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Array Seismology Advances Research Into Earth's Interior

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The densification of regional seismic networks, the proliferation of temporary portable seismometer deployments, and the increasing ease with which traditional seismic array data may be obtained all facilitate a new wave of imaging Earth's interior at the shortest-ever possible scale lengths using array methods. In fact, seismic array techniques are often necessary for retrieval of subtle, yet important, deep Earth seismic structures, particularly those containing fine-scale features.

While only a handful of investigations over the past few decades have used traditional seismic array processing for imaging Earth's deep interior, the recent data renaissance in our community enables utilization of methods once predominantly devoted to the near surface for peering deep into the planet, from upper mantle discontinuities to the solid inner core, from the earthquake source to near-surface receiver structure.

Thus, it is anticipated that this branch of seismology will become increasingly important in the pursuit of deciphering Earth structure and the earthquake source in unprecedented detail, especially with the emergence of the U.S. National Science Foundation (NSF)-funded USArray of the EarthScope initiative (see http://www.earthscope. org). Presented here are a brief outline of the history of seismic arrays, several array methods that enhance seismic wave field resolution, and some current developments in array seismology.

In the early 1960s, seismology experienced a boost in funding and interest due to its utility in monitoring underground nuclear explosions. Following the 1958 conference of scientific experts at Geneva, a new seismological instrument was developed that has proven its benefits both for nuclear explosion monitoring and Earth structure studies. These "new" instruments were seismic arrays, a multitude of seismometers installed with an aperture of a few to a few hundred kilometers. Seismic arrays work similarly to arrays in other disciplines—for example, sonar, radar, radio astronomy, optics, acoustics, and infra sound—and are described by the same mathematical principles.

An array is considered to be any deployment of seismometers that satisfies the following criteria: (1) three or more seismometers; (2) an aperture of more than 1 and less than a few hundred kilometers; (3) uniform instrumentation and recording; (4) a means of analysis of the data as an ensemble, rather than in separate channels; and (5) a common time signal [*Davies et al.*, 1971]. This definition applies to classical short-period arrays as well as the larger permanent and temporary broadband seismometer networks that have proliferated recently. Stations should be separated by at least 2 km to minimize noise coherency, and the total aperture should be less than ~200 km for maximum signal coherency. After the 1958 Geneva conference, the first arrays were installed in Arizona, Oregon, Tennessee, and Utah. These employed a symmetrical distribution of up to 16 short-period seismometers, with apertures of less than 10 km, and were mainly used to gather knowledge about noise conditions and array capabilities for further array installations.

The United Kingdom Atomic Energy Administration (UKAEA) subsequently installed arrays on five continents (Eskdalemuir, U.K.; Yellowknife, Canada; Gauribidanur, India; Warramunga, Australia; and Brasilia, Brazil) configured as two roughly perpendicular ~20-km lines, totaling 18–20 seismometers each. Most of the UKAEA installations are still operative today (Figure 1), and many data are available. In 1964, the United States constructed the Large Aperture Seismic Array (LASA) in Montana, the largest-ever seismic array, with more than 500 short-period stations and an

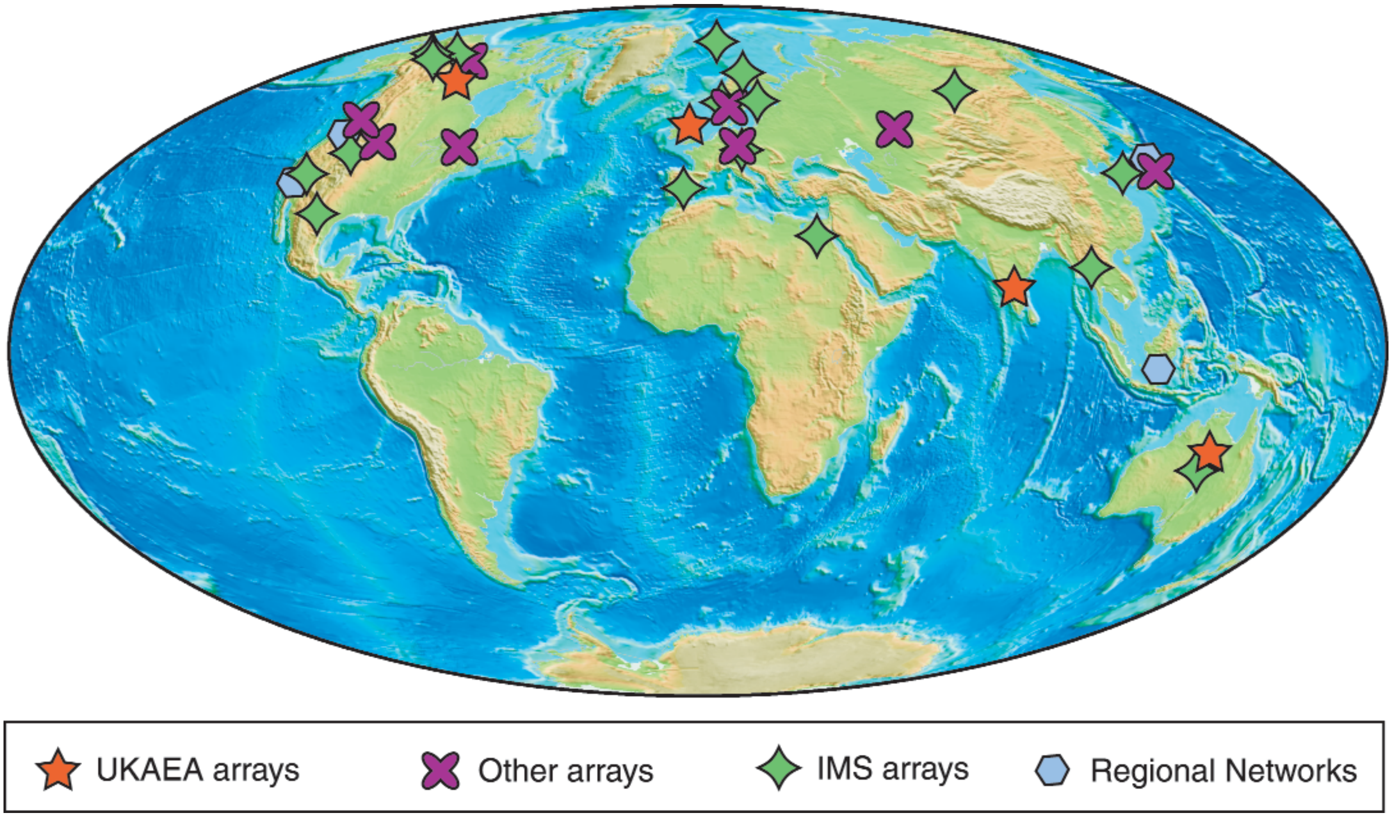

Fig. 1. Map of sample array installations. The background shows the ETOPO5 topography model from the National Geophysical Data Center (Boulder, Colorado). Symbols correspond to different array types. "Other arrays" are installations like LASA, NORSAR, or Graefenberg (GRF), but also arrays of the Canadian POLARIS consortium. Locations of regional networks, e.g., TriNet (California), JISNET (Indonesia), and J-Array (Japan), are also shown.

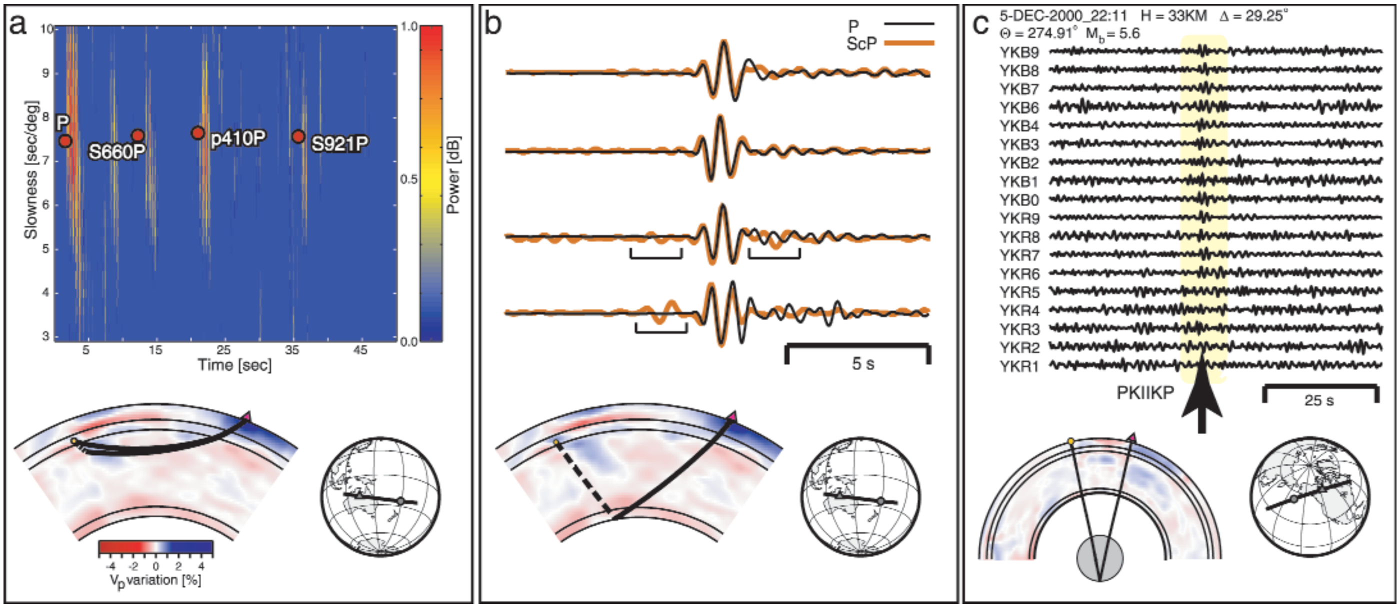

Fig. 2. Examples of array applications that enable the detection of fine-scale structure throughout the Earth. (a) Nth root vespagram of data from the Warramunga array (WRA). The time window shown includes the P arrival and its coda. Arrivals (reflections and conversions) from the upper mantle discontinuities (e.g., S660P, p410P) are marked. Later in the P-coda, a conversion from a depth of 921 km is seen. Also shown is a map view of source and receiver and a cross section through the Karason and van der Hilst P-wave tomography model [2001] (below) with the ray paths for P and S921P. The cross section shows that the existence of S921P may be due to the presence of the subducted Tonga slab. (b) Examples of P (black) and ScP (red) beam-formed wave forms from WRA. Each P and ScP pair is from a different Tonga-Fiji event. Beam-forming increases the SNR of the arrivals and makes the detection of precursors and post-cursors to ScP possible, which, when present, indicate fine layering at the CMB. (c) Detection of the inner core phase PKIIKP in data from Yellowknife. Raw data are shown. Insets show source receiver geometry (top) and cross section (bottom). The identification of the arrival as PKIIKP was done using the travel time and slowness information from Nth root vespagrams and frequency-wavenumber analysis (not shown).

aperture of ~200 km. While LASA was dismantled in 1978, the similarly designed (but half the aperture) NORSAR array in Norway is still operative today. Also noteworthy is the National Science Foundation-supported portable seismometer array program of the Incorporated Research Institutions for Seismology (IRIS; see http://www.passcal.nmt.edu).

These and other important arrays are listed on an array resource Web page (http://arrayseismology.asu.edu). Readers are invited to contribute array location, type, and processing information to this Web page. In recent years, many dense, permanent seismometer networks were built or fortified (Figure 1) and provide many of the advantages of classical arrays, but do not follow traditional array designs.

Network apertures sometimes span over several hundred kilometers and contain sufficient station density for array methods to be employed. In the following, the term "array" is used for both the classical arrays and such distributed networks.

Arrays have several advantages over the use of single-station recordings. If an array is larger than one horizontal wavelength of the energy of interest, then the time lag of a transient signal arriving at individual array stations is a direct measure of the incoming wave field's directivity (vertical incidence angle = slowness; horizontal angle = back azimuth). Since noise at different array stations should be relatively incoherent, a station summation after removing the time lag (delay-and-sum) for a specific slowness and back azimuth results in an increased signal-to-noise ratio (SNR) for that particular resulting beam trace.

Summing for different slowness values, the array can be adjusted like an antenna, enhancing seismic arrivals out of the noise according to their arrival angles. This procedure is in principle a velocity filtering of the wave field and even allows the separation of phases coincident in time (such as core phases like *PKP* and a mantle or surface wave). As 3-D heterogeneity along the wave path can perturb the energy away from the great circle path and predicted incoming angle of incidence, a grid search over different slowness and back azimuth values yields the highest amplitude beam trace as well as directivity information of the incident wave field. In principle, this information makes earthquake localization possible with a single array.

Commonly used array methods include (1) velocity spectral analysis (vespagram construction) [*Kelly*, 1967], whereby array data are stacked for different slowness values and resulting amplitudes contoured in slowness-time space (also called slant-stacking); (2) Nth-root stacking [*McFadden et al.*, 1986], where coherent signals in traces are enhanced by extracting the Nth-root from the array trace amplitude, slowness slant-stacked, then raised to the Nth power (Figure 2a); and (3) frequency-wave number (*fk*) analysis [*Capon*, 1969], which calculates both slowness and back azimuth simultaneously from the time lags by performing a grid search over various incident angles and finding the maximum energy in the stacked time window. (See *Rost and Thomas* [2003] for an in-depth review of these and other approaches.)

The elevated SNR of beam traces enables the detection of reflections and/or scattering from small and weak structures in the deep Earth, which would otherwise be undetectable in single-seismogram analyses. Hence, arrays are extremely well-suited to studying Earth's internal boundary layer interfaces, such as the upper mantle discontinuities, possible D" layering, and the core-mantle boundary (CMB) and the inner core boundary, each of which has important connections to chemistry and dynamics of Earth's interior. Some of these applications of the array method are presented here.

Upper and mid-mantle studies. The rapid increase in station coverage within regional networks permits upper mantle investigations of all types, including (for example) receiver function analyses that produce depths to interfaces, triplication studies for detailed velocity-depth profiles, and tomographic inversions for local 3-D structure. Incorporation of array methods helps to resolve even finer detail, such as localized transition zone thickness (between the 410- and 660-km deep phase boundaries) as well as thickness over which the upper mantle phase transitions occur. For example, *Yamazaki and Hirahara* [1994] utilized recordings from a regional Japanese network (J-Array) of Tonga-Fiji earthquakes to constrain the thickness of the 410-km and 660-km discontinuities to be less than 5 km.

The array approach can also be applied to dense groups of earthquakes recorded at a single location (utilizing reciprocity). However, application of source arrays requires earthquake location accuracy of around 1/10th of the source array aperture, which can then be treated exactly as receiver arrays.

Simultaneously combining source and receiver arrays to focus on a common target, a method called double beam, results in resolution capabilities of even more subtle structural features. For example, small-scale scatterers in the mid-mantle near the Mariana slab, which were inferred to be related to subducted oceanic crust below the 660-km discontinuity, were detected using double beam [*Krüger et al.*, 2001]. A similar example is shown in Figure 2a, where an Nth root vespagram shows evidence for a reflection from a subducted slab in the Tonga-Fiji region.

Lower mantle studies. Beam forming and migration techniques hold great promise for elucidation of the deeper Earth as well, since they are well suited for imaging sources of scattered and reflected energy.

For example, double-beam migration of J-Array data combined with coherency measures resolved two non-planar lower mantle P-wave discontinuities [*Kito and Krüger*, 2001]. Arrays are especially valuable for detecting low-amplitude arrivals commonly below noise levels on single seismograms (Figures 2b and 2c), such as energy generated by small-scale or weak homogeneities, reflections off discontinuities with small impedance contrast, or in distance ranges with unfavorable reflection coefficients. One recent example involves the low-amplitude, near-vertical incidence *PcP* and *PKiKP* phases. Their differential travel times from array data were used to infer long-wavelength variations of outer core thickness of the order of 3.5 km in specific regions [*Koper et al.*, 2003].

In recent years, the quantity and density of stations in permanent regional and portable temporary installations have increased to an extent that now makes feasible multi-channel signal processing methods adapted from exploration seismology. Studying thin layers of strongly reduced seismic velocities (ultra-low velocity zones or ULVZ) at the base of the mantle, *Rondenay and Fischer* [2003] used a phase-stripping principal component analysis to remove the high-amplitude main arrival *SKS* from recordings to reveal the behavior of $SP_{diff}KS$, a secondary arrival sensitive to fine layering of reduced velocities at the CMB. Using this adapted method, they were able to reveal a diffuse upper boundary to the ULVZ in their studied region. Figure 2b shows an example of how beam forming of array data increases the signal-to-noise ratio of subtle arrivals (*ScP*) probing the core-mantle-boundary, making the resolution of fine layering at the CMB possible.

Core studies. Although LASA was dismantled over 25 years ago, its data collection has been relatively untapped. Fortunately, some of the LASA data (153 events) were recently rescued from decaying magnetic tapes by the U.S. Geological Survey and are available today. One recent revisiting of LASA data detected a long (200 s) coda following the inner core reflection *PKiKP* [*Vidale and Earle*, 2000], which was interpreted to be scattered energy from fine-scale inner core heterogeneity. Such scattering can be explained by distributed heterogeneities of 1.2% with a scale length of 2 km across the outermost 300 km of the inner core, possibly due to compositional changes, melts, or anisotropy. Figure 2c shows the array detection of the phase *PKIIKP*, a phase that is well-suited to studying inner core structure in great detail due to the long path length in the inner core.

Outlook. Only a handful of array studies aimed at Earth interior targets are noted here. The present time is particularly ripe for array methods and analyses primarily for two reasons: (1) Earth interior seismological research over the last 5 to 10 years has witnessed increasingly detailed models of structural details in both forward and inverse studies of "single seismogram" data sets. The array approach is an extremely valuable tool to confirm these proposed fine-scale structural details, as well as to reveal new ones; and (2) past and present traditional array data sets are increasingly available, regional networks are more commonly dense enough to use array analyses, temporary portable seismometer experiments are similarly available and useful, and EarthScope's USArray will soon contribute valuable data to the community.

Nonetheless, some challenges remain for global studies of Earth's deep interior. Many array data are not publicly available or are very hard to access. In some cases, only the triggered front part of seismograms is retained, and deep Earth studies rely on information much later in the traces. Many recordings from the 1960s and 1970s were recorded on magnetic tape, which are decomposing and decaying over time. More funding and community effort are necessary to rescue these yet unparalleled data sets. More installations in the southern hemisphere are desired, including utilization of ocean bottom seismometry, for approaching better global coverage. Finally, 2-D and 3-D wave propagation methods should be folded into array analyses that seek to reveal structure in strongly heterogeneous environments.

With the continuing trend of more and more availability of array data, it can be assumed that array seismology will provide key constraints on the interior of the planet for generations to come. It will play an important role in bridging the gap between seismologically determined, medium-to-large-scale structure studies (500–1000+ km) and inferences from mineral physics, geochemistry, and geomagnetic and geodynamical studies, undoubtedly leading to a new understanding of the processes that make our planet so dynamic and fascinating.

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