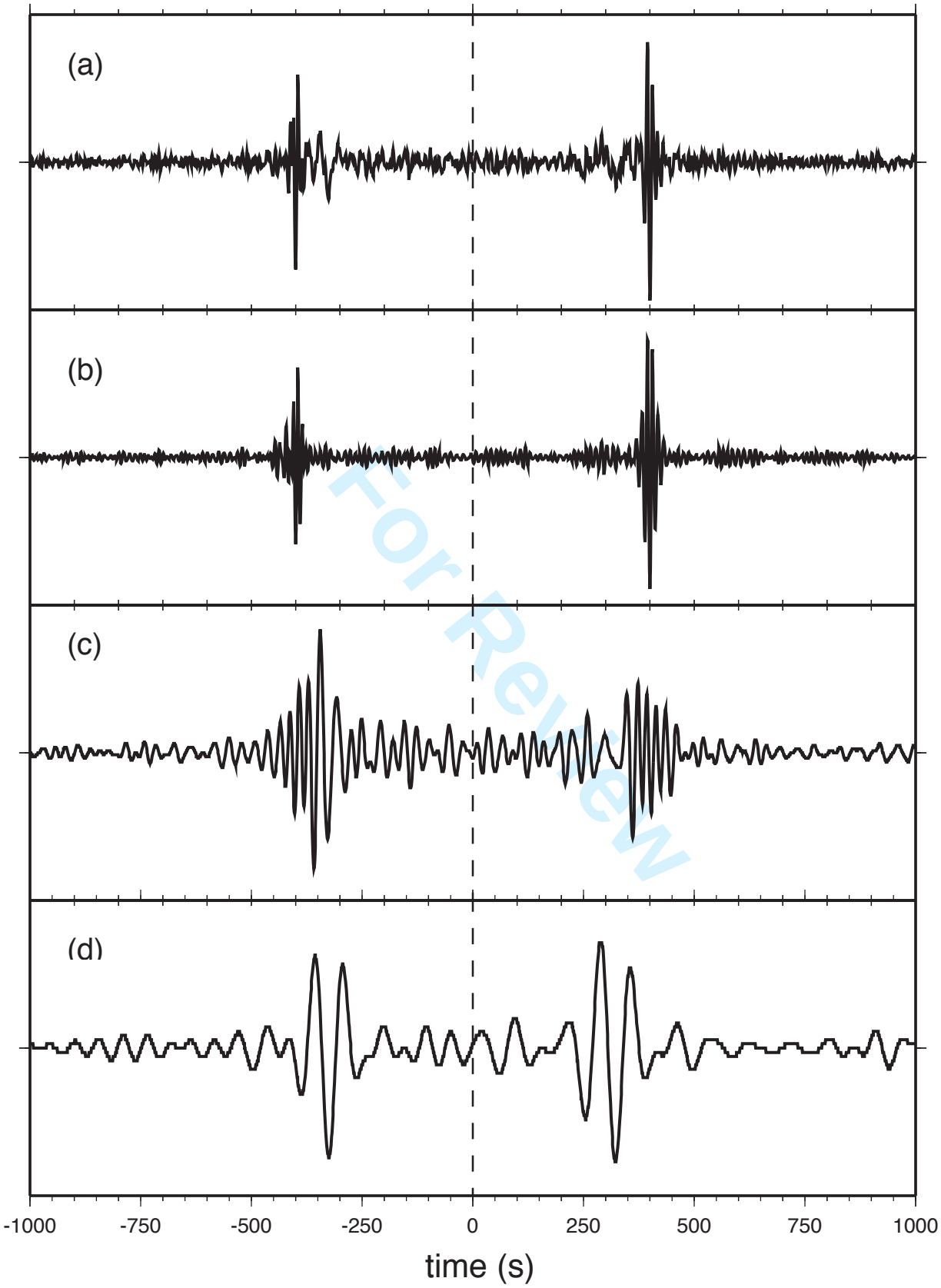


Figure 1

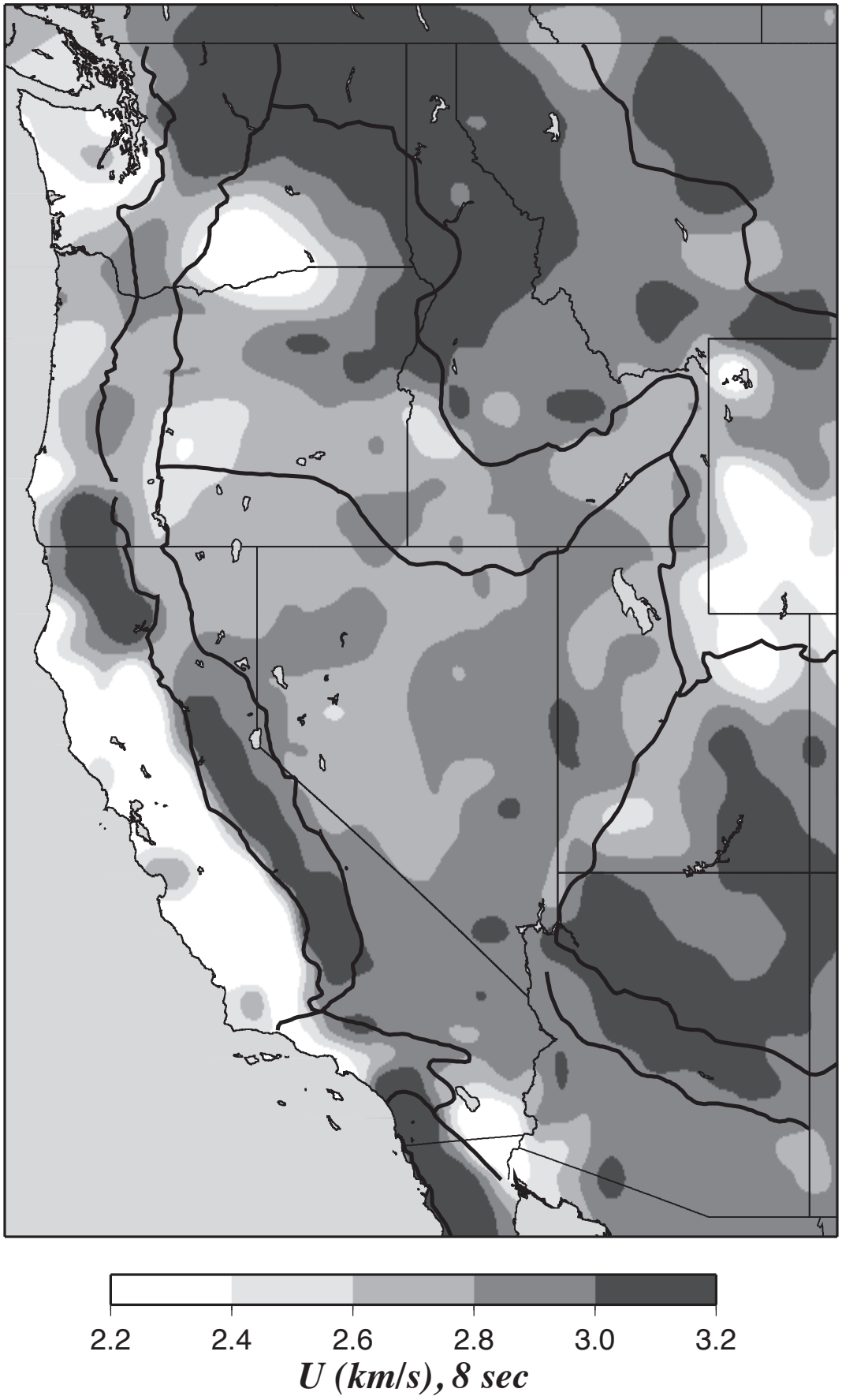
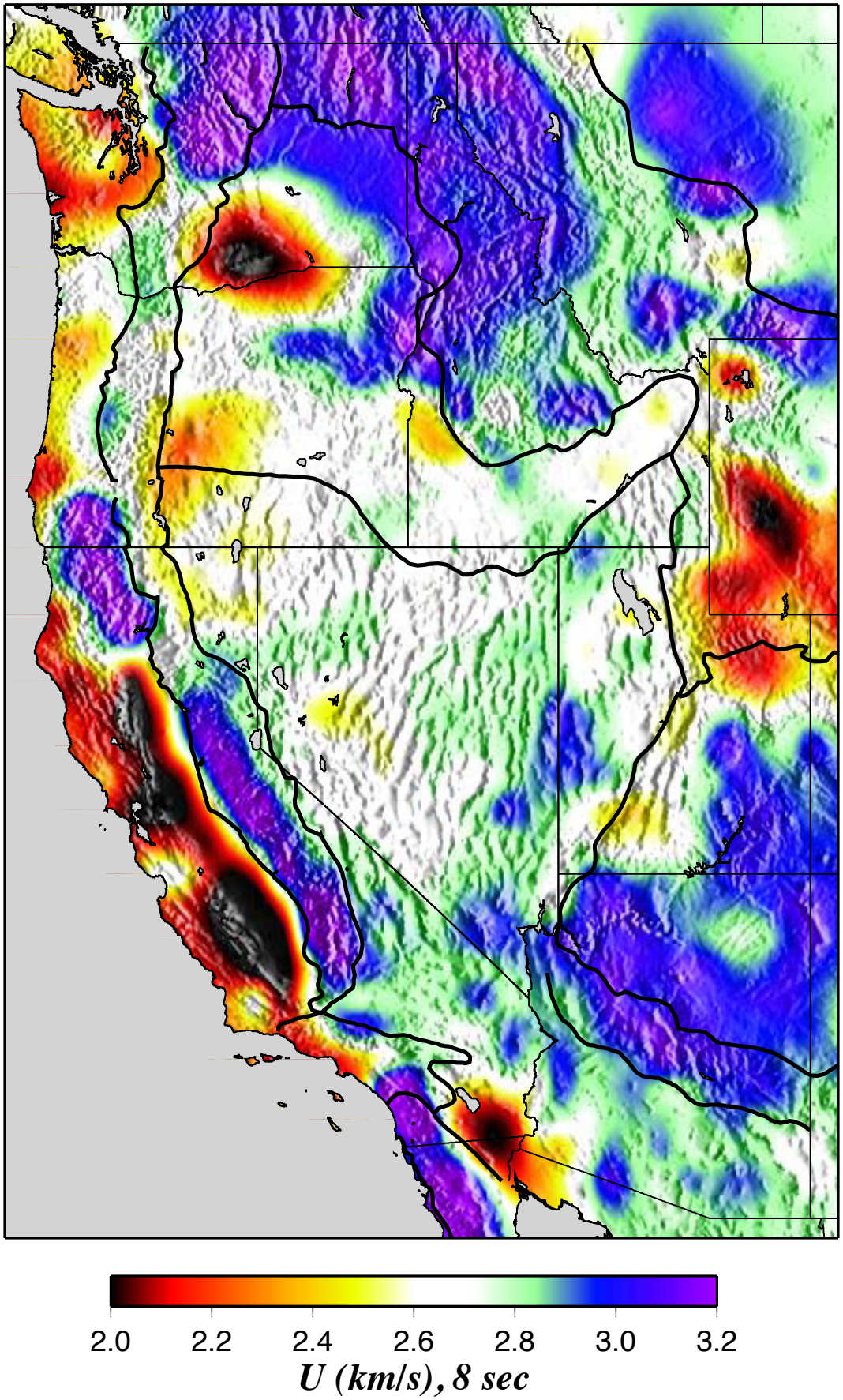


Figure 2 (black & white)



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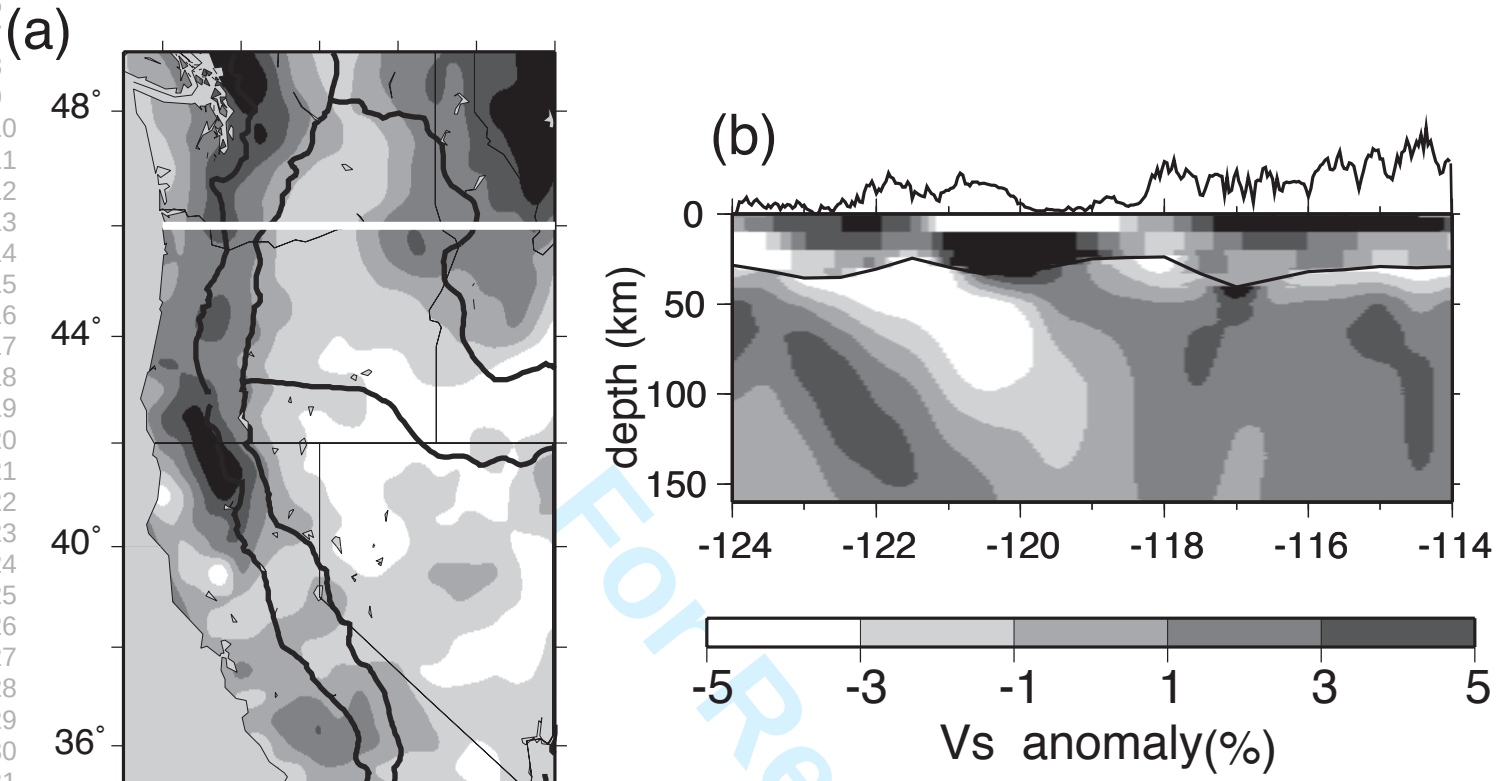

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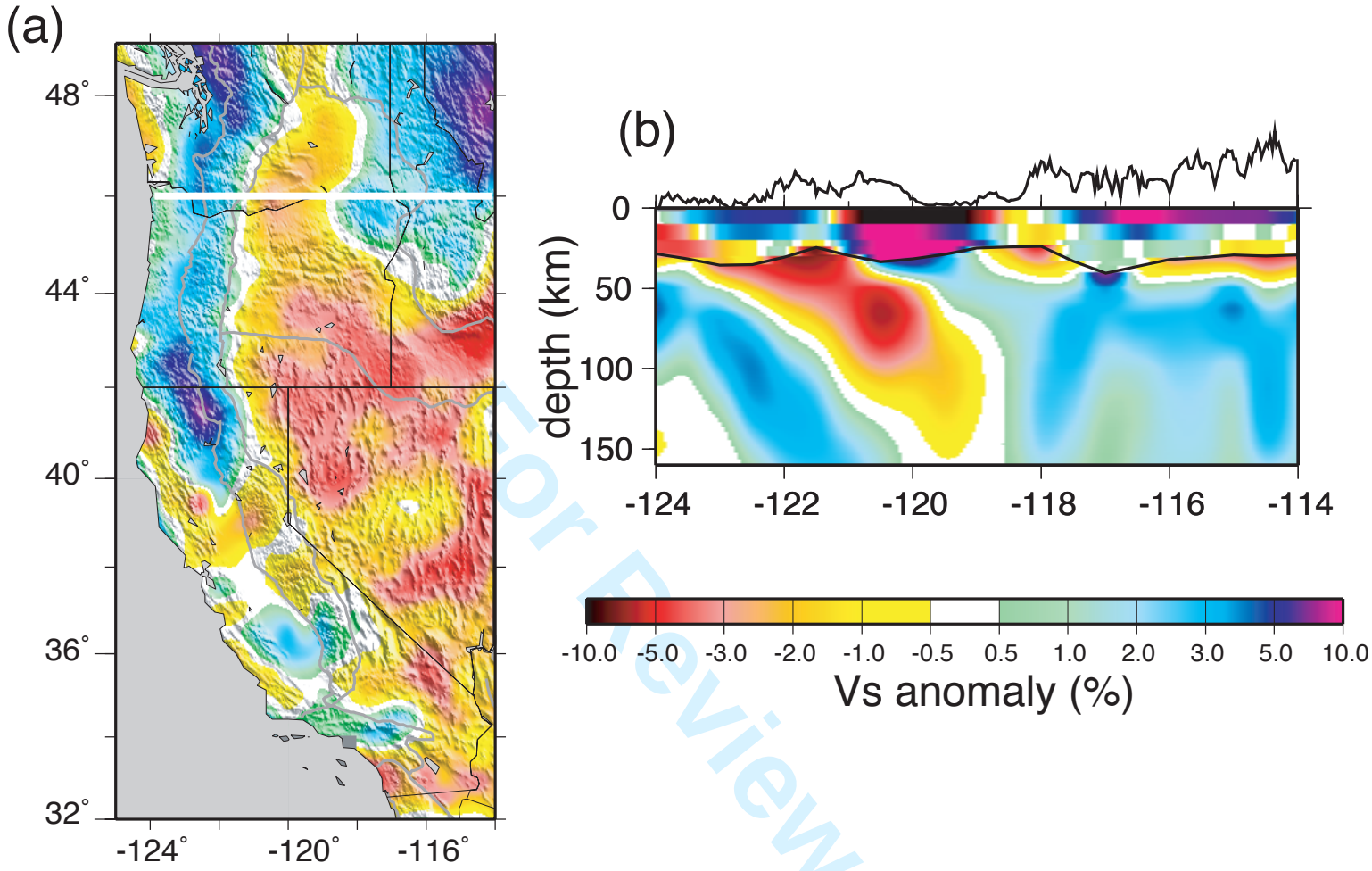

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