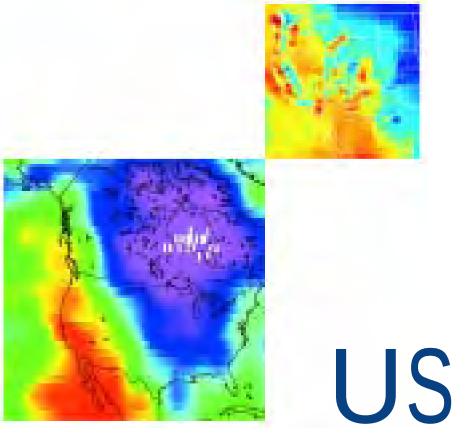
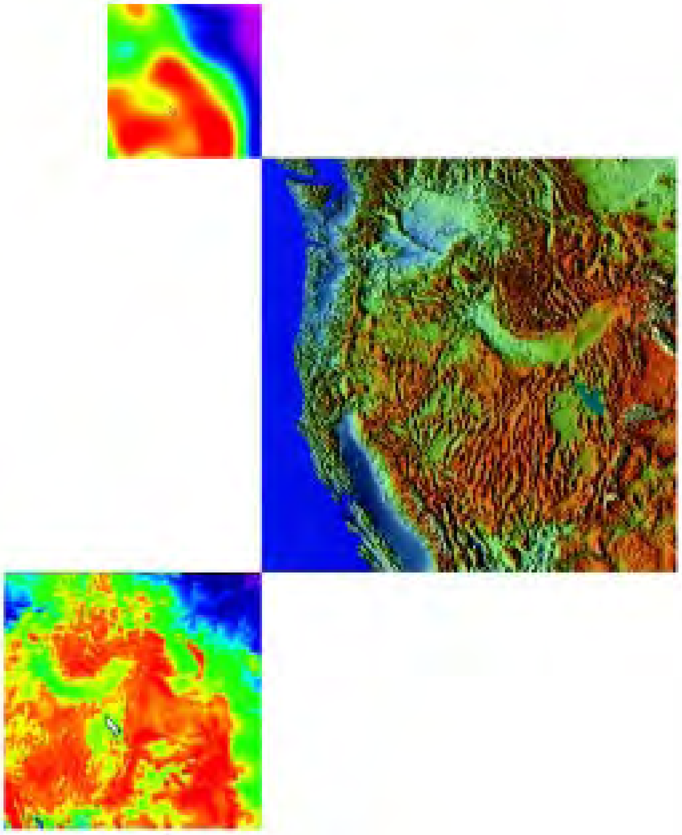
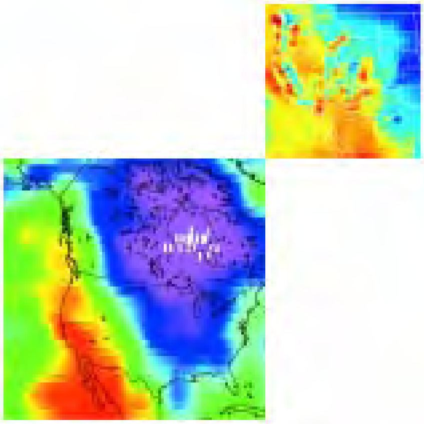


USArray

A Synoptic Investigation of the Structure, Dynamics, and Evolution of the North American Continent





During 1999, a workshop in Albuquerque, NM and another in Houston, TX, provided a forum to discuss the design and implementation of an ambitious program to develop an integrated understanding of North American geology and deep Earth structure, the USArray. A broad spectrum of Earth scientists from academia, the US Geological Survey, regional seismic networks, and the National Science Foundation attended these workshops, jointly sponsored by NSF (National Science Foundation) and IRIS (The Incorporated Research Institutes in Seismology). Workshop participants identified scientific challenges for USArray, helped define its technical and multidisciplinary components, discussed an operation and management scheme, and identified ways in which USArray can best be used to advance Earth science research, education, and outreach.

Subsequent to the Albuquerque workshop, program officers of NSF's Division of Earth Sciences (EAR) united several intertwining streams of research into a single, integrated effort known as "EarthScope — A Look into Our Continent." EarthScope is a distributed, multipurpose set of instruments and observatories designed to expand the Earth science community's observational capabilities. EarthScope includes four facility components: (1) USArray, a continental-scale seismic array that will provide a coherent three-dimensional image of the lithosphere and deeper Earth, (2) SAFOD (San Andreas Fault Observatory at Depth), a borehole observatory across the San Andreas Fault that will directly measure the physical conditions under which earthquakes occur, (3) PBO (Plate Boundary Observatory), a fixed array of strainmeters and GPS receivers that will measure real-time deformation on a plate-boundary scale, and (4) InSAR, synthetic aperture radar images of tectonically active regions that will provide spatially continuous strain measurements over wide geographic areas.

The USArray Steering Committee preparted this white paper and the attached appendices. It documents the outcome of the two USArray workshops and discusses USArray within the context of EarthScope.

THE USARRAY STEERING COMMITTEE

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Additional input to the appendices came from Gabi Laske, Guy Masters, Frank Vernon, and John Orcutt (University of California, San Diego), Steve Park (University of California, Davis), Catherine Johnson (IRIS), Randy Keller (University of Texas, El Paso), and Robert Harris (University of Utah). We gratefully acknowledge the help and support of David Simpson, President of IRIS.

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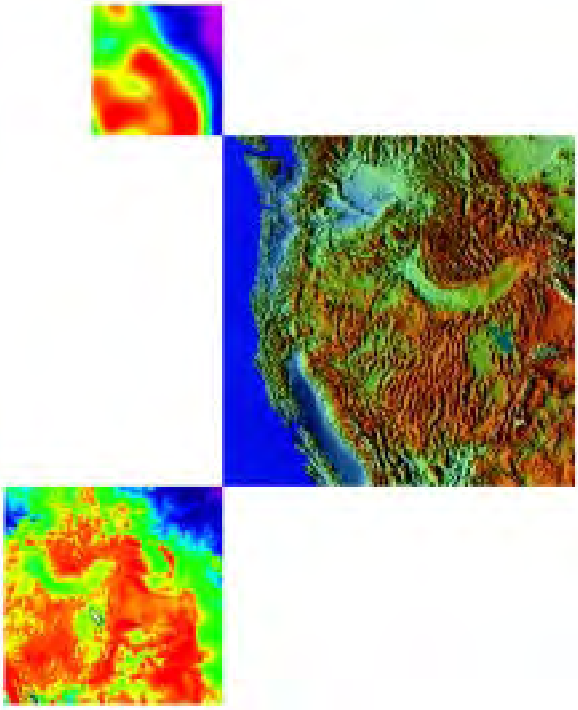
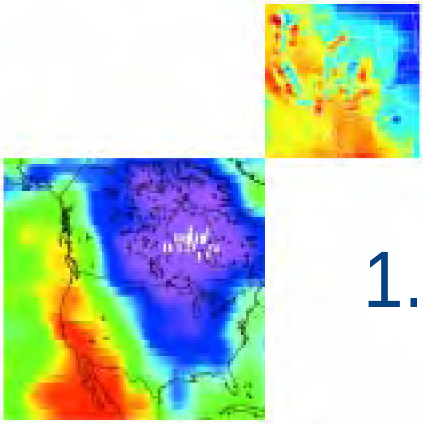




1. EXECUTIVE SUMMARY

Images profoundly shape our view of the world. Thirty years ago, the simple image of Earth from space changed our perspective on the fragile beauty and finite limits of our planet. Today we treat such views of Earth as commonplace, but the impact of these images is no less profound. For example, satellite images now routinely track weather and storms, providing critical information to mitigate weather-related hazards. Courtesy of television news programs, people in all walks of life can now appreciate and visualize the complex dance of atmospheric dynamics to a degree previously unthinkable. Without question, these synoptic views of Earth revolutionized our comprehension of our environment and the way we react to our natural surroundings.

USArray will extend the imaging revolution to the solid Earth, to North America in particular. At USArray's core are three major seismic components: (1) a transportable array of 400 broadband seismometers that will systematically cover the US, (2) ~2400 seismometers of various types designed to augment the transportable array so that a range of specific targets can be addressed in a focused manner, and (3) a permanent network of high-quality seismic stations coordinated with the US Geological Survey within the context of the National Seismic Network. These components are designed to image Earth continuously at all scales, from the whole Earth, to lithospheric and crustal, to local. If experience is any guide, USArray's striking new Earth images will change our views of continental dynamics, plate tectonics, and our relationship to the physical environment.

Why image the continent? Plate tectonics provides a framework that explains many first-order observations such as the global distribution of earthquakes, volcanoes, and mountain belts, and the relative heights and ages of continents and ocean basins. While plate tectonics works well in explaining the relatively simple structure and dynamics of oceanic plates, it does not provide an encompassing theory of the more complex and heterogeneous continents. Unlike the oceanic lithosphere, the long-lived, inherited structures and compositional variations in the continental lithosphere modulate modern tectonic processes and deformation, and likely play a crucial role in determining global convection system patterns. Continents and their margins provide all of our petroleum and most of our mineral resources. Feedbacks between tectonic and surficial processes shape the environment where we build our cities, get our water and other natural resources, and cope with geological hazards. The only way to unravel some of these complex interactions is by combining high-resolution seismic images of the continental lithosphere and deeper Earth provided by USArray with a diversity of geologic data.

USArray can contribute to a number of scientific goals and address a range of issues of societal concern:

- mechanisms of continent formation and breakup;
- relationship between crustal tectonic provinces and upper mantle structure including the structures of terranes and their accretional histories;
- rheological stratification and lateral heterogeneity in the lithosphere and its variation from orogenic belts to the cratonic interior of the continent;
- lithospheric deformation and earthquake hazard assessment and the related problems of fault-zone imaging to determine fault zone material properties, and geometry;
- the detailed structure of Earth's major seismic discontinuities and their role in tectonics including:
  - controls of the transition from brittle to plastic deformation in the crust;
  - the Moho, and mass transfer between the crust and mantle;
  - lateral variation in depth and sharpness of the 410 and 660 km seismic discontinuities and their relationship to surface tectonics;
  - geometry and properties of the Ultra Low Velocity Zone (ULVZ) at the base of the mantle;
- heterogeneity, anisotropy, and flow in the crust and mantle;
- role of fluids (magmas, hydrothermal, meteoric) in the crust;
- the history of North American subduction and the locations of ancient slabs in the mantle;
- crust/mantle coupling and crust/mantle mass flow during subduction, orogenesis, and rifting;
- intraplate stress distribution and its relationship to modern structures and seismicity;
- development of dynamic topography;
- feedbacks between surficial and tectonic processes.

USArray, together with the other elements of EarthScope, can also serve to advance our understanding of natural hazards throughout North America. USArray will provide critical data for understanding earthquake and volcano hazards, and will focus academic attention on unresolved problems related to the earthquake cycle, strong ground motion amplification, and the causes and recurrence of volcanism. The flexible array in particular will be a powerful tool for focussed studies of hazards such as magma movement around active volcanoes in the Pacific Northwest and movement on faults in seismically active regions. Elements of USArray will also provide information on local and regional scales useful to resource managers to help evaluate groundwater, hydrocarbons, and mineral resources.

USArray can also, over the next decade, fundamentally change the way Earth scientists carry out their investigations and convey their results to the public. The USArray infrastructure provides a platform for stimulating new mechanisms for collaboration, data integration, and data management of a diverse suite of geologic, geochemical, and geophysical data sets. This will provide the catalyst to harness and integrate our expanding databases and to combine diverse perspectives into new synoptic images. The geologic component of USArray will provide the time dimension for understanding how continents evolve and the processes that shape them. The USArray education and outreach component will provide an important new centralized framework for Earth science education at all levels. The outcome will be an integrated “whole continent” view of North America and improved understanding of the processes that have shaped and continue to shape the continent, and that directly affect our lives.

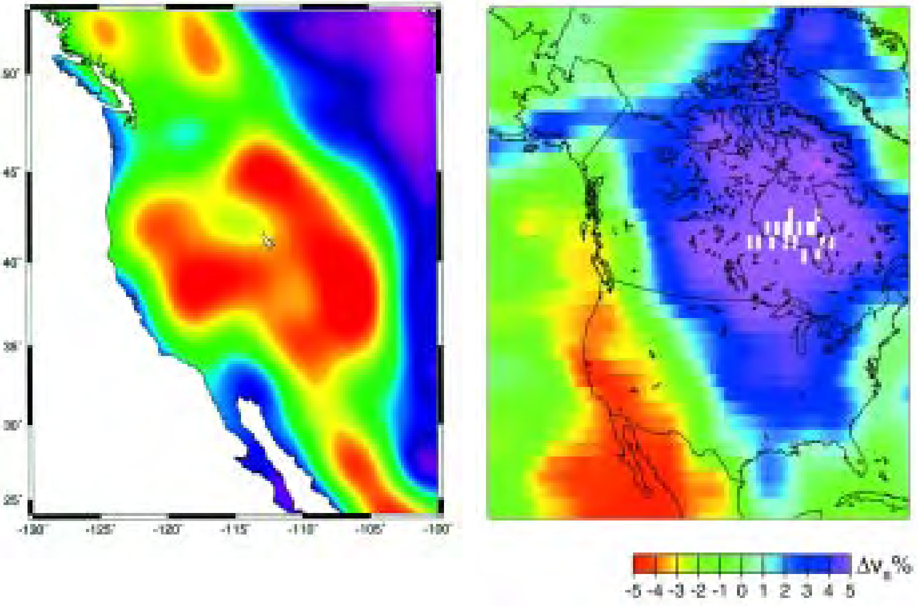


Figure 1a. Topography of western US filtered at 500 km wavelength (left). S-wave velocity structure at 100-175 km depth (from Grand, 19xx; right) Stable craton is marked by fast velocity and low topography. Mobile belt is marked by slow velocity and high topography.

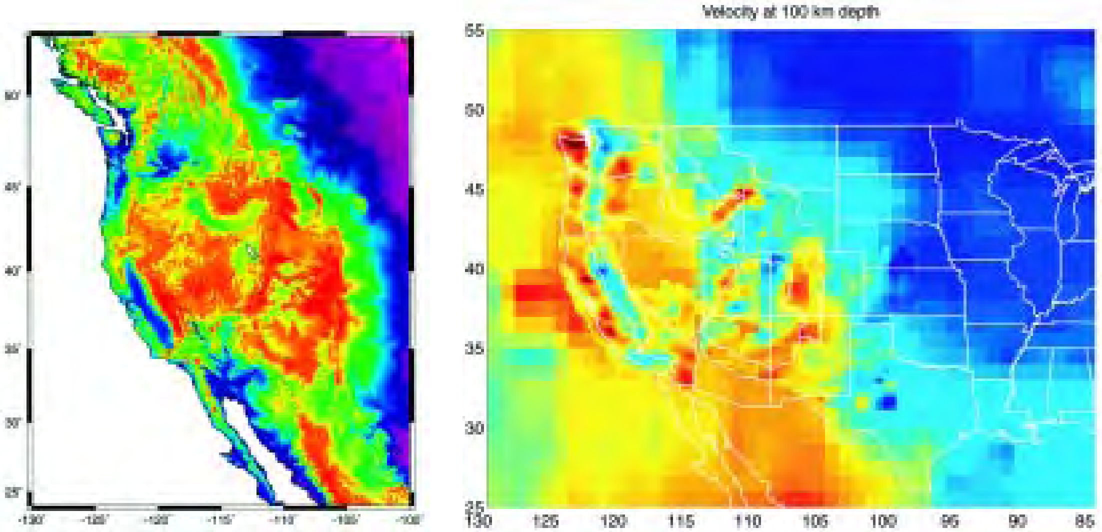


Figure 1b. Topography of western US filtered at 30 km wavelength (left). P-wave velocity structure at 100 km depth (from Dueker and Humphreys, 19xx; right). Linear Sierra Nevada/Great Valley structures are colinear with mantle anomalies. The mantle beneath the Snake River Plain and Yellowstone hotspot is slow, while the Colorado Plateau has relatively fast mantle ringed by low velocities in the basin and range and Rio Grande rift system.

Figure 1c. Topography of Western US filtered at 1 km wavelength (Simpson and Anders, 1992). Many structures, marking extension, volcanoes in the Pacific northwest, a crustal welt marking the Mendocino Triple Junction, the track of the Yellowstone hotspot.

2. RATIONALE FOR THE FACILITY

Consider what our understanding of North American tectonics would be if the only topographic information we had to work with was similar in resolution to modern traveltime tomographic images. First-order features such as the division of the continent into a stable continental interior (characterized by fast seismic velocities and low topography) and an active western margin (exhibiting low velocities and high elevation) are resolved, but little more than this gross subdivision is possible (Figure 1a). With increased resolution we begin to see more detailed structure corresponding to the largest-scale tectonic provinces (Figure 1b). Where seismic observations are available, the trends in surface features often correlate with mantle structures. Where we have data, the upper mantle shows considerable variation at lateral scales of ≤100 km. Areas with little mantle structure correspond to regions with few or no observations. At 1-km resolution in topography (Figure 1c) we see the richly detailed morphology that defines the tectonic subprovinces of North America, with much of this topographic detail representing the manifestation of deeper-seated geologic processes. Clearly, however, our images of deeper lithospheric structure are orders of magnitude coarser than our surface images and, more importantly, they lack continuity over the large lateral distances necessary for understanding continental dynamics.

In places, individual seismic experiments and investigations using dense source/receiver geometries have produced spectacular results and new insights of specific local or regional tectonism (Figure 2) but collectively these results provide only a rough patchwork understanding of the structure and evolution of the continent. It is difficult to tie results from individual experiments, spaced sparsely across the continent, into a coherent picture that ties surface geology and detailed lithospheric structure to driving forces within the deeper mantle. In numerous experiments we see examples of coupling between the crust and mantle. We see whole-crustal faulting at strike-slip plate boundaries and orogen-wide crustal detachment faults implying mantle control of the crust in orogenic belts and along plate boundaries. We see crustal recycling and dewatering within subductionzones, and delamination and phase change of mafic lower crust beneath orogenic belts, all providing crustal control on upper mantle structures. The abrupt transition from cratonic to tectonic upper mantle in western North America implies long-lived (1.5 Ga) structural control on modern tectonics (i.e., Proterozoic terrane accretion boundaries have guided Mesozoic-Cenozoic tectonism). The smallest resolvable scale mantle structures in tomographic images of tectonic North America show a strong correlation between surface geology and dynamic upper mantle structure. Moreover, the few available higher frequency observations imply that detectable mantle structure exists across the entire spatial bandwidth; the structure of the mantle is as rich as that of the crust. Nevertheless, we currently lack a coherent understanding of the degree of coupling and mechanisms of stress and mass transfer across

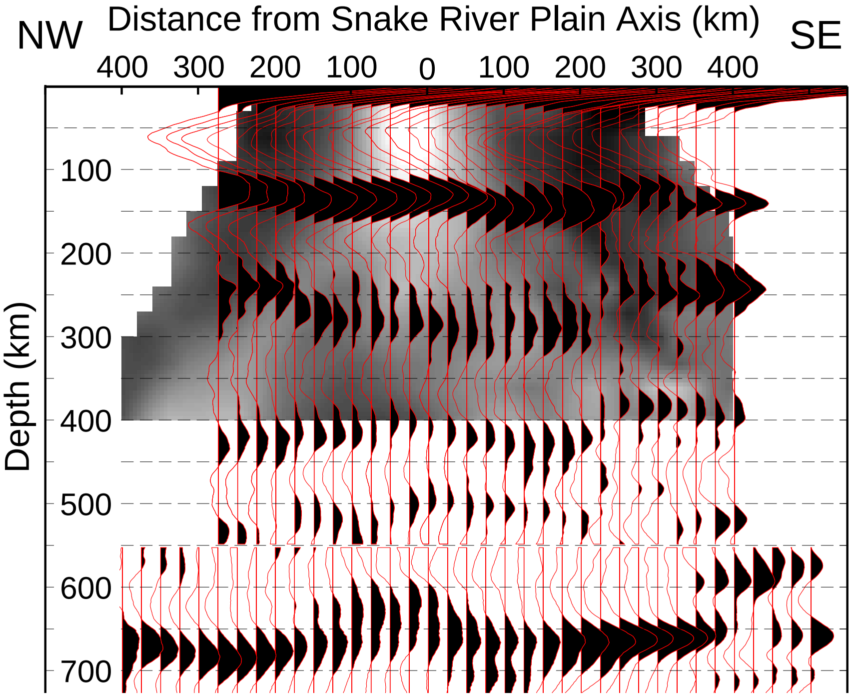


Figure 2a. Mantle structure under the eastern Snake River Plain from receiver function common midpoint stack. (Dueker and Sheehan, 1997) The 410 and 660 discontinuities show topographic relief beneath the axis of the Snake River Plain. S-wave velocity structure from tomography shown in grayscale (light areas 8% slower than dark areas). (Figure courtesy of Ken Dueker and Anne Sheehan from Ekström et al, IRIS Newsletter, **16**, Fall/ Winter 1998)

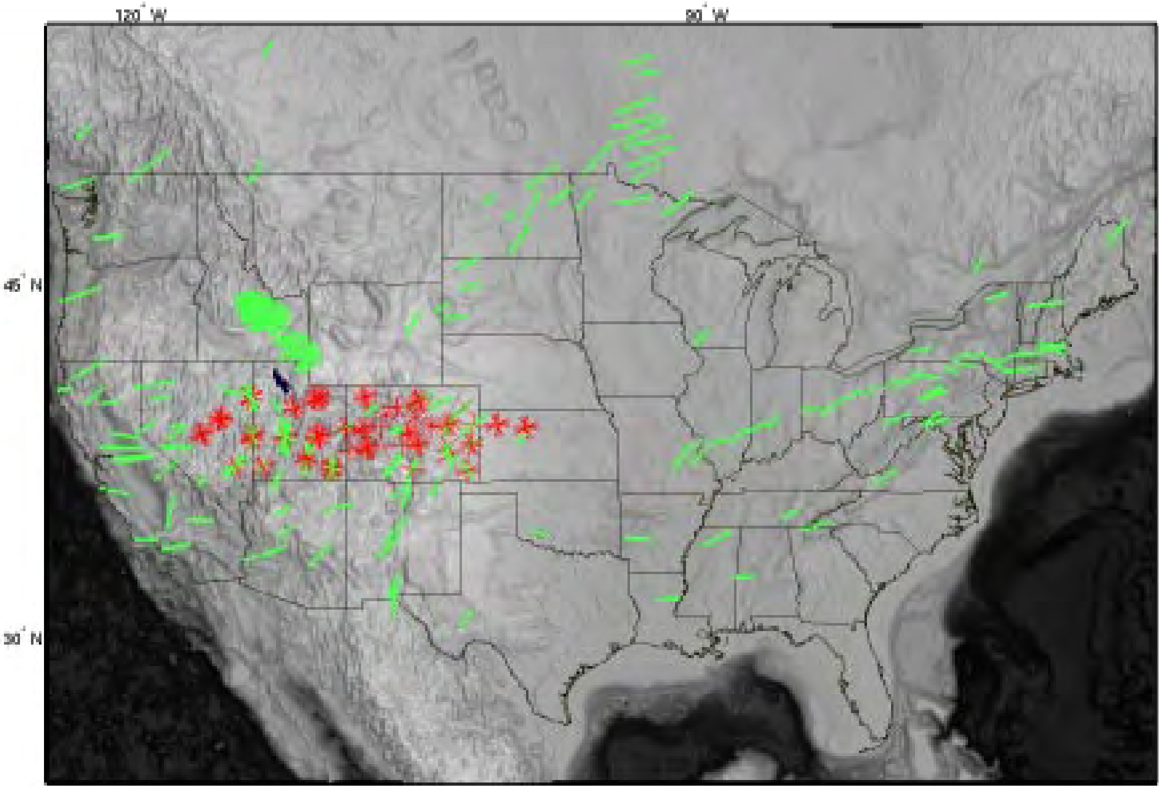


Figure 2b. S-wave splits from the US and southern Canada compiled from several different studies and publications. Green lines indicate the fast direction and split time of SKS arrivals. Red lines indicate the backazimuths of null arrivals in areas where null arrivals are common. (from Ekström et al, IRIS Newsletter, **16**, Fall/Winter 1998)

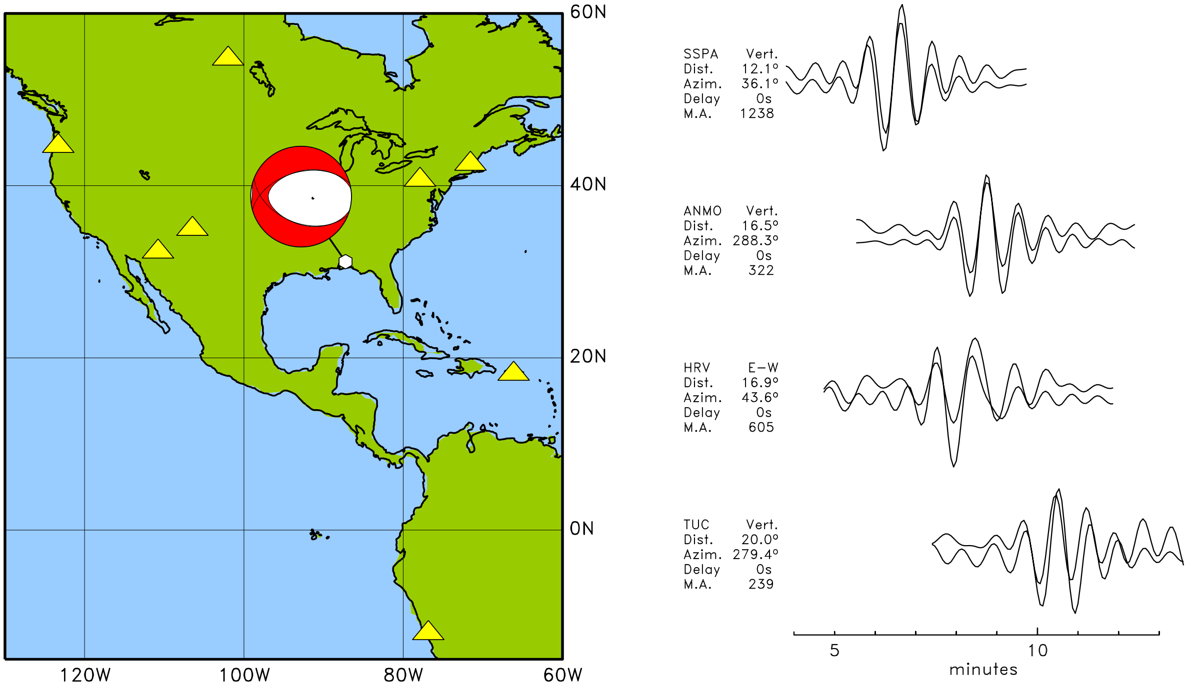


Figure 2c. Moment tensor solutions and waveform modeling for the 1997 M=4.9 Alabama earthquake using stations at far-regional distances. Expanded coverage of USArray would allow study of events as small as magnitude 3.5 (from Ekström et al, IRIS Newsletter, **16**, Fall/Winter 1998)

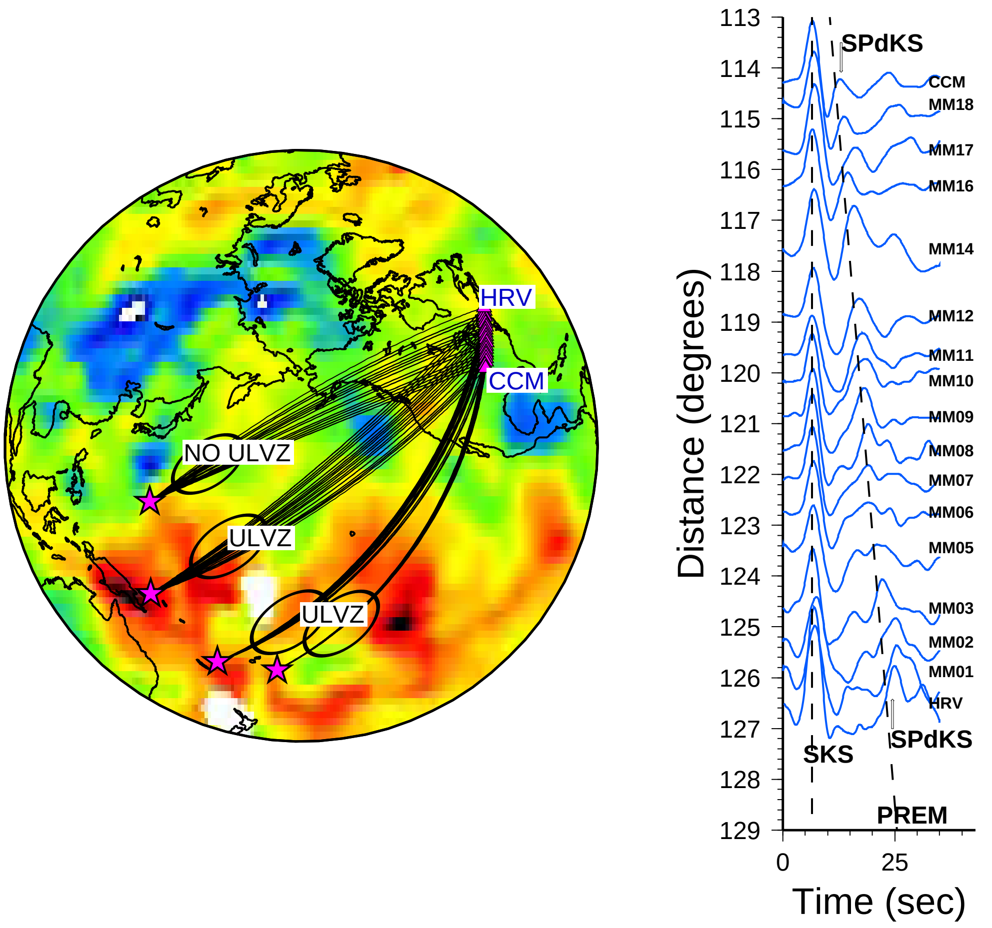


Figure 2d. Paths to the stations of the MOMA array from earthquakes in the western Pacific. The regions sampled by SPdKS phases on the source side of the path are shown by ellipses. Background is S-wave velocity model of Grand et al (1997). Paths from Tonga and New Britain require ultra-low velocity zones at the CMB, paths from the Marianas do not. Record section from SKS/SPdKS phases for the New Britain earthquake. SPdKS is clearly observed moving out from SKS, but its peak arrives up to 5 seconds late with respect to the time predicted by PREM (dashed line). These observations are consistent with the existence of a thin, ultra-low velocity zone and possibly partially molten mantle (figure courtesy of Karen Fischer from Ekström et al, IRIS Newsletter, **16**, Fall/Winter 1998).

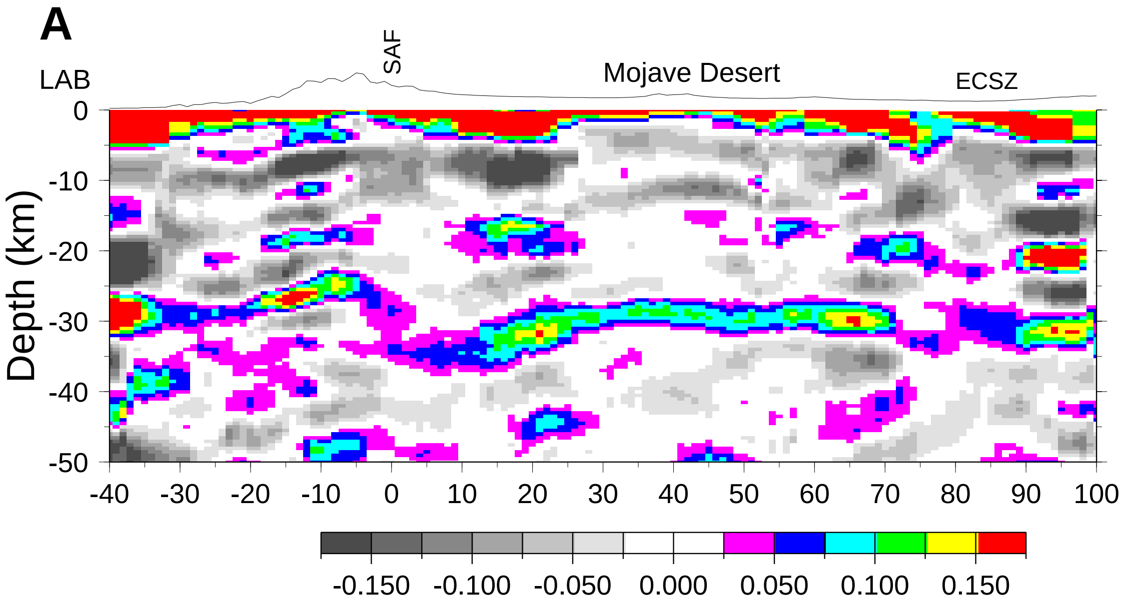


Figure 2e. (A) Amplitude of CCP stacked receiver function profile across the San Andreas Fault (SAF). No vertical exaggeration except that the surface topography is amplifies by a factor of 2. LAB: Los Angeles Basin; SMF: Sierra Madre Fault.

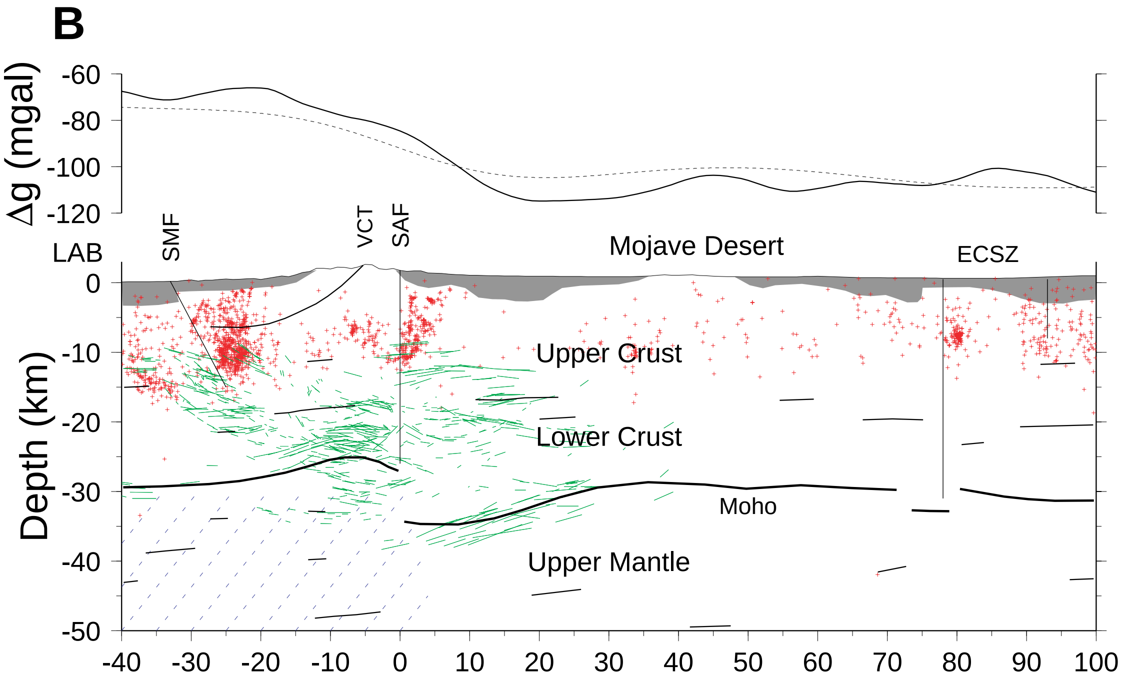


Figure 2f. (B) Crustal structure along the profile based on A. Plotted on the top are the observed Bouguer gravity anomaly (heavy trace) [16,] and the predicted Bouguer anomaly (dashed line) using the determined MOHO topography with an assumed density contrast of 800 kg/m. Red crosses are hypocenters of earthquakes within the profile between 1981 and 1988. Green lines are the crustal reflectors imaged by the LARSE active source experiment [11,]. Hatched area in the upper mantel represents the Transverse Range high velocity anomaly from the seismic tomography study[17,]. VCT: Vincent Thrust Fault.

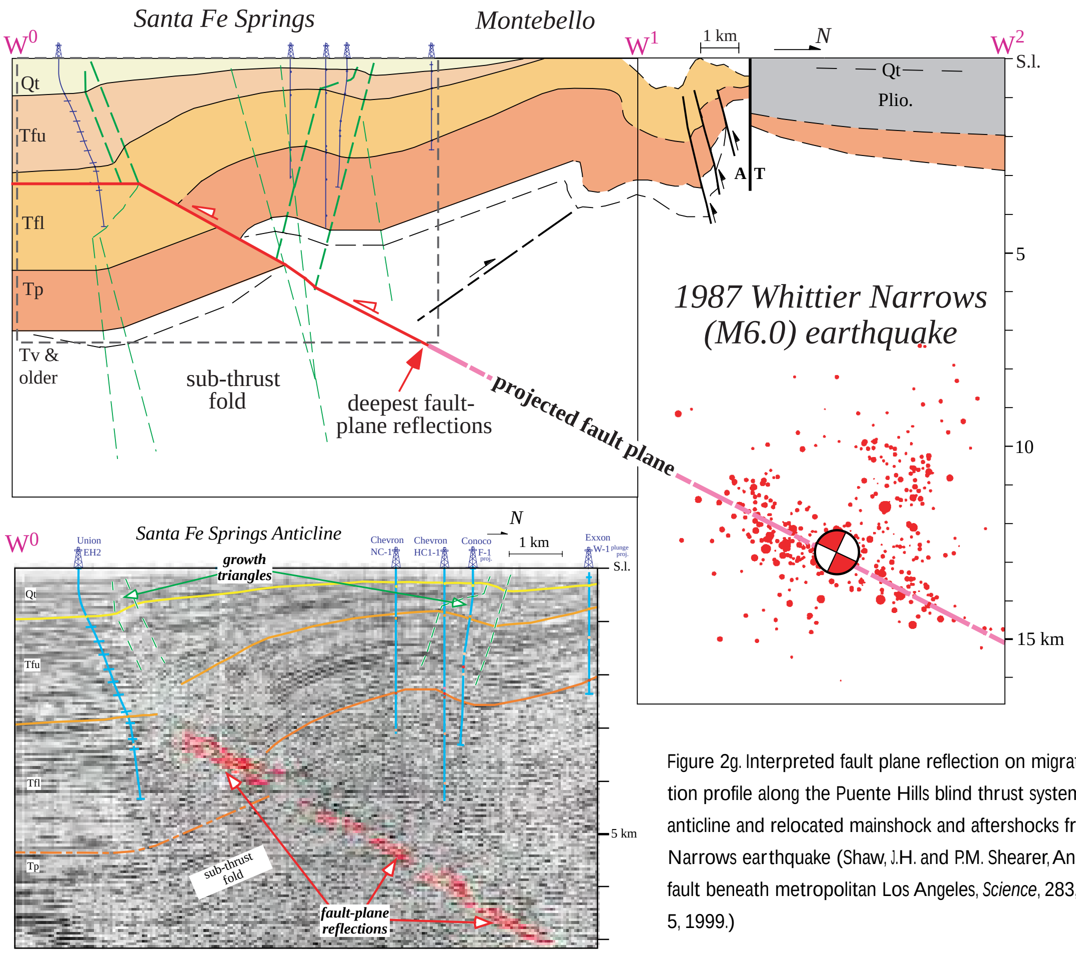


Figure 2g. Interpreted fault plane reflection on migrated seismic reflection profile along the Puente Hills blind thrust system, Sante Fe Spring anticline and relocated mainshock and aftershocks from the Whittier Narrows earthquake (Shaw, J.H. and P.M. Shearer, An elusive blind-thrust fault beneath metropolitan Los Angeles, *Science*, 283, 1516-1518, March 5, 1999.)

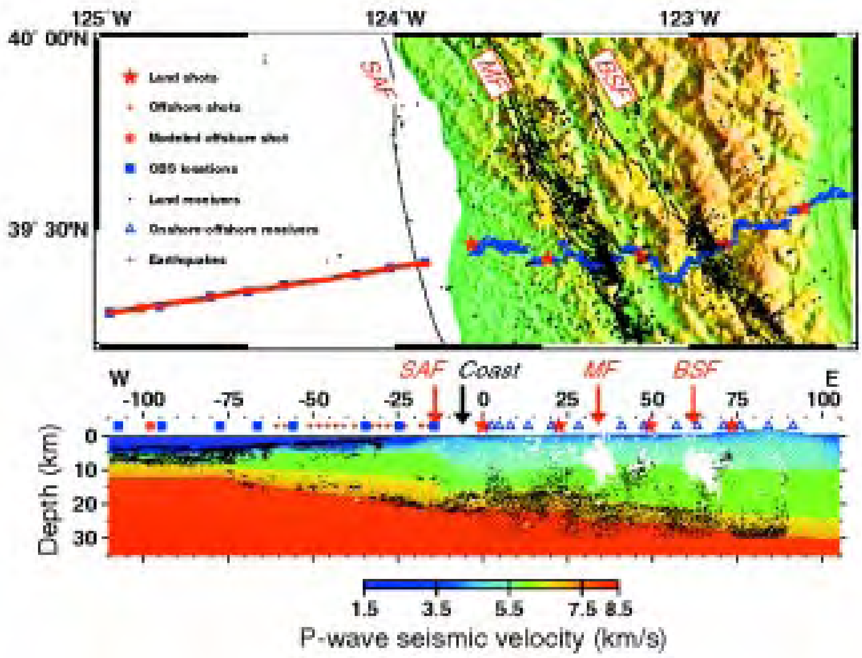


Figure 2h. Seismic velocity-reflectivity cross section across the San Andreas Fault transform system in northern California. The lower crust and Moho is offset across the San Andreas and Macaama faults. At this latitude (~39.5°N) the transform system is ~2 Myr old. (Henstock, T.J., et al., *Science*, **278**, 650-653, 1997. and Henstock T.J., and Levander, A., *Geophysical Journal International*, **140**, 233-247, 2000.)

fundamental rheological and compositional boundaries in the lithosphere. USArray will provide a continuous imaging capability that will tie together North America's seemingly disparate tectonic provinces into a coherent model of the origin and evolution of the continental lithosphere.

Our knowledge is even more incomplete when we look deeper at the asthenosphere and lower mantle. The upper mantle plays an extraordinarily important role in Earth dynamics, but the three-dimensional structure beneath continents has not been resolved sufficiently well to answer many fundamental questions. It is clear that the upper mantle is anisotropic and that this anisotropy probably results from the preferred orientation of minerals controlled by mantle flow. We do not know the details of this anisotropy, however, which can be a powerful tool for illuminating three dimensional mantle flow. Furthermore, the thermodynamics of the two major jumps in seismic velocity at 410 km and 660 km depth, probably resulting from solid-solid phase transitions, are not well understood. The constraints from small, regional studies around the world are not easily rationalized and the absolute magnitude of the topography, the lateral scale-lengths of topographic undulations, the sharpness of the boundaries, and how the topography of the discontinuities varies with volumetric changes in seismic velocity are all poorly known. USArray will enable scientists to determine the true nature of the mantle transition zone with unprecedented lateral resolution and better understand how this relates to dynamic processes within the mantle, both upwellings and downwellings, and in turn how deeper dynamics is related to surface geology. This would be a spectacular advance for the Earth sciences. USArray will also provide data for forefront research on deeper Earth structure, including, the core-mantle boundary, and the inner core/outer core boundary. (see Appendix 2 for details)

The time is right for an initiative of this magnitude. Significant advances in technology, theory, and imaging capabilities have taken place over the last ten years. The seismological community has gained significant experience collecting large, broad band, high-quality, digital data sets from array deployments of seismometers. Global tomographic images with a resolution of 5° (~550 km) hint at links between shallow and deep Earth processes, while advances in reflection profiling allow us to see whole lithospheric structure at scales of less than 100 m. At the same time there is an increased recognition that the next major advances in our field will come from the integration of measurements contributed by a diverse set of Earth science disciplines. Many problems in Earth science, particularly those of the scope to be addressed by EarthScope/USArray, are increasing in complexity beyond that which a single discipline can successfully solve. A multidisciplinary approach is required to make links between disparate datasets, to provide constraints for interpreting each dataset, and to develop a complete understanding of the structure of the continent and the dynamics and history of continental development. Finally, advances in information technology now make it possible to manage and manipulate large and disparate data sets, facilitating joint interpretation.

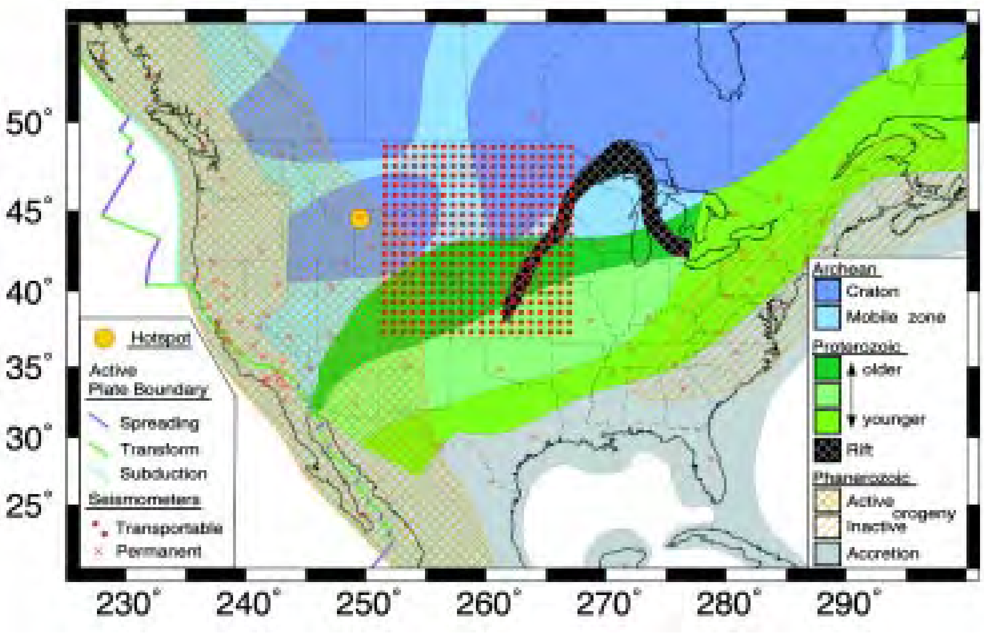
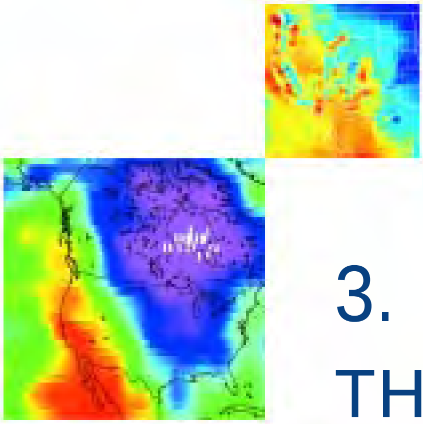


Figure 3. Tectonic provinces with array footprint (from Ekström et al, IRIS Newsletter, **16**, Fall/Winter 1998)

The science objectives of EarthScope/USArray require a multidisciplinary approach. Seismology returns information about the variation in density and seismic velocity of the subsurface. Electromagnetic techniques provide information on electrical conductivity of the subsurface, and geodesy gives the current velocity field of the surface. Petrology and mineral physics provide the data to translate seismic velocity into rock type. Rock mechanics and structural geology offer the link between strain and the movement of rock. Geochemistry and field mapping provide information on what rock types might be present in the subsurface, and geochronology provides information on the timing and sequence of events in geologic history. Geomorphology and stratigraphy provide critical constraints on vertical motions, geologic history, and feedbacks between surficial and tectonic processes that shape the surface of the continent. Finally, geodynamic modeling integrates this information in an attempt to understand the plate and local interactions that led to North America's current structure and predict its behavior in response to the existing forces acting on North America. The combined input from these varied disciplines contributes to a better understanding of the images returned from the USArray geophysical "instrument." The explicit coordination of these varied tools within EarthScope/USArray is essential to maximize the scientific return from this project.

The North American continent exhibits a diverse array of tectonic provinces (Figure 3). The western US contains a Mesozoic-Cenozoic mobile belt and orogenic plateau including a Cenozoic collapse structure, a developing rift system, a continental hotspot, and one of Earth's most important ocean-continent strike-slip fault systems. The eastern US contains a Paleozoic continent-continent collision zone, a Mesozoic rift, and a Mesozoic-Cenozoicpassive margin. The passive margin developed along the Gulf coast contains one of the best examples of salt tectonics and one the world's largest accumulations of hydrocarbons. In the interior of the continent, Proterozoic collisional belts ring the Proterozoic-Archean craton which is also the site of one of the Earth's largest upper mantle velocity anomalies. The mid-continent also is blanketed by platform sediments, which represent a long and detailed record of what are probably mantle-controlled vertical motions. In the western US, the youngest tectonic activity, operating over the last few million years to tens of millions of years, is responsible for much of the architecture that we observe today. Understanding this recent activity provides insight into plate boundary processes and associated hazards from earthquakes and volcanoes, and also provides insight into processes that have operated over geologic time. However, this recent activity overprints older structures developed during previous plate collisions and rifting events and the existing structures modulate modern processes. Unraveling the complex geologic history of the continent requires understanding both the modern and ancient records. A systematic investigation of the North American continent provides a broad sampling of geologic processes across the widest possible range of scales and ages. In essence, moving spatially across the continent provides a snapshot of continental evolution and continental dynamics through time. As a natural laboratory, North America provides a diverse array of processes and structures for investigation, an opportunity for studies with societal relevance (investigation of earthquake and volcanic processes, hazards, and natural resource evaluations), and an existing infrastructure (communication, transportation, and educational) which makes the project feasible.

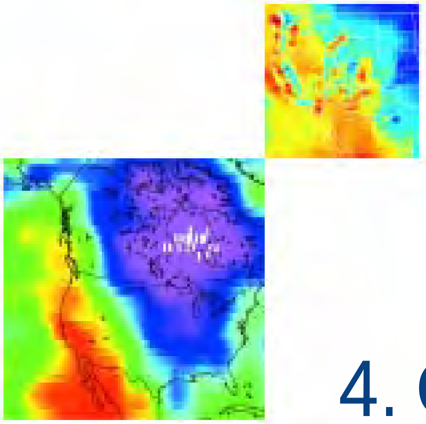


3. DEVELOPMENT OF THE INITIATIVE

Over the past few years, there has been discussion within the seismology community of the opportunities, both scientific and technical, for an initiative to improve the resolution at which we can image the structure of the continental lithosphere and mantle, and to merge seismological results with other Earth science investigations (see Appendix 1). At the same time, there is growing interest in the use of dense deployments of broadband seismometers to investigate deep Earth structure. These discussions culminated in a workshop in March 1999 in Albuquerque, NM. Over 90 participants, representing a broad spectrum of Earth scientists representing academia, the US Geological Survey, regional seismic networks, and the National Science Foundation attended the workshop, jointly sponsored by the National Science Foundation and IRIS (Incorporated Research Institutions for Seismology).

At this workshop, seismologists and geologists discussed the design and implementation of an ambitious plan to explore, image, and develop an integrated understanding of North American geology and deep Earth structure. Workshop participants helped define the technical components of the USArray facility, identified scientific goals, and discussed an operation and management scheme for the facility. The Albuquerque workshop led to substantial enthusiasm and momentum for USArray and increased recognition that this initiative needs to integrate geological and geophysical investigations into a single unified effort to best achieve its scientific goals.

A second workshop was held in September 1999 in Houston, TX to integrate a diverse group of Earth scientists into the early planning stages of USArray to enhance its scientific goals, better define its multidisciplinary character, and identify ways in which USArray can best be used to advance Earth science research, education, and outreach. The workshop also included discussions of how the Earth science community can work together with the National Science Foundation to enhance support for our research endeavors — through development of compelling scientific studies, through integrative community projects such as USArray, through clear statements of our long-term science goals, and through enhanced public appreciation for Earth science research. This white paper and the attached appendices document the outcome of these two workshops.



4. OUTLINE OF THE FACILITY

USArray is designed to probe the three-dimensional structure beneath continental North America using a spatially dense network of high-quality seismic stations. USArray can be thought of as an inverted telescope, imaging with unprecedented clarity the spatial distribution of rock properties. The seismic network serves as a platform for additional geophysical measurements, and the associated integrated geologic studies provide critical links to surface constraints and an extension to the fourth dimension, time. The combined efforts produce a natural laboratory from which we can elucidate Earth structure and test hypotheses about how the lithospheric mosaic making up our continent was assembled.

4.1 THE GEOPHYSICAL COMPONENT OF USARRAY

The geophysical component of USArray consists of three interrelated parts (see Appendix 1 for additional details). The first component of USArray is a transportable telemetered array of 400 broadband seismometers designed to provide real-time data from a grid with dense and uniform station spacing of ~70 km and an aperture of ~1400 km (Figure 4). The array will record local, regional, and teleseismic earthquakes, providing resolution of crustal and upper mantle structure on the order of tens of kilometers and increased resolution of structures in the lower mantle and core-mantle boundary. The transportable array will roll across the country with 18-month deployments at each site (Figure 5). As the array moves, it will systematically and uniformly image structure beneath the continental US. Continuous redeployment will cover the entire conterminous US over a period of 10 years, providing unprecedented three-dimensional seismic imaging. The result of this experiment will be the first coherent, high-resolution, plate-scale image of the lithosphere and underlying mantle for either the continents or the oceans; it will focus the blurry images presented in Figure 1, producing the synoptic image that will form the foundation of a new and comprehensive understanding of continental tectonics. In addition to the investigation of the rich variety of lithospheric structures provided by the complex tectonic fabric of North America, the location of the US with respect to earthquake sources in the SW Pacific will allow USArray to provide an excellent view into the deep mantle. The transportable array will provide a three-dimensional "volumetric map" of seismic velocities and anisotropy beneath the US down to at least 1,000 km depth at a uniform 50-200 km resolution. Within this volume of the mantle, the topography and sharpness of the principal jumps in seismic velocity will be mapped out beneath the continent with a lateral resolution of several tens

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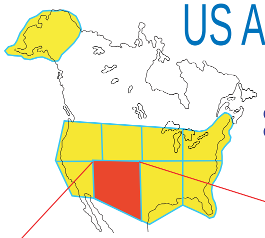


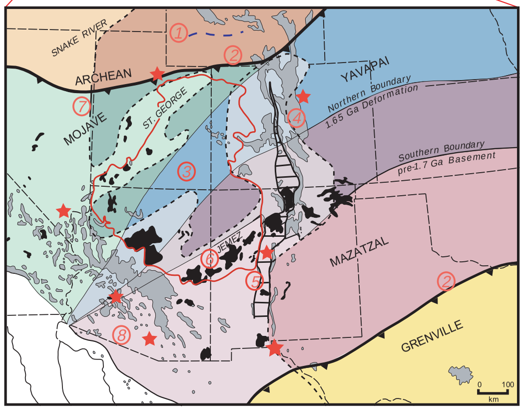
US ARRAY:

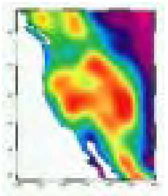
SOUTHERN ROCKY MOUNTAIN FOOTPRINT

CONTINENTAL COVERAGE:
- **Transportable Array of 400 Instruments**
  - 2000+ sites in 10 years

3 BILLION YEARS OF RE-SHAPING OF A CONTINENT, AND IMPLICATIONS FOR SOCIETAL NEEDs

CONTINENTAL STRUCTURE & EVOLUTION AT ALL SCALES





MANTLE VELOCITY STRUCTURE
at 100 km depth: Blue = cold, fast, old
Red = warm, slow "young" mantle

HIGH TOPOGRAPHY correlates with warm mantle, *not* thick crust

⑩ *WATER: QUANTITY & QUALITY*

Middle Rio Grande Basin Study USGS
U.S. Department of the Interior U.S. Geological Survey

POTENTIAL TARGETS FOR THE FLEXIBLE ARRAY:

① Archean cratons: structure and history? did plate tectonics operate?

② Proterozoic lithosphere: how was it assembled? why has it been persistently weak & fertile?

③ Colorado Plateau: a strong microplate?

④ Rocky Mountains: what holds them up? when did they go up?

⑤ Rio Grande Rift (and Basin & Range): continental extensional processes

⑥ Neogene Volcanism: what controls it?

⑦ Mantle reorganization: separates stable U.S. from tectonically active U.S.

⑧ SEISMIC HAZARDS
Salt Lake City & Intermontane Seismic Belt

⑨ EDUCATION & OUTREACH
US Array
Trail of Time

Figure 4a, b. Array deployment and example of multiple scale of observations, integration of regional networks.

A

of kilometers. While the initial focus of USArray is coverage within the US, extensions of the array into neighboring countries and onto the continental margins through collaborations with scientists from Canada, Mexico, and the ocean science community are natural.

Approximately 50 magnetotelluric (MT) field systems will be embedded within the array to provide constraints on conductivity which translate into temperature and fluid content within the lithosphere (see Appendix 5 for additional details). The MT method is most sensitive to conductors in the crust and upper mantle. Silicate minerals at subsolidus temperatures in the crust are very resistive, so natural electrical currents are attracted to regions of low resistivity. These conductive regions can be caused by solid phases such as graphite and metallic sulfides or oxides, aqueous fluids (especially brines), and partial melt. A common requirement in all of these causes is that the conductive fraction must be interconnected, thus leading also to inferences about fluid migration paths. In the mantle, the apparently simpler mineralogy leads to fewer potential causes of lower resistivities.

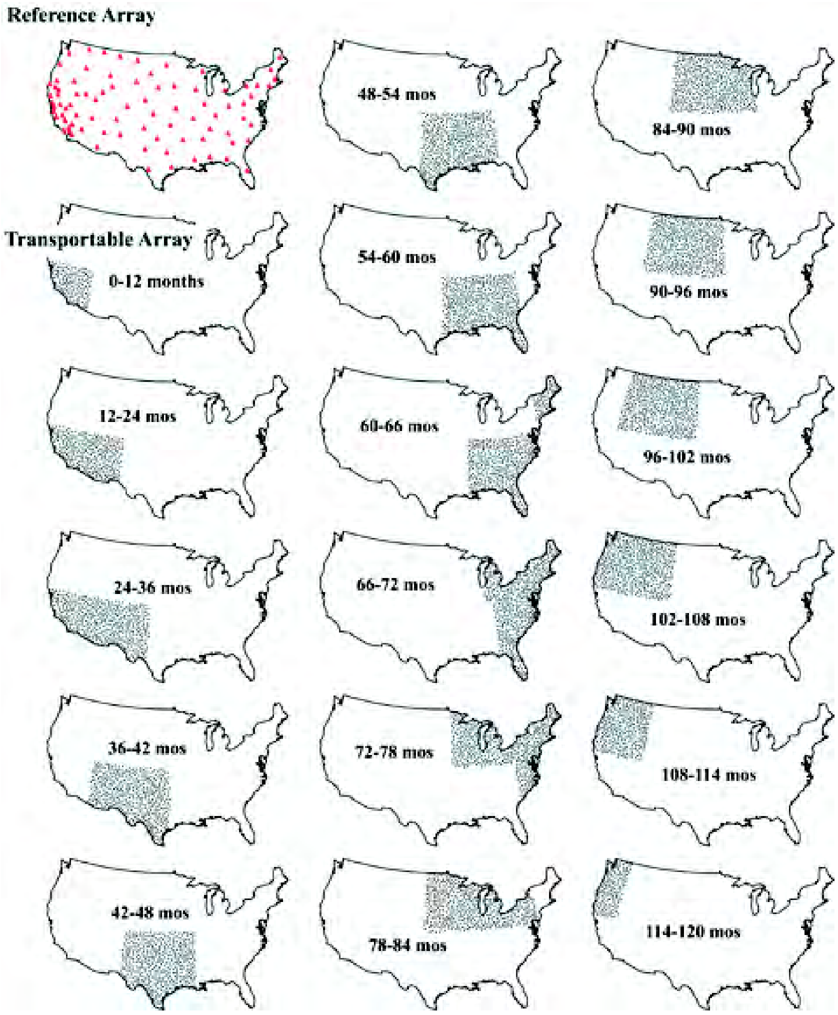


Figure 5. Snapshots of deployments, plotted above tectonic provinces or topography. (Figure courtesy of Alan Levander.)

Resistivities of silicate minerals in the mantle decrease systematically with temperature, allowing estimates of temperature from MT soundings. Seismic properties such as attenuation and compressional and shear wave velocities can be coupled with electrical resistivity to allow discrimination of the type and state of crust. For example, the conditions under which partial melting can occur can be ascertained by the joint use of velocity and resistivity. Interpretation of MT data is truly a three-dimensional problem but few surveys have the regional distribution of stations to permit development of a regional three-dimensional model. Coupling MT soundings with the transportable array would provide this needed three-dimensional regional MT structure and permit a quantum leap in our ability to interpret data. Reinterpretation of existing surveys in this regional context could reveal structures missed in the earlier, two-dimensional models, and new surveys would be planned with the regional network in mind. An outstanding scientific issue is the controversy over the existence of fluids in the old continental crust. Many MT surveys report the existence of moderately conductive lower continental crust, but petrological considerations appear to require a dry lower crust. One criticism of the conclusion that the lower crust is conductive is that MT surveys are most often done to delineate anomalous crust so that perhaps all we can conclude is that anomalous crust is conductive and we do not know the properties of normal crust. An advantage of coupling MT soundings with the transportable array would be a systematic sampling of the entire continental US, which is underlain in many areas by old, stable continental crust.

An important second component of USArray is an additional pool of ~2400 instruments (200 broadband, 200 short period, and 2000 high-frequency) that can be deployed using flexible source-receiver geometries. These additional portable instruments will allow for high-density, shorter-term observations of key targets within the footprint of the larger transportable array using both natural and active sources. This flexible component of USArray offers exciting opportunities for a variety of focused investigations requiring higher resolution images embedded within the context of the larger array. Resolution provided by this flexible array will vary from the 60-kilometer scale provided by the transportable array to the tens of meters scale, making it ideal for tying surface geology to deeper structures in the crust and upper mantle.

Many geologic targets are amenable to investigation using the flexible array. Examples include: the structure of seismogenic and creeping faults; delineation of magma chambers beneath active volcanoes; the relationship between crustal tectonic provinces and mantle structure; the shape of terrane boundaries; the deep structure of sedimentary basins and mountain belts; and the structure and magmatic plumbing of continental rifts. In addition, aligning the flexible component of USArray with respect to earthquake sources in the SW Pacific and South America will image the complex and dynamic structure of the core-mantle boundary with unprecedented clarity. These improvements in imaging will provide fundamental constraints on regions of the Earth that contain the boundary layers of mantle convection. The multi-scale observations provided by high-resolution images from the flexible array, deployed in coordination with geological, geochemical, and/or geodetic studies, combined with observations from the larger-scale transportable array will provide an unparalleled opportunity to understand whole systems and can be used to address a wide range of problems in continental geodynamics and tectonics. Examples include imaging and study of the continental arc system in the Cascades from slab to edifice, examination of the deep roots of the North American craton, imaging both ancient and modern orogens and rifts to determine secular variation in continental tectonics, identifying the role of the mantle lithosphere during orogenesis and rifting, and unraveling the relationship between deep mantle convection and surface tectonics.

The third component of USArray is an augmentation of the permanent seismic network in the US operated by the US Geological Survey. Permanent observations from a uniform, high-quality network provide fixed reference points for calibration of the transportable array and a platform for continuous long-term observations. Relatively dense, high-quality observations from a network with uniform spacing of 300-350 km across the continent is important for tomographic imaging of deep-Earth structure and will provide a continent-wide unaliased wavefield for long-period surface wave traveltime and diffraction tomography. Some or all of the stations of the permanent component of USArray will be equipped as expanded geophysical observatories, with GPS receivers to provide direct real-time data on crustal deformation.

The permanent component of USArray will be undertaken in coordination with the US Geological Survey, complementing the initiative underway at the Survey to install an Advanced National Seismic System (ANSS). The USGS is developing the ANSS to meet its mission in earthquake-hazard analysis and mitigation. To meet these goals requires a densification of the National Seismic System (NSN) with a focus on urban areas that have significant seismic hazards. USArray goals are to illuminate structure and understand dynamics of lithosphere and deeper mantle, which also requires densification of the NSN and uniform coverage of the continent. Thus, there is clear synergy between these efforts. The combined efforts and funding of the separate initiatives creates a single integrated network of ~100 high quality stations to meet the goals of both constituencies. All data from this network will be available in a single data stream to both communities. Coordination of these two initiatives is a prime example of interagency cooperation and cost sharing and continues the long-standing relationship and interaction between IRIS/NSF and the USGS on permanent seismic stations.

The GPS component of USArray is an important complement to the seismic instrumentation (see Appendix 4 for details). At least 65% of North America’s area has potential “signal” for a continent-wide array of high-precision GPS stations. Even the remaining “stable” area is important for GPS observations, partly because such stations help define a stable North American reference frame for the velocity field, and because it is possible that signals will be detected in the “stable” regions that are beyond our current understanding of displacements and stresses for cratonic regions. A continent-wide array of high-precision GPS stations, with strict configuration control to ensure accuracy, is also an imaging device, but in this case we seek to “image” the continent’s present-day surface velocity field. Over the length of the USArray project the velocity field can be processed to give the modern strain field in the plate boundary zone, as well as elsewhere in the continent. With this velocity field, we can constrain neotectonic processes at plate-boundary zones and other regions, contribute to earthquake-hazardestimates, test the limits of plate rigidity, and infer mantle rheology. We can also test hypotheses about how the current lithospheric mosaic responds to plate-scale and local stresses, and investigate enigmatic mid-plate seismicity such as the New Madrid zone.

4.2 THE GEOLOGIC COMPONENT OF USARRAY

The various geophysical components assembled into USArray will provide an unprecedented examination of seismicity, seismic-velocity variations, crustal and upper-mantle conductivity, and crustal movements on a continent-wide scale. To translate these images into a better understanding of the structure and evolution of the North American continent will require substantial interplay from various disciplines within the Earth sciences (see Appendix 3 for details). A strong geologic component to USArray is required to interpret the geophysical images, enable an understanding of continental evolution by providing timing and rate constraints, guide targeting of the flexible component of the array, and provide a multidisciplinary perspective for studies of problems that can no longer be solved by one technique alone.

The seismic instrumentation employed in USArray will create an image of the current seismic velocity structure of North America's crust and upper mantle. The seismic velocities of rock however, are affected by their physical state and chemical composition so that temperature, composition, mineralogy, shear fabric, and the presence or absence of pore fluids all play a role in their values. Important geochemical and geotechnical studies must be used to help interpret observed seismic-velocity variations, including: laboratory determination of phase proportions, mineral elastic parameters, and rock physical properties at differing pressure, temperature, and pore-fluid content; correlation of patterns revealed by surface exposures identified during field mapping with patterns observed in seismic data throughout the crust and upper mantle; analysis of xenoliths of deep material brought to the surface by certain types of explosive volcanism to correlate with seismic images and constrain the composition and physical state of the upper mantle; examination of the geochemical properties of magmas generated in the deep crust or upper mantle. Within the last decade, the fields of mineral physics, petrology, and rock mechanics have greatly expanded their ability to measure and understand these parameters, particularly at the temperatures and pressures of Earth's interior. However, to realize the full benefit of the seismic images produced by USArray, much work remains to be done in determining high-quality elastic parameters and their pressure and temperature derivatives, in order to translate seismic velocity maps into information about rock-type, physical state, and rheology.

In areas where tectonism and erosion have brought deeper materials to the surface, petrologic and structural analysis provide a wealth of information concerning the history of rock units and the conditions they experienced at depth. Detailed field mapping is a critical constraint for any seismic interpretation of continental structure and evolution. In concert with this, petrologic laboratory experiments that determine metamorphic reaction kinetics are necessary for understanding key components of the orogenic cycle. Geochronologic measurements can provide precise timing for both rock-forming and deformational events, and exhumation. Stratigraphic studies, some employing techniques in high-resolution geophysical imaging, can provide a detailed measure of vertical motions. Geomorphic studies can complement these data, particularly in more active regions, and particularly now that methods have been developed to measure rates of erosion using cosmogenic isotopes. Field examination is a critical component of continental structure and evolution studies, and a new focused program coordinated with USArray deployments will be needed, as well as a systematic effort to compile and make accessible the great deal of data that already exist (see section 4.3).

Xenoliths, random fragments of the deep crust and upper mantle brought to the surface by explosive volcanism, provide critical constraints on what rock types are present in the deeper crust and upper mantle, and permit construction of the compositional stratigraphy and thermal profile of these regions. Complementary but independent constraints on the composition of the deep crust and upper mantle can be obtained through geochemical and isotopic study of magmas, now crystallized and exposed at the surface. Such data can be combined with modern geochronological analyses capable of providing precise ages of formation and time-temperature histories for both xenoliths and exposures of igneous and metamorphic rocks. Such information is critical for understanding the degree to which surface and deep features are connected.

Modern geochronology can address many time scales, from the precise Holocene record now available through dating techniques that employ short-lived radioisotopes to developments that allow uranium-lead ages to achieve precisions of ±1 million year on rocks as old as 4 billion years. At shorter time scales, geochronologic techniques can be directed at issues such as the record of movement along faults, the rate of uplift or subsidence in tectonically active settings, and the recurrence interval of active volcanoes. At longer time scales, geochronology can address issues of continental growth rate, identify terranes of differing age and history, define the timescale of deformation accompanying continental collision or rifting, and address whether seismic anisotropy in the crust and upper mantle is a response to modern strain fields, such as plate movement, or was frozen in from ancient deformation events.

Geochronology is a technique of similar maturity to seismic imaging. With recent breakthroughs in analytical throughput and cost, and with the precision and range of applications currently available, resolution of most of the important events in the development of the continent is possible, and doing this at a continental scale is feasible. The quality of continent-scale imaging that will be provided by USArray can only be fully exploited by a coordinated geochronological effort capable of resolving major events involved in the assembly and break-up of North America, and providing rate and timing constraints on both ancient processes and those that are currently responsible for North America’s geologic hazards.

4.3 EARTH SCIENCE INFORMATION SYSTEM

Shared and critical requirements for all components of the EarthScope/USArray are communication (telemetry), a data archive, and access to and management of diverse data sets. A data management system (archive, distribution, and visualization) that will simultaneously allow integration of geological and geophysical information is critical to scientific analysis. All seismic, MT, and GPS data from USArray will be archived and available in near-real time and integrated with appropriate geologic datasets and provided openly to the research community, educators, government agencies, and agencies responsible for hazard assessment.

EarthScope/USArray provides a forum to aid the development of an Earth science information system that can be accessed easily by the broad Earth science community, educators, government agencies, and the interested public. Development of an Earth-science information system fits within NSF priorities to develop and enhance information technology. Ultimately, such a system could end up as the greatest legacy of the EarthScope/USArray initiative. Consider the state of the Internet, just some 10 years ago (or less, from many people's perspective). The Net was a rich source of information, but it was also a relatively hard-to-use, hard-to-navigate, hard-to-integrate jumble of ftp, telnet, gopher, wais and other sites and protocols. The arrival of the world-wide web in a short time transformed and democratized the Internet, and initiated a revolution in information exchange. In the natural sciences today, although we have many data and many tools for manipulating and visualizing these data, we have few if any software tools analogous to a web browser that can seamlessly bring Earth and environmental science data to our attention and use. This system would be highly transportable to other fields of science and data management.

The IRIS Data Management Center (DMC) has a well-established system for distributing and archiving large volumes of digital waveform data over the Internet. The huge data stream to be produced by the seismic component of USArray requires a dedicated data management facility. IRIS has also agreed to archive and distribute MT data from EMSOC (the University Consortia for ElectroMagnetic Studies Of the Continent). Both IRIS and UNAVCO can archive and distribute GPS data. The USGS is developing archives of potential field data, geochemical data, digital elevation, remote sensed data, and map data that are accessible via the Internet, but these efforts are in various states of completion. A concerted effort will be required to bring these data bases to a level where they can be used routinely in Earth science investigations. An attempt also needs to be made to develop a data base of drill hole and industry reflection profile data.

A growing realization in information systems is the need to provide end users not only with access to data, but also with software to aid data integration and manipulation. Software for data exchange, integration, and visualization tools needs to be developed. With today's technology, a "facility" encompassing an Earth Information System could be distributed, but it needs to have underlying standards and coherence to accomplish the research and applied goals of EarthScope/USArray. Such a facility would vastly improve the ability to combine geologic and geophysical information to meet the scientific goals of the EarthScope/USArray project and can serve as a tremendous resource to the whole Earth science community.

A considerable amount of information already exists from decades of geological, geochemical and geochronological studies of North America. Much of these data, however, are in a form that is not readily compared with other information, such as the geophysical images to be returned by USArray. A large portion of this geological data exists only in print-published tables and maps, or in electronic format in an individual scientist's computer. For several large categories of Earth science data, no data exchange standards exist to facilitate information sharing. To maximize the availability of the existing information there is a need to assemble these disparate data into a consistent format that can be accessed and used by the whole geoscience community for multidisciplinary studies. The need for format standardization and for data archiving is obvious. One need only consider some potential applications to understand the utility of such an easily accessible database. For example, one might wish to overlay a map of seismic velocity in the upper mantle with a compositional map of basaltic volcanism in the western US. Similar efforts in the ocean sciences have revealed a global correlation between degree of partial melting and elevation of ocean ridges that was quickly translated into dynamic models of the temperature structure beneath the ridge and its relation to spreading rate and volcanic productivity.

Full interpretation of the information returned from the USArray geophysical instrument will be aided greatly by ready availability of geological data for North America. An important part of the data management mission is to facilitate the adoption of standards for data exchange by the geologic community and to facilitate the transcription of existing data into these standards. EarthScope/USArray provides a forum to coordinate and work with the USGS, State Geologic Surveys, and other agencies with geologic data to establish data exchange formats and protocols to ensure that overall data access and management is facilitated for the benefit of the entire scientific community.

4.4 EDUCATION AND OUTREACH

A highly visible, science-driven initiative such as USArray offers many possibilities for outreach and education to reach the general public, K-12 students and teachers, and Earth science students and professionals at all levels. USArray will capitalize on the public's natural interest and excitement in earthquakes and Earth science and will make these subjects relevant on a region by region basis as the array is deployed across the country. The USArray education and outreach program will convey both the new scientific results that emerge from the USArray national scientific effort, and perhaps as importantly, the nature of our scientific method.The USArray program will extend across the country and continue throughout and beyond the lifetime of the project (see Appendix 6 for more details).

As USArray moves across the country it will be coordinated with a comprehensive educational and outreach program highlighting both overarching and regional Earth science issues (hazards, structures, resources) and links between Earth science and society. Specific initiatives will include development of Virtual Seismic Network Explorer (see Appendix 6.6), software for use by educators in K-16 educational programs, museum displays, public and commercial media programs, teacher workshops, and educational materials and activities linked to array data and Earth models available over the Internet. As a result of the National Science Education Standards and state standards, many K-12 teachers are having to teach Earth science for the first time. USArray can help get new and exciting content into the curriculum through a real experiment. Students can learn science by doing science. Programs will be designed and targeted to engage communities in USArray before, during, and after passage of the array through specific regions of the country. USArray can reach national audiences through PBS/Discovery Channel programs, an "Earth Minute" on NPR, and regular feeds to Weather Channel. The latter could include earthquake reports, real-time data feeds, and an "Earthquake of the Day" and could highlight geologic structures and hazards that are unique to the region currently occupied by the array.

4.5 OPERATIONAL MODE, COMMUNITY INPUT, SCIENCE SUPPORT, PARTNERSHIPS

USArray is science-driven, and the facilities developed through its deployment are community resources. To maximize the scientific return from USArray and maintain the flexibility to fund the best science, the operation, management, and use of the facility must incorporate high-quality, peer-reviewed, PI-driven research; quality controlled data acquisition and archives; standardized data exchange formats; and open and timely access to data. These requirements must be met with an attitude of cooperation within the Earth science community using the data and a commitment to service from the USArray facility operators.

The flexible component of USArray will provide high spatial resolution images of features in the lithosphere and deep mantle. Unlike the transportable and permanent components of USArray, the flexible array will not be capable of imaging all of North America. Consequently, deployments of the flexible array will be selected through proposal competition with the expectation that specific geological problems requiring multidisciplinary investigations encompassing a wide spectrum of the Earth sciences will be a critical component of a successful proposal. Many geologic and deep Earth targets are amenable to investigation with the flexible array. To choose the best targets from those proposed for the flexible array will require balanced review from a wide segment of the Earth science community.

To engage the broadest possible participation of the Earth science community and to maximize scientific return as USArray sweeps across the country, regional workshops need to be held to define regional science objectives and to engage a broad spectrum of scientists in the initiative. Three workshops, one each focusing on the western US, central US, and eastern US, should be held within the first year of the project. The purpose of these workshops is to inform and educate the community about the capabilities of USArray, to begin to engage and enfranchise a broad spectrum of scientist and educators, to begin to facilitate and encourage cross-disciplinary investigations, and to begin to develop the infrastructure, contacts, and databases to maximize the use of USArray.

Additional regional workshops should be held two years in advance of the transportable array deployment in an area. The purpose of the second set of workshops is to focus on important targets and investigations within the array footprint, to foster early multidisciplinary exchange, and to identify and utilize existing infrastructure, contacts, and databases in each area. If done successfully, this will ensure the development of compelling, high-quality science proposals to make use of the USArray facility. Additional workshops should take place six months in advance of deployments after proposals are funded for project coordination, a year after the deployments to share initial results, and two years after deployment for data integration. These workshops will help foster the best science plans and the most timely publication of results.

The Earth science community, working in concert with NSF EAR and other appropriate federal and state agencies, will need a higher level of research support than is currently available for the broadly based science envisioned for EarthScope facilities. Possible models of support to explore include those employed by the Ocean Drilling Program, the NSF Science and Technology Centers, and focused NSF programs similar to MARGINS and RIDGE. Regardless of the final mechanism (or set of mechanisms) used to support science, it is essential that NSF's peer-review system evaluate proposals submitted to use the USArray facilities.

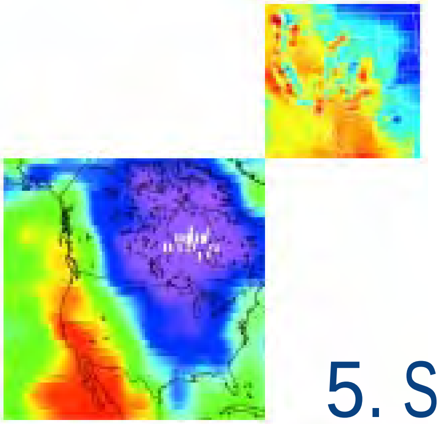
The goals of the USArray review are to: (1) to maintain the delicate balance between excellent single-investigator science and larger multidisciplinary projects, (2) over the next ten years, to forge a truly national initiative to image North America and (3) to facilitate a gradual change to more integrated science that will last well beyond the time span of USArray. To achieve these goals will require a pool of reviewers familiar with the objectives of the initiatives and the fundamental scientific issues, and also an NSF panel structured to accommodate the potential multidisciplinary nature of the investigations. The review process needs to include mechanisms to facilitate multidisciplinary investigations, provide oversight, long-term perspective, and fair review, all the while encouraging the individual creativity, insight, and innovation that comes with PI-driven research. Finally, while we seek to maximize the potential scientific return from coordinated studies of the North American lithosphere and deeper Earth, the best science must continue to be funded wherever these investigations take place around the globe. An appropriate balance and level of funding must be found and maintained.

An initiative of this scope obviously requires a number of partnerships between the academic Earth science community and a variety of organizations including: the National Science Foundation, US Geological Survey, regional seismic networks, State Geological Surveys, and academic consortia (IRIS, UNAVCO, and EMSOC). International partnerships and collaborations with industry will also be important as the project matures. These partnerships should be explored and developed at the earliest stages possible.

4.6 BEYOND RESEARCH

The resources and results from USArray will find wide application in a variety of issues of growing societal need by advancing our understanding of natural hazards and natural resources throughout North America. The opportunity for these applications should be included in the early planning and implementation stages of USArray. The flexible array in particular will be a powerful tool for focussed studies of natural hazards such as magma movement around active volcanoes in the Pacific Northwest. The flexible array will also extend the instrumentation available for attacking a wide range of problems in fundamental studies in earthquake dynamics, fault zone imaging, characterization of fault zone properties, and movement on faults in seismically active regions. The instruments of the flexible component of USArray will also provide a unique resource for basin studies to characterize the potential for strong ground motions in urban areas. Many such studies are already underway as part of efforts by the USGS and other organizations, but partnerships between these studies and USArray will be especially powerful because USArray offers additional instruments for process-oriented studies and the ability to link small-scale tectonic activity through to large-scale driving forces.

Different elements of USArray will also provide information on local and regional scales useful to resource managers. The high-frequency instruments in the flexible array will be available for three-dimensional regional groundwater resource assessment and management studies. For example, studies of the detailed geometry of aquifers around major western



5. SUMMARY

A national program on the scale of USArray, within the framework of EarthScope, can catalyze solid-Earth science research and help organize this discipline's contribution to Earth-system science in North America. The scientific and organizational structure underlying this multidisciplinary facility can serve as an umbrella for Earth-science studies in continental structure, dynamics, and evolution, and studies of the deeper Earth, and can:

- Provide a structured and flexible platform for integrated studies of the North American continental lithosphere and deeper Earth structure;
- Provide a context for understanding and integrating diverse geological, geochemical, geophysical, and geodetic data sets;
- Provide continuity between studies from local to global scales;
- Greatly expand the culture of shared and coordinated resources within Earth sciences including data management, technical resources, E&O expertise, and readily and openly available data;
- Involve and engage many colleges and universities across the country;
- Improve science education (K-12, and general public), science literacy, and the profile of the Earth sciences.

Finally, perhaps the most exciting aspect of this initiative is the prospect of unanticipated discovery, the unveiling of results and insights we can not yet imagine. We need only look back 10 to 15 years to see the dramatic evolution of our discipline by comparing our views of Earth structure and dynamics then and now. Advances in facilities, techniques, theory, and data integration have made and will continue to make this dramatic progress possible. USArray, as an element of EarthScope, presents an exciting opportunity for growth and development of new ideas. There is no doubt that a facility like USArray and our approach to solving scientific problems will evolve over the 10-15 year period of its operation. Novel ideas will emerge and new research targets will be identified which will require new theory, analysis techniques, and research tools. Our understanding of Earth structure and dynamics will undoubtedly be more comprehensive and complete and perhaps as different from our view today as that of 10-15 years ago.

APPENDICES

Appendix 1: The Seismic Component of USArray

- 1.1 History of the USArray Initiative
- 1.2 USArray Imaging Science Technical Specification
  - 1.2.1 Earthquake Detection and Frequency
  - 1.2.2 Resolution Measures for Direct Wavefield Imaging
  - 1.2.3 Direct Teleseismic Imaging with USArray
  - 1.2.4 Teleseismic Imaging using Surface Waves
  - 1.2.5 Active Source and Microearthquake Seismology
- 1.3 Development of a Virtual Seismic Network
- 1.4 Station Operations within USArray

Appendix 2: USArray and the Deep Earth

Appendix 3: The Geologic Component of USArray

- 3.1 The Need for Multidisciplinary Investigations
- 3.2 Time – The Fourth Dimension
- 3.3 Heat flow and Potential Field and Remotely sensed Data
- 3.4 The Geologic Facility for USArray

Appendix 4: The GPS Component of USArray

- 4.1 Scientific Applications for a Continental GPS Array
- 4.2 Scope, Cost, and Logistical Considerations

Appendix 5: The Magnetotelluric Component of USArray

- 5.1 Scientific Applications for Continental Scale MT Images
- 5.2 Magnetotelluric Instrumentation

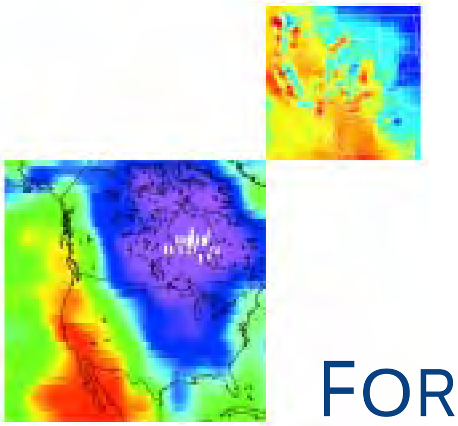
Appendix 6: Education and Outreach

- 6.1 Development of Educational Products.
- 6.2 USArray web site
- 6.3 Pre-installation E&O Activities
- 6.4 Education and outreach efforts during the deployment
- 6.5 Education and outreach activities subsequent to deployment
- 6.6 The Virtual Seismic Network Explorer

Appendix 7: USArray and Continental Margins

Appendix 8: Synergy with other EarthScope Initiatives

Appendix 9: Viewgraphs/Overheads



FOR FURTHER READING

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