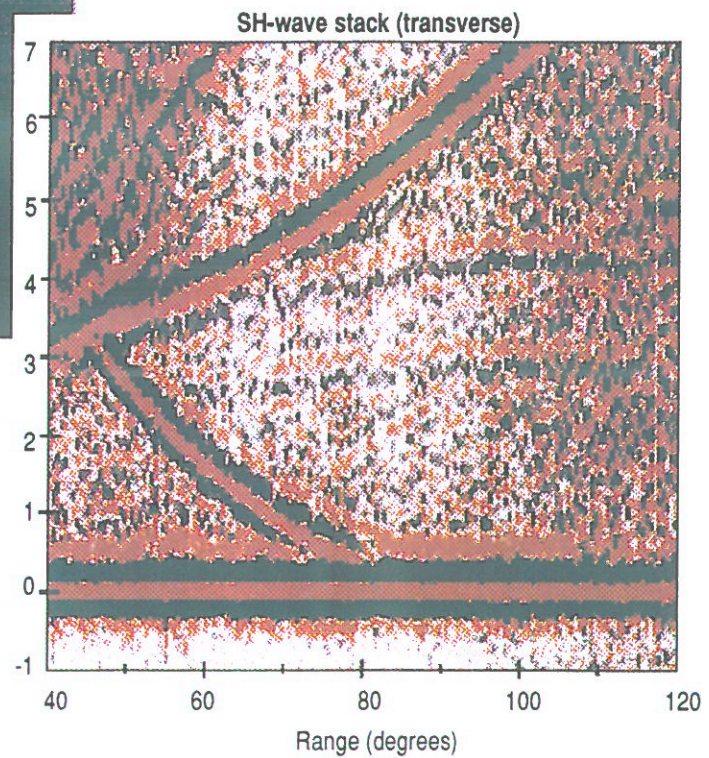


Impact

The importance of modernized seismic instrumentation
for basic Earth science research

Research Opportunities — Recent accomplishments — New Possibilities



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The past decade's advances in seismic instrumentation and supporting technology have increased by orders of magnitude our capability for studying the Earth. We can now track, in detail, an earthquake in dynamic rupture. It is possible to map discontinuities and anomalies in the Earth's interior with an unprecedented degree of resolution and robustness. Sophisticated seismological tools can now be applied to practical problems in society.

One of the most exciting frontiers in understanding the earth's dynamic evolution, and the origins of the continents and oceans, is access to the third dimension provided by seismic methods. The impact should be as significant to the field of seismology as imaging and noninvasive diagnostics have been to the field of medicine.

From studying the Earth and earthquakes, it is now possible to envision an increase in the order of magnitude of obtainable resolution. The qualitative jump in perspective should be comparable to that resulting from planetary imaging by spacecraft.

These capabilities can be mobilized in large programs involving dozens of scientists, or may be put at the disposal of investigators with modest needs. With current communications and computer capabilities, seismic data can be obtained and analyzed in near-real time.

The past six years have seen the gestation of the IRIS facilities programs, now functional and ready for deployment at the levels recommended in 1984. At the same time, the geophysical community has welcomed a new cadre of motivated young scientists who have a keen sense of anticipation for the new instrumentation, and strong analytical skills for making the most of it. Several efforts at developing multidisciplinary cooperative or consortium science programs have appeared, and the community is only now becoming skilled in working together at this level.

The breadth of Earth science, and its manifold possibilities for the next decade, are too vast to be encompassed in a manageable science plan. We present, therefore, a selection of short essays and recent cases which concretely illustrate the progress being made in observational seismology, and the promise for the future. We also recommend rereading the 1984 IRIS Proposal and Program Plans, whose vision of the future has been well-vindicated, and whose long-range goals remain fresh and relevant.

I Research Opportunities

- 1 Global Dynamics
- 2 Earthquake Sources and Seismic Hazards
- 3 Dynamics of the Crust-Mantle System
- 4 Crustal Structure and Tectonics
- 5 Physics of Wavefields in the Earth
- 6 Research on Seismic Verification of Proposed Nuclear Testing Treaties

II Recent Accomplishments: Selected Examples

- 1 Rapid Determination of Focal Parameters: The Iran Earthquake of 20 June 1990 Kanamori, Wallace
- 2 Structure of the Middle Mantle from Tomographic Techniques Dziewonski
- 3 The Lowermost Mantle: P and ScS travel times Dziewonski, Woodhouse, Woodward et al
- 4 The Lowermost Mantle: Diffracted P McClurg & Creagar
- 5 The Inner Core, with Free Oscillation Splitting Widmer, Masters, Gilbert
- 6 Globally Averaged Record Section Shearer
- 7 Regionally Averaged Upper Mantle Reflections Revenaugh & Jordan
- 8 Portable Arrays for Teleseismic Recording: the Subcontinental Mantle Silver et al
- 9 Portable Arrays for Teleseismic Recording: the Lower Mantle and Core Silver and Bina
- 10 Tomographic Image of the Upper Mantle under the Great Basin Dueker and Humphreys
- 11 Tomographic Image of the Slab under the Cascadia Subduction Zone VanDecar, Crosson, & Creagar
- 12 Surface Wave Tomography for Upper Mantle Structure Snieder
- 13 Mountain Belts Driven by Subduction and Delamination Oldow, Bally, Ave Lallemand
- 14 Velocity and Structure of Paleozoic Orogenic Crust Braile et al, Keller et al
- 15 Robust Velocity Inversion of Wide Angle Reflections Lutter et al
- 16 Tectonic Underplating of Oceanic Crust, Alaska Page et al, Fisher et al
- 17 Airgun Sources for Imaging the Continental Margin Henyey
- 18 An Array for Crust and Mantle Imaging Using Converted Waves Randall, Owens
- 19 Use of Explosive Source for Crustal Reflection Imaging Jarchow et al, Brocher et al
- 20 Reflection Profile of the Southern Appalachian Thrust Sheet Coruh et al
- 21 GLIMPCE Profiling of Precambrian Crust Behrendt et al
- 22 Imaging the Continental Lithosphere: New Body Wave Techniques Clarke & Silver
- 23 Hawaii: Imaging the Big Island using Earthquake Clusters James, Savage, Thurber
- 24 Reflection Imaging of Extensional Crust: the Whipple Mountains Okaya et al
- 25 Tomographic Image, Medicine Lake Volcano Evans, Zucca
- 26 Loma Prieta Velocity Structure: Correlation with Aftershock Distribution Lees, Malin
- 27 Earthquake Hazard and Subsurface Structure: the Kettleman Hills Anticline Meltzer, Ekstrom et al
- 28 Very Broad Band Study of an Intraplate Earthquake Zhao & HelMBERGER
- 29 Loma Prieta Focal Mechanism From Global Seismic Stations Wallace
- 30 Very Broad Band Study of a Local Earthquake Kanamori, Mori, and Heaton
- 31 Rapid Determination of Earthquake Mechanisms from Global Digital Networks Dziewonski
- 32 "Slow" Seismic Events inferred from a Decade of Continuous Normal-Mode Data Beroza & Jordan
- 33 Field Determination of Earthquake Site Response Hajnal, Park, Hough
- 34 Yield Estimation of Underground Nuclear Explosions Hansé, Ringdal, & Richards
- 35 Coherence of Seismic Body Waves as Measured by a Small Aperture Array Vernon et al
- 36 Discrimination between Nuclear and Engineering Explosions Hedlin, Minster, Orcutt

III New Possibilities: Selected Examples

- 1 Imaging Dynamical Processes in the Mantle and Core
- 2 Detailed imaging of upper mantle dynamics North American Transect
- 3 Structure and Dynamics of the Sierra Nevada uplift
- 4 Core-Mantle Boundary Structure from Regional Portable Arrays
- 5 EDGE: Onshore-Offshore Studies of Passive Margins
- 6 Dynamic Study of an Active Blind Thrust
- 7 Dynamics and Structure of the Tien Shan- Pamir Collision Zone
- 8 Imaging the Loma Prieta fault zone using a marine airgun
- 9 Interdisciplinary Crustal Experiment: Terrane Accretion in Southeast Alaska
- 10 Subducting Ocean Crust beneath the Oregon Continental Margin
- 11 Beamforming of portable array data for imaging mantle discontinuities
- 12 Undergraduate Field Camp: Detect and Locate Small Earthquakes
- 13 Earthquake Rapid Response Experiment
- 14 Reconnaissance for shallow anomalies: hazardous waste site

I. Research Opportunities

Seismology has been a primary observational tool for the geophysical and geological study of the earth. Each advance in the capabilities of seismology has opened up new opportunities for earth science. In these essays we consider the advances made by the advent of the high dynamic range, broadband digital seismology of the Global Seismographic Network and the PASSCAL arrays.

1 Global Dynamics

A fundamental goal of the Earth scientist is to understand the origin and evolution of our planet. A combination of advances from seismology and other solid Earth disciplines is now leading to the development of a global dynamic theory — the next step beyond plate tectonics. Its task is the quantitative integration of a broad range of observations spanning geology, geophysics and geochemistry. The first order dynamic model will provide a common framework that integrates thermal and chemical transport processes occurring inside the planet, from inner core to upper mantle and lithosphere. The observations contributing to this dynamic theory must include a wide range of measures of both physical and chemical properties in three dimensions and (if possible) in time. Important observations include:

- The gravity field (especially the geoid) which gives an integrated measure of mass anomalies in the interior.
- The topography, especially dynamic topography, which measures the bowing up and bowing down of the Earth's surface in response to mantle convection.
- The wide variety of observations which constrain the kinematics of oceanic and continental plates.
- The variations in the magnetic field which we think may constrain core-mantle interactions.
- Variations in both the rotation and gravitational field of the Earth and the post-glacial deformation of crust, all of which constrain the rheology of the mantle.
- The heat flow out of lithosphere constraining the efficiency of thermal convection.
- Isotopic observations of mantle derived basalts constraining the time scale of mantle processes and the chemistry of mantle reservoirs.
- Laboratory measurements of the chemical and physical properties of materials at simultaneous high temperature and pressure.

Geodynamics has recently made considerable progress with use of broad frequency band seismic observations from global networks (e.g. IDA, GDSN, Geoscope, NARS), as well as regional arrays (e.g. Warramunga, Grafenberg, NORSAR). There are now preliminary three-dimensional models of seismic velocity structure at all depths in the Earth from the inner core to the upper mantle. Some of the specific results of these seismic models include:

- The first quantitative explanation of the Earth's low order gravitational field in terms of lower mantle structure.
- The correlation of the distribution of hot-spots occurring on the Earth's surface with the location of seismically slow (and perhaps hot) zones in the deep lower mantle.

- The unexpectedly high ratio of shear to compressional velocity perturbations in the lower mantle. A similar ratio was found in the upper mantle where it was explained by partial melting.
- The detection of a high level of regional heterogeneity at the base of the mantle which has characteristics reminiscent of near-surface structure.
- The detection of anomalous signals which sample the inner core, and may be caused by large-scale anisotropy.

These and many other issues, especially slab penetration into the lower mantle, and topography on the core-mantle boundary, remain controversial. Despite this, the results are spectacular, for features of mantle and core motions, previously only theoretical, are now being observed. Knowledge of the deep three-dimensional seismic structure leads not only to a static view of mass anomalies' locations inside the planet, but contributes to our understanding how the convecting system evolves over time. Although mantle maps provide only a snapshot of a time evolving system, the morphology of thermal structures integrates the changing convection pattern over time, and gives us direct clues as to how mantle material is transported. This approach becomes particularly attractive when the seismological models are combined with the kinematics and topography on the Earth's surface. It is not difficult to envision dynamic models of mantle convection which satisfy three-dimensional seismic structure on the one hand, and predict the evolution of plate motions and continental dynamic topography on the other.

A wide variety of seismic observations is needed in order to constrain the mantle convection and other processes now occurring in the interior. These observations can be divided into two broad categories: maps of lateral structure, and maps of the deformation (topography) of internal boundaries. From a dynamic perspective the maps of internal structure are images of the buoyant entities inside the Earth driving the flow pattern, while the deformation is the result of those flow patterns.

The lateral structure is determined from tomographic studies, in which waveform distortions from a large number of raypaths crossing each target region are inverted. This is to determine velocity or attenuation. The internal boundaries are located by scattered waves, either reflections or conversions. In both cases, a large number of signals must be observed and processed. We envision that seismic data of all frequencies and wavelengths will be used in constructing maps of internal structure. At the lowest frequencies, free-oscillation measurements are sensitive to the largest scales of heterogeneity, and give direct constraints on lateral variations in density. Surface waves give good lateral resolution of upper mantle structure, but need to be augmented with other data to give good depth resolution. Body waves give the best depth resolution of aspherical structure, and can be used to map topography

of internal discontinuities. All these data are sensitive to both anelastic and anisotropic structure, as well as the large-scale lateral variations in elastic structure. Several problems require high resolution of specific structures such as slabs, plumes and small-scale scatterers. These problems can be addressed by experiments which locally densify the global array with PASSCAL instrumentation.

With the existing network, global seismology has been able to provide some of the necessary observations for developing a coherent picture of our planet. Lack of good global coverage, and of specific types of data, have led to areas of controversy. Here are some of the major scientific problems that global seismology faces:

- Characterization of the nature and depth extent of differences between oceans and continents. Do differences extend to great depth, or are the major chemical and thermal differences confined to the upper 200km of the Earth?
- The enumeration and location in depth of the global-scale discontinuities in the upper mantle.
- The question of communication between the upper and lower mantle. Is there significant mass transfer across the 670km discontinuity, or is mantle convection layered into two or more regions? A key to answering this question is to image the geometry of subducting slabs after they become aseismic. This important question will probably not be fully resolved until we have datasets which can image the shapes of subducting slabs, and resolve the topography and property contrasts of the upper mantle discontinuities.
- What is the size-spectrum of heterogeneity in the vicinity of the core-mantle boundary (CMB)? We have evidence for very large-scale structures of continental dimensions and also for small wavelength scatterers at or above the CMB. There is also tantalizing evidence for a first-order discontinuity just above the CMB. Resolution of this part of the Earth may allow us to determine whether or not the core and mantle are chemically interacting, if there are "continents" on the CMB, if the topography of the CMB significantly affects flow in the outer core, and if there is a strong thermal boundary layer implying a large heat flux from core to mantle.
- What is the physical nature of the inner core? This body is only slightly smaller than the Moon, yet we have little understanding of its properties. Seismic signals which sample the top of the inner core reveal a body which is highly attenuating and which appears to have extremely anomalous wave-propagation properties. Improved resolution of this body will lead to a better understanding of the evolution of the core and mantle.

Exploration of the earth's interior is still exploration of a terra incognita. Greatest excitement comes from discovery of hitherto unseen animals. We propose looking for:

- Images of plumes, rising from the lower mantle, narrowing upward, defined by tomography and by scattered signals.
- Images of old pieces of lithospheric slabs, "parked" in the mantle. Perhaps these are accreted to the base of the lithosphere, perhaps near the 670 km discontinuity, perhaps at the base of the mantle.
- Definitive recognition and resolution of "continents" accreted on the core-mantle boundary.

We have the technology (both intellectual and computational) to provide a high resolution image of the entire Earth's interior. Such images would provide the fundamental input needed for developing a coherent model of the dynamics of our planet. What we lack are the truly global-scale datasets needed for giving us the overall picture of structure, and special datasets for yielding high resolution images of particular features. The GSN and PASSCAL programs are the keys to providing us with these datasets, and should be implemented as quickly as possible.

2. Earthquake Sources and Seismic Hazards

The word seismology is derived from the Greek word "Seismos" which means earthquake. A literal translation of the word seismology would be "earthquake science". The role of seismology has expanded considerably beyond this definition, but the quest to understand earthquakes will always remain central to the science. Beyond basic research into the physics of the fault rupture and seismicity, this subfield of seismology makes an important contribution to the needs of society. Earthquakes are one of the most devastating and frightening forces in nature. The contributions that our science can make toward mitigating their adverse effects are considerable.

Predicting the precise timing of damaging earthquakes is an oft-voiced goal and remains a major challenge. It is clear that our knowledge of fault mechanics in the real Earth is incomplete. However, many recent geophysical and geological field results show that the detailed processes taking place in an earthquake are now subject to experimental investigation. The accumulation of these results now makes it possible to make forecasts, and to assign risks; acquiring the data needed to do this is now a high priority. Moreover, the mitigation of earthquake damage critically depends on the interaction of man-made structures with ground motion in the near-surface geology. Detailed seismological investigation of this interaction is a relatively new enterprise, but has already given important insight into damage caused by recent earthquakes in Mexico, Northern California and Soviet Armenia. IRIS, in collaboration with the National Center for Earthquake Engineering Research (NCEER) and the U. S. Geological Survey, has facilitated the collection and distribution of an unprecedented aftershock data set following the 1989 Loma Prieta earthquake.

New technologies are crucial to learning, in detail, the dynamics of earthquakes, the phenomena which precede earthquakes, and their relationship to geological structure. They provide near-real-time capability for monitoring fault and aftershock behavior in the critical hours and days immediately following a major earthquake. The IRIS facilities, services and standards play a major role, in partnership with the new U.S. National Seismic Network (USNSN), and earthquake programs of the U.S. Geological Survey. A significant modernization and integration of regional and local monitoring networks can be anticipated in the next decade, based on increasing integration of the IRIS and USGS technologies.

The GSN will provide broadband data on a global scale, enabling detailed study of the rupture process of larger earthquakes. The rapid dissemination of such data through the Gopher system and through satellite telemetry has, in the past 18 months, encouraged a variety of researchers to study the mechanisms of large earthquakes. In North America, the US National Seismic Network and regional networks, with the growing number of IRIS/GSN stations, will allow detailed modeling of smaller earthquakes. Special deployments of portable PASSCAL instrumentation can provide detailed local information.

Seismic Sources

The recognition that fault displacement is not uniform, but is concentrated on patches of high strength, is a major advance of the last decade. The locations of these strong patches (asperities) seem to influence several important properties of major earthquakes: (1) speed of propagation and limits of the rupture, (2) which areas are subject to the largest strong ground motion in a major earthquake, and (3) the location of the rupture zone of the major earthquake in relation to smaller earthquakes. Each can influence the amount and location of damage caused by the earthquake.

Our understanding of the earthquake rupture process in a variety of tectonic settings will increase greatly with installation of the proposed global broadband network. Broadband data from the GSN may overturn many generalizations about the rupture process made from older narrow-band data. Recent analysis by Kanamori (1989) of a small earthquake in Southern California, using broadband data, has shown that the stress drop on local asperities can exceed 2 kilobars. A decade ago, researchers were mostly content with estimates of stress drop averaged over the entire rupture (typically 20-100 bars), because narrow-band data lacked the time resolution necessary for detailed modelling. The old paradox of fault rupture with low estimated stress release may be a false one.

The detailed imaging of the fault zone of a large earthquake depends on high quality data in the near-field. GSN and PASSCAL instrumentation are comple-

mentary in this regard. GSN stations provide broadband, high dynamic range data needed to quantify basic properties of the earthquake source (e.g. moment and mechanism), while PASSCAL instruments are designed for flexible deployments to address specific scientific issues. For example, PASSCAL instrumentation has proven to be an excellent monitoring system for aftershock studies; after the recent Loma Prieta earthquake 25 instruments were deployed and recorded more than 10,000 events. The 2-Hz three-component sensors used in this deployment provided data for mapping of residual stress release around the fault zone, and for tomographic inversions of the near-fault velocity structure. The advent of portable broadband sensors for aftershock deployments will allow researchers to better model the rupture processes of individual aftershocks, and to better follow the physics of stress release in the fault zone.

The phenomena that *precede* damaging earthquakes are most provocative. Continuous geodetic and seismic monitoring of these precursory phenomena, such as transient uplift and foreshock seismicity, are being conducted in many locales (e.g. the San Andreas Fault near Parkfield, California, the San Jacinto Fault near Anza, California). Portable PASSCAL instrumentation using broadband sensors can be used to densify coverage temporarily near fault segments identified as high-risk, so that the physics of presumed foreshock activity can be better modeled. For unmonitored fault zones with low-levels of seismicity but significant hazard potential, PASSCAL instrumentation can be used in short-term, yet detailed, studies of the local seismicity and stress release. The discovery by Beroza and Jordan (1990) of "slow" or "silent" earthquakes [Figure II.32] whose source spectrum is concentrated in the normal-mode band, provides a new tool for studies using the GSN to look for premonitory phenomena; this work particularly requires the highest performance of very broad band, high dynamic range, and continuous, high quality data.

Seismicity and the Relation of Earthquakes to Geologic Structures

Basic questions remain about how geologic structures determine where earthquakes of different sizes occur. There is much debate about whether or not earthquake rupture termination is controlled by geometric obstacles (fault bends or jogs), or by rheological barriers (strong or weak "patches"). The factors involved are diverse. Collecting a large base of quality seismic data will be essential to resolving this debate. As long as the number of events with adequate data coverage is small, the generalizations that are made are, at best, anecdotal. To understand how geometric factors influence the earthquake rupture process, an integrated approach combining high resolution imaging of geologic structures (e.g. seismic reflection) with precise location and dynamical analysis of earthquakes provided by a dense, local seismic network, will be essen-

tial. An example from the Kettleman Hills blind thrust structure is given in *Figure II.27*. Future experiments are likely to involve use of PASSCAL instruments in multiple configurations with some instruments used for earthquake monitoring, and others used for crustal imaging.

Site Effects and Microzonation

It has now been firmly established that ground-motion amplification caused by low velocity, near-surface materials profoundly influences what areas are likely to suffer the most in a major earthquake. Although surface geology itself is a good first-order indicator of seismic hazard, quantitative assessments of ground motion amplification during an earthquake require a combination of seismological surveys and modelling studies. PASSCAL instrumentation can provide an important resource for allowing seismologists and earthquake engineers to produce microzonation maps for urban areas at risk. A range of experiments for studying site effects are feasible. Small-scale experiments with 10 or fewer instruments would suffice in recording local sources (microearthquakes or quarry blasts), or ambient noise. Such experiments can identify preferential shaking directions, as have been noted in recent data from the Loma Prieta deployment. Larger experiments involving 3-component stations arranged in a small array could examine the spatial coherence of energy trapped in unconsolidated, near-surface materials. Near-surface scattering has been found to dominate the wavefield in several recent coherence studies on hard-rock sites, but the longer-period wavefield associated with sediment resonances has not been studied in the same manner. If the 0.5-3 Hz sediment resonances observed in many urban basins are laterally coherent over distances of order 1 km, the duration of damaging shaking may be longer than if the local velocity structure (e.g. rough bedrock topography) scatters the wavefield.

Need for Rapid Response

Immediate access to IRIS global seismic stations is important so that investigators can determine earthquake mechanisms in near real time. In the case of the Loma Prieta earthquake, for example, short term access to data was needed to make informed decisions about deploying seismic instruments for recording the aftershock sequence. Within two hours of the earthquake, seismologists throughout the U.S. could obtain data from the global stations, and determine a preliminary mechanism for the earthquake, whose large thrust component was atypical for the San Andreas Fault. This allowed investigators to plan the aftershock deployment even as the PASSCAL instruments were being flown out to California. The quick access to data and rapid deployment of PASSCAL instruments resulted in the recording of over 10,000 seismic events, and provided critical site response data explaining the collapse of the Nimitz Freeway. In the future, access to near real time data could allow assessments to be made of other short

term hazards such as tsunamis, which are typically the result of offshore seismic events.

3. Dynamics of the Crust-Mantle System

Knowing that the continents are assembled from structural packages and igneous inputs driven by mantle dynamics, suggests that the upper mantle represents a significant portion of the continent system. Portable 3-component broadband instruments formed into large arrays now promise upper mantle images of detail sufficient enough to completely revolutionize our understanding of continental dynamics.

The large-scale variation of upper mantle velocities appears to correlate with the large-scale variation in tectonic environment of the overlying crust. In active tectonic areas, upper mantle velocities are slow, and low velocity zones are well developed. Underneath stable cratons, velocities are fast and low velocity zones are weaker, if not absent. This large scale picture has provided a useful context for developing models of continental formation and evolution. But unambiguous conclusions about the genetic relationships between crustal tectonics, and the structure of the underlying mantle, are limited by the availability of high quality data at global, continental, and regional scales. Working out these genetic relationships is crucial to an understanding of the life-cycle of continents; their formation, evolution, and demise, and the interactions of continents with global geodynamics.

One example of this is the debate concerning the existence and long-term stability of large-scale continental root zones. One point of view suggests that the upper mantle underlying stable cratons is inextricably linked dynamically, and geochemically, to the overlying crust. An opposing point of view holds that the mantle beneath continents and oceans is equivalent, except for thermal age. While most recent studies of body-wave travel times and surface wave dispersion have proved that fast mantle underlies stable cratons, the conclusion that there is a geochemical or intrinsic structural relationship based on seismic data remains circumstantial. Further, the upper mantle structure beneath orogenic belts, and its relation to crustal tectonics at large and small scales, is not well understood. Less well understood is the transition from what is commonly assumed to be normal, or convecting mantle beneath tectonic provinces like the Basin and Range, and what may be basalt-depleted mantle beneath adjacent stable cratons. A comprehensive picture of the involvement of mantle convection with the tectonic deformation of overlying crust on a variety of scales has not emerged.

The limiting factor in each of these instances is the lack of data, or experiments with sufficient resolution to image "typical" structures in and around continental upper mantle. Critical issues include: the discrimination of Archean cratons from adjacent Proterozoic ter-

ranes; the fine-scale structure of the transition in the upper mantle from cratons to surrounding, or adjacent mobile belts; the fine scale vertical variation of velocity just beneath the Moho; the existence of continent-wide low-velocity zones, and the concomitant existence of seismological "lids"; the structure of the "high-gradient" zone between 200 and 400 km depth; the existence, structure, and topography of upper mantle discontinuities; the orientation and depth dependence of anisotropy; and the measurement of attenuation and very small-scale heterogeneity.

One of the underlying issues is whether the upper-mantle can be classified as a collection of tectonic "domains" in equivalence to the tectonic regionalization of the continental crust. At present, this can only be done reliably at scale lengths greater than a few thousand kilometers. In the case of continental root zones, the best seismological experiments have been able to determine that fast velocities in root zones persist to a depth below 200, and perhaps as deep as 400 km. But almost nothing is known about the structure of the transition from "root mantle" to "normal convecting" upper mantle because it has never been directly imaged in a targeted experiment. Information which is necessary to understand how continental structures interact dynamically, thermally, and chemically with the rest of the mantle is thus lacking. In addition, the internal structure of root zones, which has bearing on their formation and subsequent evolution, has not been resolved.

The major issues of continental evolution and dynamics will remain unsettled until the resolution of mantle images is improved by an order of magnitude. Current images [Figure II.10] only hint at the geophysical significance of images which are now possible with portable arrays having hundreds of channels. Several basic issues need to be addressed:

Characterization of Discontinuities. The existence of discontinuities on continent or global scales needs to be verified. The long-established existence of discontinuities at depths of 220, 400, and 670 km depth has not yet been extended into a global map of the continuity and variability of these interfaces. In addition, new information emerging on the potential existence of interfaces at 80 km depth (Zandt and Randall, 1986) and 550 km depth (Shearer, Revenaugh) highlights how far we have to go in understanding the crust and upper mantle. Discontinuities need to be characterized by velocity and density contrasts across them, as well as their thickness and continuity. Converted and reflected phases from teleseismic and far-regional earthquakes, plus large-scale active-source continental profiles, will be the primary tools for interrogation of these interfaces. Broad-band instrumentation is necessary for clear indications of the frequency dependence of reflection and transmission coefficients, in order to get at questions concerning the fine-scale structure of the discontinuities.

Upper Mantle Velocity Profiles. The nature and existence of continental low-velocity zones remains elusive with current technologies. The IRIS instrumentation initiative should finally provide us with the tools needed to address this question. The existence question can be addressed with continent-sized arrays placed at critical distances. These arrays of broadband instruments will be especially effective at imaging the mantle lithosphere with reflected and converted arrivals. A fundamental difference in surface wave upper mantle profiles and those obtained from Pn and Sn observations, is the existence of a high-velocity upper mantle lid beneath the continental Moho. This region of the Earth must be the target of focussed studies. Below this depth, the high-gradient zone between 200 and 400 km depth is another region that has been difficult to resolve with present technology. Ironically, this is a critical region in unraveling the forces responsible for the movement of tectonic plates. Seismology is the only tool for examining this region, so a major goal for improved recording technology will be the imaging of this region. New opportunities for direct imaging will be presented by complete high-density recording of the direct wave interval, especially at far-regional (10-30°) distances, including converted phases.

Anisotropy: Recent studies of the upper mantle revealed significant seismic velocity anisotropy beneath North America. The variation of the directions of the symmetry axes, magnitude of anisotropy and its dependence with depth on a continental scale, will help us to understand the role of anisotropy as an indicator of present and past tectonic stress. New observations will include shear-wave splitting, azimuthal travel-time anomalies, dispersion and polarization anomalies in surface waves, and broadband recording of regional events.

Attenuation and Scattering: The disposition of attenuation between intrinsic (internal friction) and energy loss due to small-scale heterogeneity and its depth dependence is critical to the examination of the lithosphere-asthenosphere boundary, and the question of partial melt in the upper mantle. Observations of amplitudes and broadband signals (up to 50 Hz or so) on three components are necessary.

The extension of these issues to three-dimensions is a natural and needed development. Higher resolution maps and targeted studies will, however, make less ambiguous the attempt to "regionalize" the upper mantle-crust system into dynamic provinces. An important aspect of this will be the existence and structure of "lateral discontinuities," or the apparent sharp transitions now thought to exist at the edges of cratons.

The IRIS program will permit development of a logical and efficient strategy to explore the upper 700 km of the Earth. The optimum strategy involves a balance between reconnaissance observations and fo-

cused studies with specific targets. The GSN array will provide baseline observations from which large scale anomalies and interesting targets can be determined. The average station spacing of GSN is 2000 km, so that only large scale features can be delineated. Arrays of portable 3-component instruments may then be used to interpolate the geologically important details in experiments with a scale of 100-2000 km. Organizing a long-term program to determine, in detail, the structure of the upper mantle on a corridor across the US, embodies this concept [Part III]. A mixture of deployment geometries will make it possible to use many different types of signals: reflected and refracted waves from explosions; converted body waves from teleseisms; teleseismic travel times and attenuation for tomography; and surface waves.

An important tool in such studies is the use of subarrays. These have small enough sensor spacing that the wavefield is sampled without spatial aliasing, from 100 m to 1 km, depending on the signal band. Beamforming with such subarrays is used to increase the signal to noise ratio. It can be used, for example, to suppress ambient noise, and to detect and analyze teleseismic P-waves from smaller events. It may be used to detect weak body waves in the midst of other source-generated signals, such as surface waves. The so-called "fat spot" approach, which combines beamforming with stacking of signals with a common reflection point, could revolutionize mantle imaging just as common depth point stacking revolutionized reflection seismology in the upper crust.

An earthquake or large explosion at 400km distance should produce high frequency reflections from upper mantle discontinuities. The signal would be predictably weak, arriving in the midst of Pg crustal reverberations, but would have a distinct slowness across a subarray. Detecting and imaging such signals will be critical to the goal of mapping the structure of the upper mantle.

A by-product of this increase in quality, is that the recording time required for obtaining an interpretable dataset may be vastly reduced, from several years of recordings taken at isolated stations, to a 4-6 month deployment of an array of instruments.

Focusing on North America, the following goals come to the forefront:

- Establish existence and properties of reflective discontinuities in mantle
- Establish baseline 3-d picture of P and S velocities, attenuation, and anisotropy
- Establish behavior of these discontinuities across major geophysical boundaries: Basin and Range, Colorado Plateau, Rocky Mountains, Snake River Plain, Columbia Plateau, High Plains.

The strategy for such a program requires that the permanent broadband stations serve as the anchor points for intensively studied trans-continental swaths. To

start, each swath would require a 6-month to 1-year deployment of 100-200 3-component stations. "Fat spot" experiments aimed at particular targets would then follow. Most deployments would incorporate coherent subarrays, to permit focusing and beamforming.

4. Crustal Structure and Tectonics

Archean to Quaternary age rocks exposed in North America offer an opportunity to study continental growth over the last 3.8 billion years. By seismological imaging, it is possible to study and compare areas of current growth with older terranes. The processes of volcanism, rifting, subduction, imbrication, delamination, and uplift at modern plate boundaries have their cognates in the ancient crust, now deeply exposed.

Methods for Seismological Imaging of the Crust:

Seismological methods are central to imaging the earth's crust. With the advent of high dynamic range broadband digital arrays, new opportunities arise for answering the important questions about the dynamics and history of the continents. Imaging methods fall into two categories: (1) tomographic methods, which measure some attribute of the signal, integrated along a ray path, such as the travel time, and (2) scattering methods, which detect reflected or forward scattered energy generated in local regions of high impedance gradient. The former involve spatial averages, and the latter spatial gradients. Tomographic methods yield physical properties, and scattering methods yield structure. Only by combining the two kinds of information, based on different kinds of experimental data, can adequate crustal images be assembled. In a wide-angle reflection/refraction experiment, the travel times of the first arrivals and wide angle reflections are inverted to yield velocity structure, while the narrow angle reflections are inverted to give a structural image.

An integrated approach, incorporating several different kinds of information, thus presents the opportunity to image some of the physical properties of the crust. This will require substantial new research into data processing and inversion techniques.

High resolution digital seismology was first applied to the study of the crust. It was utilized, in the mid-1970's, by the COCORP program, with the technology developed by industry for the imaging of prospective hydrocarbon-bearing sedimentary rocks. The sources for this work are vibrator trucks, and the recording system utilizes a large number of equally spaced (vertical) geophone groups digitally recorded at a central system. A similar adaptation of industrial technology by the marine research community uses large-capacity marine airgun arrays and multichannel hydrophone streamers. Although many variants exist, most studies maintain the recording array at a fixed, short offset from the source; consequently, the primary signals are nar-

row-angle reflections from target zones at depths greater than the source-receiver offset.

In a productive decade of reconnaissance studies in the US, COCORP demonstrated that reflections could be obtained from all crustal depths in many different settings. The BIRPS program in the UK adopted the marine multichannel technique for reflection profiles in the shallow waters around the British Isles. By the mid-1980's reflection profiling had become an accepted tool for application by groups in many different countries. The diversity of narrow-angle reflection profiling is illustrated in *Figures II.20 and II.21*.

Reflection studies have demonstrated that basement terranes formed by accretion are composed of highly deformed tectonic packages, bounded by low-angle thrust faults or shear zones. The factors which make some of these terranes easily imaged, others seemingly transparent, others strongly layered and some not, remain elusive. The nature of the commonly observed lower crustal reflective banding is not clearly established. Moho is often, but not always imaged in reflection profiling; whether this is a question of weak signal, or low reflectivity, is not always well-determined. There is some agreement that the continental Moho is in general an often-reactivated tectonic boundary between crust and mantle, as well as a compositional boundary. Recognizable images of large intrusive bodies are seldom achieved. Vertical discontinuities are not imaged by reflection profiling, although specialized field deployments have done so.

The success of reflection profiling has led, inevitably, to a recognition of its limitations. Signal to noise ratios are seldom capable of imaging the Moho well. Source-receiver offsets are insufficient for the job of inferring velocity in the lower part of the image. Shear-wave measurements are uncommon.

During the past 5-10 years, the research community has been engaged in a number of field programs designed to transform the traditional wide-angle reflection/refraction profiling into an integrated imaging protocol. This protocol records both wide-angle and narrow-angle data, achieves adequate signal to noise ratio, and incorporates shear information. The examples in *Figures II.19-21* illustrate these methods. Experiment design must be dependent on local conditions; in general, however, it will use most of the following tools: (1) recording arrays with close sensor spacing, (2) offsets ranging from zero to 100+ km, (3) both dynamite sources and vibrator sources, (4) 3-component recording. In addition, the use of converted shear waves from teleseisms provides a powerful new tool for reconnaissance imaging of Moho (see next essay). The PASSCAL array facilities provide the flexibility for achieving the full potentiality of an integrated approach.

Many geological settings still remain where crustal imaging has yet to provide very satisfactory results.

These are a challenge to the new integrated array techniques. For example:

The active, tectonically fragmented terranes of the California borderlands and Coast Ranges: Signal attenuation is high, many faults are steep and hard to image. Lateral heterogeneity is extreme.

The volcanically active Pacific Northwest collision region.

Continent-ocean transitions

Two new tools will be particularly useful for such regions:

The use of portable arrays in areas of earthquake activity permits the microearthquakes themselves to serve as sources for tomographic and scattering data, as well as to define the morphology of the faults. (*Figures II.23, II.26 and II.27*).

The combined onshore-offshore experiment. A ship with a marine airgun and a multichannel reflection cable runs a series of nearshore traverses for conventional near-vertical reflection. Onshore 3-component portable recorders acquire unaliased signals which have been scattered from the deep structure beneath the margin. Airgun signals are now routinely observed at 200km offset. With such an experiment it is easy to obtain 3-dimensional images (*Figure II.17*).

Continental Dynamics: 1990-2020:

Field programs for crustal imaging organized by cooperative, multidisciplinary, and multi-institutional teams have proliferated in the past decade. They have been stimulated by the singular geological importance of the original COCORP and BIRPS reflection profiles, and by the possibilities inherent in the new array technologies being developed by IRIS. The importance of crustal imaging to the Earth science community is proven by the existence of many consortia which formed to conduct crustal seismic programs during the recent decade:

The international reflection profiling programs: COCORP, BIRPS (U.K.), ECORS (France), DEKORP (FRG), and programs in Switzerland, Australia, Italy, and several other countries.

CALCRUST: A problem-focused, multidisciplinary group of California scientists with projects in the Whipple Mountains, the Tehachapi Mountains, the Mojave Desert, and the East Bay.

GLIMPCE: A joint effort of the U.S. Geological Survey and the Geological Survey of Canada for deep crustal imaging in the Great Lakes (*Figure II.21*).

LITHOPROBE: A Canadian national program for the multidisciplinary problem-based study of particular corridors. Particularly noted for imaging the underthrusting of the Juan de Fuca plate beneath Vancouver Island.

The USGS Deep Crustal Studies Program: A continuing USGS program for the focused study of key areas. Has included the Quebec-Maine-Gulf of Maine transect, the PACE transect across southern California and Arizona, the TACT north-south corridor through Alaska (*Figure II.16*), profiling in central California, and a new emphasis in the Pacific Northwest. Has been a major developer of integrated method combining reflection and refraction information.

The PASSCAL interim experiments: The Ouachita experiment (*Figure II.14-15*), the Basin and Range experiments, and the Brooks Range experiment, which were specifically aimed at developing integrated profiling methods.

The EDGE/PG&E central California onshore-offshore experiment was the first to combine offshore airgun profiling with onshore portable instruments.

The Workshop on Continental Dynamics was held in March 1989, with sponsorship by the NSF, the USGS, and the DOE. It took up the future of crustal imaging in the context of the important scientific issues in continental studies. The multidisciplinary, multi-pronged experimental program, focusing upon a key field area, emerged as the tool by which the newer technologies could be expected to be utilized. The NSF has designated *Continental Dynamics* as its focus for supporting such programs. Crustal seismic imaging, expanded in scope to include the newer capabilities, is a centerpiece of nearly every new initiative.

The vignettes in part III discuss many programs now being proposed by the community. The demand for facilities, performance, and resolution probably exceeds the funding available by a factor of 10. Even so, within the range of the affordable, the demand for state-of-the-art seismic arrays still greatly exceeds the supply. The past decade's consortia initiatives tended to be based either on the standard reflection profiling technology, or on the conventional refraction approach. However, the distinction has recently become hard to maintain, as integrated profiling methods incorporate both reflection and refraction, as well as newer types of information.

Outstanding Geologic Problems

The major problems that crustal seismology techniques must be used to address in the next decade are those fundamental to continental dynamics: understanding continental growth; the internal structure and development of mountain belts; the structure and evolution of passive margins and continental rifts; the structure and dynamics of magmatic systems; and the dynamics of the Moho. Solving these problems requires the best imaging available, including physical properties, as well as a suitable geological context.

Effort and innovation will be required in two different directions. First, the significance of features seen in the deeper crust needs to be understood better. The

Moho takes on different attributes in different areas, clearly related to its dynamical history. The lamination/layering in the lower crust remains a matter for debate. Because correlative outcrop for the deep crust is lacking, these questions must be addressed with carefully calibrated seismic experiments. In them, the experiment design is chosen to provide high resolution, bandwidth, signal to noise ratio, and subsurface redundancy. Interpreting such data requires intensive computational effort, with advanced seismic modeling methods appropriate for complex media.

Second, field programs working in conjunction with exposed surface geology, must be able to interpolate between the surface and the conventional target depths with some reliability. It will then be possible to accrue examples in which surface geology with known lithology and physical properties can be related to seismic images of structure and physical properties. This will lead to experiments with very tight sensor spacing and shallow targets.

For these cases, as for every new study, it must be emphasized that shear waves have become established as an essential tool. Digital broadband 3-component instruments in arrays can easily identify and characterize shear waves, and determine their velocities and probable anisotropy.

- 1) Continental growth and modification
 - Accretion of exotic terranes
 - Tectonic and magmatic underplating
 - Emplacement of batholiths
 - Continental arc plateau volcanism
- 2) Development of mountain belts
 - Kinematics and relationship of high-angle faults to low-angle detachment systems.
 - Fold and thrust belts, e.g., the Brooks Range, Canadian Rockies, Alpine-Himalayan chain, are formed by simultaneous contraction and strike-slip (transpressional motion)
 - Extensional belts, such as the Basin and Range, formed by extension and strike-slip (transtensional motion).
- 3) Passive margins and continental rifts
 - Basin and deep structure of intracontinental rifts (Rio Grande, mid-continent rift)
 - Kinematics and dynamics of Basin and Range extension
 - Evolution of passive margins (Gulf and Atlantic Coasts)
- 4) Magmatic systems
 - Relationship between structure and magmatic motion
 - Volcanic hazards (St. Helens, Redoubt, Augustine Island)
 - Relationship between seismicity and magmatic systems

- Search for crustal magma bodies as a key towards understanding crustal differentiation
- 5) The Moho as a dynamic feature
- Formation and reequilibration of the Moho in young orogenic belts
 - Moho as a decoupling zone
 - Distinguishing the various seismic Mohos and petrologic Moho

A few of many experiments in different stages of planning are briefly taken up in part III. Each addresses one or several major problems in continental dynamics, and each depends on the capabilities of the new generation of seismic array instrumentation.

5. Physics of Wavefields in the Earth

The basic data of seismology is ground motion as a function of time. The motion of the ground we record is produced by a variety of sources. As far as we know, all seismograms result from some form of wave propagation from each source to a given receiver. The basic concepts of elastic wave propagation have been known for a long time, and are the theoretical foundation of the science. Our basic understanding of this process, however, is evolving rapidly due to the convergence of two technologies: (1) rapid advances in computer technology, and (2) availability of digital seismic data. The first is important because it has allowed the calculation of increasingly complex synthetic seismograms. These have yielded a new theoretical foundation for testing hypotheses posed to explain observational data. IRIS has had a major impact on the second technology in the past five years, and will probably have an even greater impact in the next five years. With IRIS facilities, a new era can be entered in understanding wave propagation by a hand-in-hand development of new theoretical tools with new, higher quality, broad-band observational data. The following are areas in which the IRIS facilities may have a major impact.

Anisotropy.

Conventional theories of wave propagation are largely limited by the assumption that a given chunk of rock is a homogeneous, elastic material. In such a material the fundamental modes of propagation are the familiar P and S waves of classical seismology. There is increasing evidence that this assumption is probably unjustified for most crystalline rocks. Anisotropy is a natural consequence of rocks with a range of scale lengths and a preferred orientation of minerals and/or cracks.

Anisotropy's importance in wave propagation is not well known, and is easily debatable. A major reason is a fundamental lack of key observational data. The IRIS facilities have already had an impact in changing this. *Figure II.8* shows results from an experiment conducted in the summer of 1989, using a 1500km array of portable instruments. Silver et al have shown that the

waveforms from these records resulted from shear wave splitting caused by anisotropy of the rocks in the upper mantle beneath the North American shield. Refraction and reflection data from crystalline mountain belts show gross anisotropy on scales of tens of kilometers, and the morphology of outcropping gneissic rocks suggests that local anisotropy, on scales of tens of meters, may be common.

Imaging of Forward Scattered Wavefields.

An important frontier for imaging the Earth is to design new techniques for imaging forward scattered seismic waves. The conversion of P to S waves in forward scattering is a classical phenomenon, known for both planar discontinuities, and for point scatterers. In the frame of reference used in reflection seismology, a backscattered wavefield may be processed by analytical continuation to produce an image of the reflector (scatterer) density. Conversion of P to S by forward scattering of teleseismic signals differs from the reflection case only in the detailed form of the scattering matrix. The literature shows two approaches to these data: (1) "Receiver functions" are equivalent to the deconvolution used to convert a 1-d normal incidence seismogram to a 1-d image of the sequence of reflectors; (2) Arrays of longitudinal component seismograms can directly display the scattered wavefield from the sub-surface scatterer, much as an array of reflection traces directly displays the wavefield from a reflector. This latter approach has been successfully used by Galperin (personal communication), with an array of 120 3-component seismometers spaced at 250m intervals, without processing. A combination of these approaches, using arrays of 3-component instruments and processed by deconvolution and migration, could be a powerful tool. With teleseismic sources, no amplitude die-off comes into play for rendering deeper events too weak to be detected. The approach might be extended to signals recorded at distances of 100 to 2000 km, for the imaging of the upper crust using the higher frequencies available.

Near surface effects.

There are fundamental questions about the interaction of seismic waves with the earth's free surface that are not fully understood. Some known complications include the following:

- The surface weathered layer is always highly attenuating. In some cases, it is debatable that the material can be called elastic.
- The extremely low velocities of the weathered layer frequently lead to complex reverberations that strongly distort seismic signals.
- Body waves can be scattered by surface topography and inhomogeneities in the weathered layer and converted to high frequency surface waves.
- How seismometers (especially 3-component sensors) couple to the ground under different site conditions, is not well known.

- Under extreme shaking, near surface materials can behave in a nonlinear fashion. Experiments to observe such phenomenon have important implications for earthquake engineering.

To fully understand near surface effects we will need to examine these various problems at a variety of levels. Large experiments can be envisioned to use 100 to 1000 3-component channels in an areal array with spacings of only a few meters. An experiment at Pinon Flat, CA, to assess the performance of an array scheduled for the Soviet Union, was conducted in Spring 1990. It sampled wavefields from local and regional events on a 60 3-component portable instruments, at a spacing of only 7 m. Similar array experiments (including experiments to assess hazards for site amplification effects) are quite feasible with PASSCAL instruments. These would study near surface effects. At the other end of the spectrum, one could do interesting experiments to understand near surface effects with a single 6 channel recorder. For example, two matched instruments could be used to compare the effect of different sensor planting methods. The PASSCAL facility will allow creative experiments to be conducted over this broad range of scales of effort.

In the interpretation of crustal imaging data, the relations between gross elastic velocities and attenuation, over paths of several km length, and the *in situ* physical parameters of complex, anisotropic crystalline basement, remain poorly understood. Lacking are experimental data taken on known, controlled geological bodies on the scale of 10m to 1km, where 3-component arrays can be used to analyze in detail what is happening when a signal traverses a real medium.

6. Research on Seismic Verification of Proposed Nuclear Testing Treaties

The verification of arms control agreements limiting nuclear testing requires that seismic signals generated by underground nuclear explosions be detected, and discriminated, from those of both naturally-occurring earthquakes and legitimate industrial explosions. Enforcing a treaty limiting testing below a specific threshold requires also that the explosive yield of the explosion be determined from the seismic signal.

The capabilities of seismic networks for monitoring nuclear testing treaties are in dispute because of the performance variables of a hypothetical network in a previously un-instrumented area. In particular, the lack of digital data from the Soviet Union has greatly limited our knowledge of seismicity and seismic velocity structure in that part of the world. The regional variations of crustal structure are of special interest, since they govern the propagation of critical wave phases, such as *Lg*. Under IRIS's cooperative agreement with the Soviet Academy of Sciences, seismic stations are being installed throughout the Soviet Union. This project is funded by an appropriation from Congress to the nuclear monitoring budget of DARPA and is jointly

administered by IRIS and the US Geological Survey. At present, four broadband stations are routinely sending data back to the United States. The IRIS Soviet network will reach seven broadband stations by this Fall, and 13 by the end of 1991. Many of these stations will be incorporated into the Global Seismic Network to provide permanent data sampling of this important region. In addition to widely-spaced fixed broadband stations, the Soviet program includes two fixed-array studies employing 10-20 instruments each, in Soviet Armenia (in collaboration with the USGS) and in Kirghizia. Data from these arrays will be used to study local compression tectonics seismicity, and the effect of mountain belts on the propagation of regional phases.

Already, the limited data emerging from the Soviet Union are resolving some longstanding issues. For example, the estimation of explosive yield has traditionally relied on the recording of teleseismic waves that reach outside the boundaries of the Soviet Union. Such measurements have been historically described as having a factor of 2 uncertainty. Further, due to attenuation, traditional teleseismic methods cannot be applied to the smallest tests because the signals are too weak to be utilized at such distances. IRIS stations within the Soviet Union now allow us to use regional waves (propagation paths less than 2000 km). Early results using the regional phase *Lg* observed from nuclear tests indicate the yield uncertainty may be reduced from a factor of two (100%) to less than 30%. To truly assess monitoring capabilities, however, the network will have to be complete so that coverage can be obtained throughout the Soviet Union. Scientifically, the detection and quantification of small, clandestine, underground nuclear explosions remains a challenge. High frequency wave propagation (>10hz), and scattering effects may ultimately limit monitoring capability. Yet these effects remain unstudied due to a lack of appropriate high frequency data. Seismic waves generated by explosions and shallow earthquakes are especially affected by the highly attenuating, heterogeneous shallow crust. This limits our ability to characterize shallow sources accurately, particularly at small magnitudes, for which high frequency information is essential. Experiments with instruments located in closely spaced arrays and boreholes may help to mitigate this problem. The Kirghizia fixed-array experiment will address it directly. Based on the tight subarray design of the NORESS array, data from the Kirghizia array will be used to examine the coherence of 10-50 Hz seismic energy on regional propagation paths in the crust. Preliminary testing with such an array near Pinon Flat, California, has shown intense high-frequency scattering in the underlying Mesozoic batholithic crust.

A major concern within the arms control community has been the development of nuclear weapons by non-nuclear states. Such a development program might include clandestine testing in a remote area, especially in the southern hemisphere. The recent expansion of the US/USSR program outside the boundaries of the US and Soviet Union could play a future role in

nonproliferation agreements. In May, 1990, the Soviet Academy of Sciences agreed to allow IRIS to install seismic stations at two of their geophysical observatories in Antarctica. With joint US/USSR seismic stations in Antarctica, and the expansion of the global network

throughout the poorly covered southern hemisphere, the IRIS program will be of substantial international interest—especially when the nuclear nonproliferation treaty comes up for review by the United Nations in 1991.

II. Recent Accomplishments

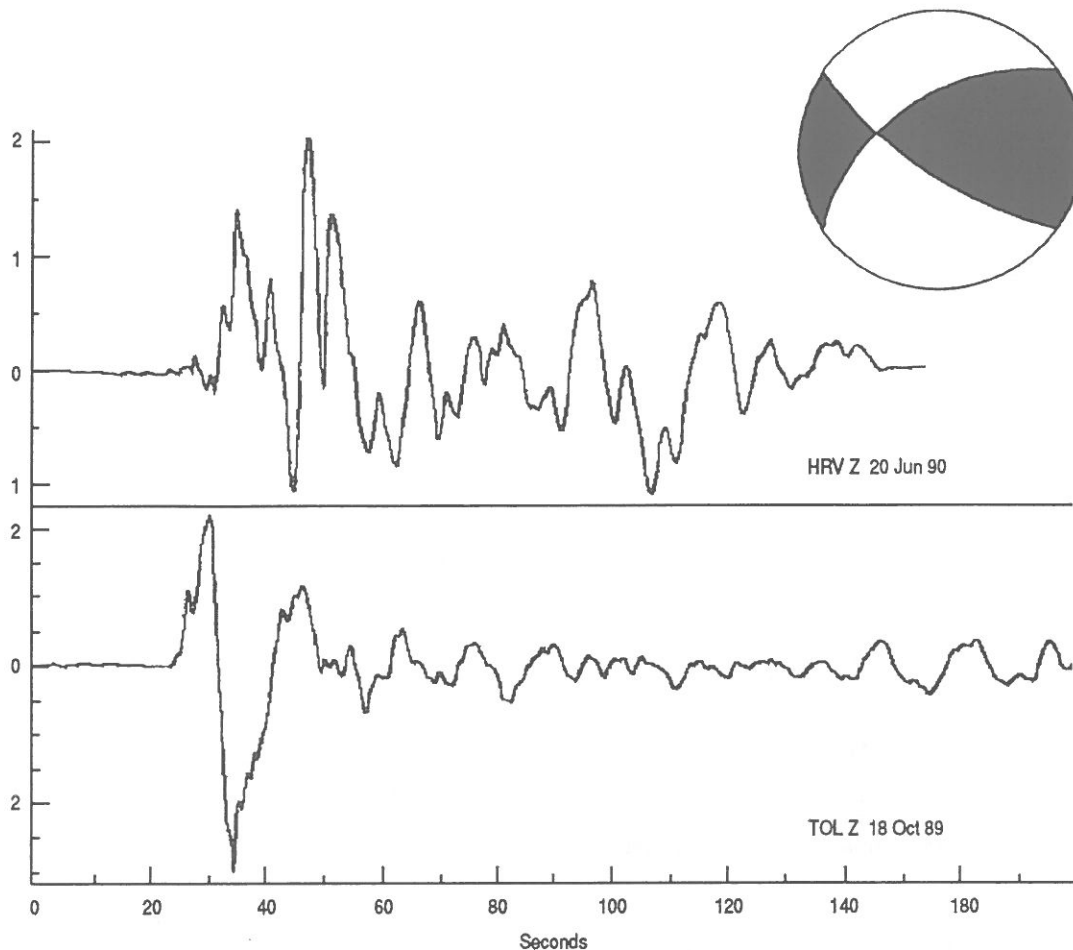
Selected Examples

The 1984 Program Plans for the Global Seismic Network and Passcal contained numerous examples of seismic studies which would be possible with a modern 100 station GSN and a supply of portable instruments for dense array deployments.

During the past 6 years, while the IRIS Consortium was being organized and the IRIS instrumentation and support facilities defined and developed, the seismological community has been engaged in the type of pioneering studies envisioned in 1984. These have been based on existing facilities, and, most recently, on the first GSN data and Passcal instruments, which became available in early 1989. The enthusiasm shown in preparing these studies shows how eagerly awaited are the fully implemented IRIS facilities.

In the following pages are examples of these recent accomplishments. They span an impressive range of problems, of scales, methods, applicability. They are presented in preference to a comprehensive, didactic essay on modern seismological capabilities and possibilities. The text is that of the investigators, with some additional commentary on the future implications of the work. These people form a vigorous, young community. Attracted by the capabilities of the new generation of instrumentation and data interpretation tools, more than half of the authors were too young in 1984 to take part in the original IRIS program planning.

1. Rapid Determination of Focal Parameters: the Iran Earthquake of 20 June 1990



On June 20, 1990 (OT 21:00:09) a major earthquake occurred in northwest Iran, about 170 km southeast of Tabriz, near Rasht. The earthquake ($M_s \sim 7.5$) caused over 40,000 deaths, making it the most deadly event since the July 27, 1976 Tangshan, China earthquake. The earthquake occurred in the westernmost Alborz mountains bordering the Caspian Sea. Both thrusting and strike-slip earthquakes are known in this region; the last major event which had surface breakage occurred 70 km to the west on March 22, 1879 (MM Intensity VIII). Four major faults are mapped in the region: (1) the Talesh, a north-south trending thrust fault, (2) the Khazor fault, an east-west trending thrust fault, (3) the Sangava fault, a thrust fault which curves from north-south to east-west, and (4) the Lahijan fault, a NNE striking strike-slip fault. Although at present there have been no reports of surface faulting, the focal mechanism indicates that the Lahijan, or similar fault, is the location of the June 20 event.

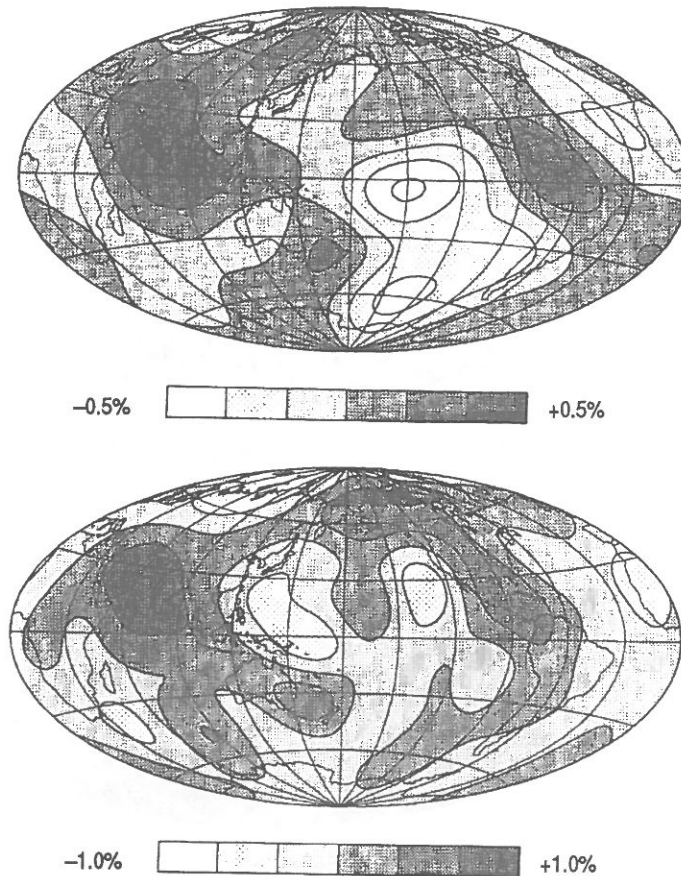
Within 24 hours of the event, Kanamori and Satake inverted for its source mechanism using R1 and G1 at stations PAS, HRV, ANMO, COR, and KIP. They obtained an oblique, right-lateral strike-slip solution (strike = 207° , dip = 51° , rake = 166°). The moment of the event is 1.3×10^{27} dyne-cm ($M_w = 7.4$). P and SH waves recorded at HRV and GRFO are, in general, consistent

with the surface wave mechanism, although the source time function is very complicated. The figure shows a comparison of the HRV P waves for the Iranian event and the TOL record for the October 1989 Loma Prieta earthquake. Both records represent travel paths of about 84° , and are from similar types of faulting events. Note that the Iranian event is much more complex; it begins as a series of emergent arrivals followed by at least 2 subevents. The complexity of the time function may account for the severity of the damage caused by the Iranian event. The rupture process lasted more than 25 seconds, while the Loma Prieta rupture was over in 9 seconds. The long duration of shaking causes increased damage to rigid structures, such as brick or stone construction. Thus far, there have been at least 5 aftershocks larger than magnitude 5.0; there have been hundreds of damaging aftershocks with magnitude less than 4.5.

The real time access of the IRIS GSN allows detailed analysis of significant earthquakes in a timely fashion. This is essential if we are to produce information on expected damage and predict aftershocks. It also allows efficient planning for deployment of PASSCAL instruments in response to an event.

Contributed by Hiroo Kanamori and Terry Wallace

2. Structure of the Middle Mantle from Tomographic Techniques



A major achievement of the last five years has been the production of three-dimensional images of seismic velocities within the Earth. This has led to major new conclusions about the nature of the core and convection within the mantle. This figure shows maps of velocity anomalies at a depth of 1200 km obtained through tomographic techniques. The top map represents the P-velocity anomalies, and the model from which this map is derived is obtained by inversion of travel time residuals of P-waves. This data set has been extracted from the Bulletins of the International Seismological Centre for the years 1964 through 1983. Nearly 2 million P-wave arrival times from 26,000 earthquakes to 2,000 stations were used to obtain this three-dimensional model of the lower mantle.

The bottom map represents S-velocity anomalies derived by waveform inversion of about 5,000 low-pass filtered seismograms. They contain, in addition to the S-wave, its multiple surface reflections (SS, SSS, etc.), as well as the reverberations between the core-mantle boundary and the surface (ScS, ScS₂, ...). Note that the scale of the S-velocity map is twice that for P.

Resolution of the two models is comparable even though 400 times fewer event-station pairs have been used in the S-wave study. This is because a complete

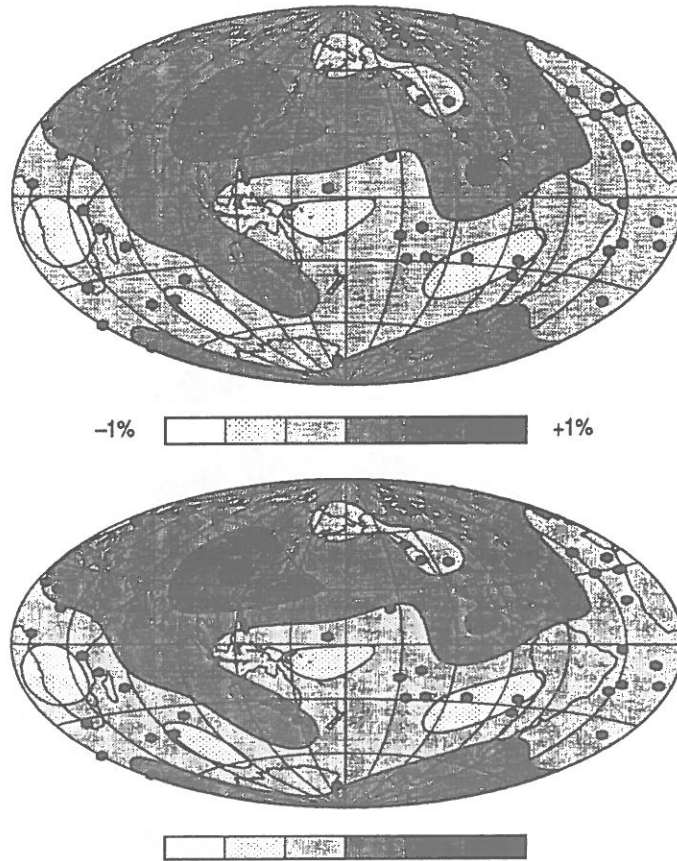
waveform contains much more information than a single reading of a phase arrival time, and also because the signal-to-noise ratio is much better. The waveforms used in the S-velocity study have been obtained by relatively few digital stations with characteristics inferior to the GSN stations.

The mantle at 1200 km reveals high-velocity anomalies following the subduction zones of the present and geologically recent past. These high velocity features include the rim of the Pacific, and a region stretching roughly from Indonesia to the Mediterranean marking the Tethys convergence zone. It may be noted that the anomalies are displaced outwards from the Pacific relative to the current loci of subduction, and that regions such as North America and southern Eurasia, which have been stronger convergence zones in the past than at present, are strongly represented in the models.

A major question concerns the continuity and change in morphology of these structures into the upper mantle. This has direct implications regarding the mass exchange between the upper and lower mantles in a convecting Earth. Resolution of these issues will require the denser broadband array capability of the GSN.

Contributed by Adam Dziewonski

3. The Lowermost Mantle: P and ScS Travel Times



There are many indications that the lowermost mantle, the 200km above the core-mantle boundary (CMB), is highly heterogeneous. Detailed knowledge of variations in the physical properties in that region, plus a reliable determination of variations in the radius of the CMB, can significantly impact our understanding of the Earth's dynamics, e.g., material and heat transfer from core to mantle, lower mantle boundary layer for plumes and mantle flow.

Data from many well-distributed sources and receivers must be combined to achieve adequate resolution of these depths, and to build the necessary tomographic reconstructions. Existing data can only demonstrate that the heterogeneities exist. The global coverage designed into the GSN siting plan, combined with the large numbers of earthquakes along the world's major tectonic belts, will provide this capability.

(Top) P-wave velocity anomalies at a depth of 2750km inferred from a large dataset of ISC travel times (Woodhouse and Dziewonski). 80% of the surface hot spot positions (indicated by black dots) fall in areas where the velocity anomaly is negative. The low velocities also correlate with the Dupal anomaly in the isotopic composition of basalts and with the latitude band where secular geomagnetic field variations, extrapolated to the CMB, are strongest.

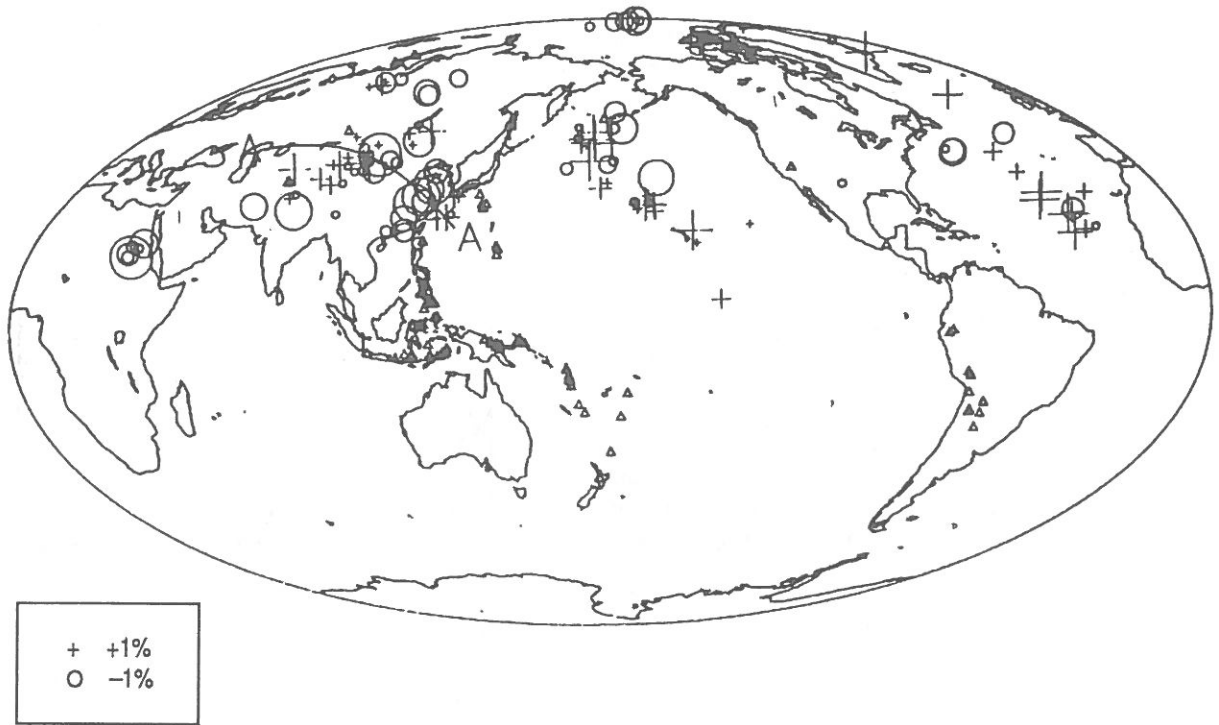
(Bottom) Shear wave velocity anomalies near the CMB are indicated by this plot of 2600 ScS-S travel time residuals measured from long-period GDSN records and plotted at their core-mantle bounce point (Woodward et al). Such measurements are insensitive to structure in the upper mantle, and mainly show the effect of structure in the lowermost mantle. The largest symbols correspond to a residual of 10 seconds, and triangles indicate a negative residual (corresponding to a fast velocity). The correlation of the pattern of residuals with the P-wave velocity model in the upper panel is quite good, though the size of the residuals indicates large shear velocity perturbations (on the order of 7% based on the geographic distribution of anomalies in the P-wave model).

Woodhouse, John, and Adam Dziewonski (1988), *The Earth's Large Scale Three-Dimension Structure, in Proceedings of a Workshop on Broad-Band Downhole Seismometers in the Deep Ocean, Joint Oceanographic Institutions, Inc.*

Woodward, Robert, Guy Masters, and Freeman Gilbert (1990), *Lower Mantle Structure from ScS-S Differential Travel Times, manuscript.*

4. The Lowermost Mantle: Diffracted P

$dT/d\Delta$ Anomaly



Diffracted P waves in the distance range 100-120° show the effects of lower mantle and CMB structure (McClurg and Creagar). Each symbol corresponds to one ISC travel time, and is plotted at the middle of the CMB sampling region. Open circles correspond to regions of fast velocity. These data again show large anomalies, agreeing in pattern with the other datasets, although the largest P-wave anomalies are on the order of 3%.

While these studies are very provocative, there is a lack of uniform data coverage, apparent in the point estimates. Seen particularly in the Southern hemisphere, this makes it quite difficult to determine the anomalous structure with any reliability. This situation will be remedied by the addition of the proposed land-based GSN stations and by the ultimate deployment of permanent broad-band ocean bottom stations.

Moreover, all of these studies are based only on body wave travel times; this is a small percentage of the

information in the signal, and merely demonstrate the existence of a geophysically significant anomaly.

The direct use of waveforms will expand the information a hundred fold. The availability of global, very broad band, large dynamic range digital 3-component data, combined with long arrays of portable instruments will make possible:

- detection and stacking of signals generated by reflection or mode conversion at deep boundaries;
- accurate determination of phase shift and amplitude behavior of diffracted signals;
- exploitation of larger numbers of (smaller) events observable at low noise stations; and
- user of arrays for beam-formed directional decomposition of seismograms.

McClurg, D. C., and K. C. Creagar (1988), *Aspherical Structure of D'' from $dT/d\Delta$ of P-diffracted*, EOS, 69, 1310.

5. The Inner Core, with Free Oscillation Splitting

The splitting and possible coupling of free oscillation overtone peaks is an indicator of something anomalous in the inner core. Amplitude spectra of long period recordings, for a small frequency band surrounding the isolated mode ${}_{18}S_4$, are arranged here by the recording station's geographic latitude.

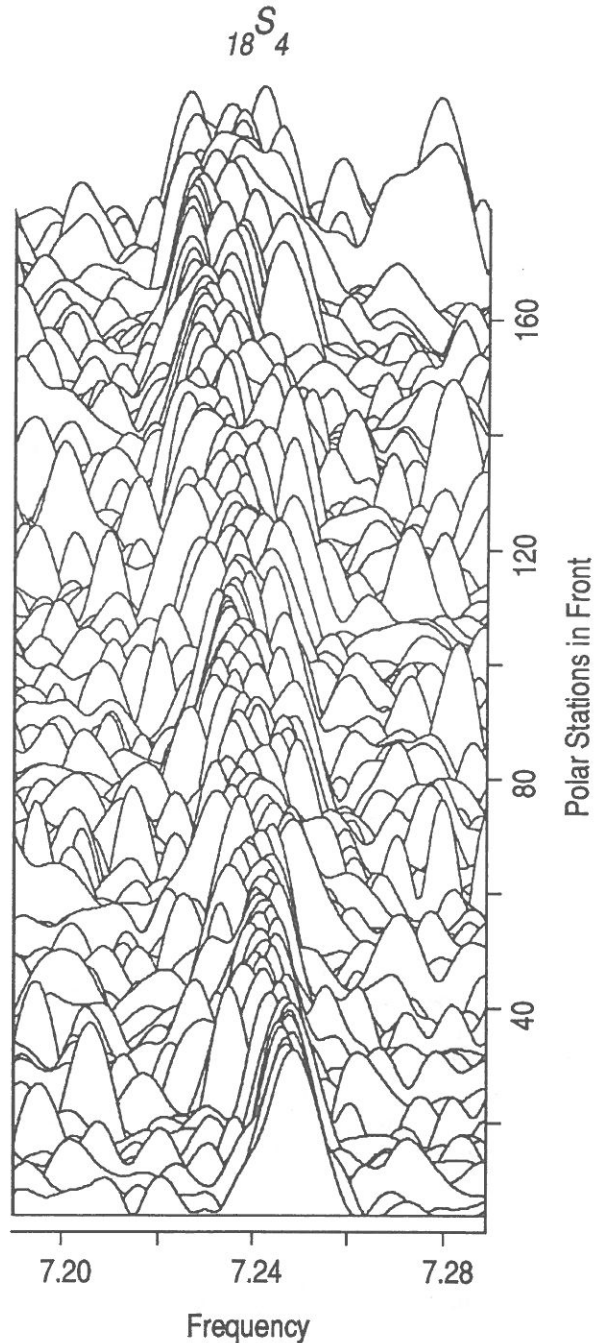
The spectra at high latitudes tend to show a single peak at high frequency, suggesting that axisymmetric structure is the dominant cause of the splitting. The total frequency band over which this mode is split, is more than twice that predicted for a rotating Earth in hydrostatic equilibrium.

Modes, such as ${}_{18}S_4$, having significant energy in the inner core, appear to be strongly split as though by an anomalously large ellipticity. Splitting, due to the presence of a strong magnetic field in the core, is ruled out based on ohmic heating arguments. Similarly, differential rotation of core material cannot give the observed splitting, if the magnitude of core convection velocities is correctly indicated by secular variation rates. In any case, this mechanism gives Zeeman-type splitting, while the observations indicate that the splitting is mimicked by the effect of anomalous ellipticity. The current best explanation of the splitting is given by a zonally anisotropic inner core. This may be a manifestation of a fabric acquired during the formation of the inner core, or it could be induced by large-scale convection within the inner core.

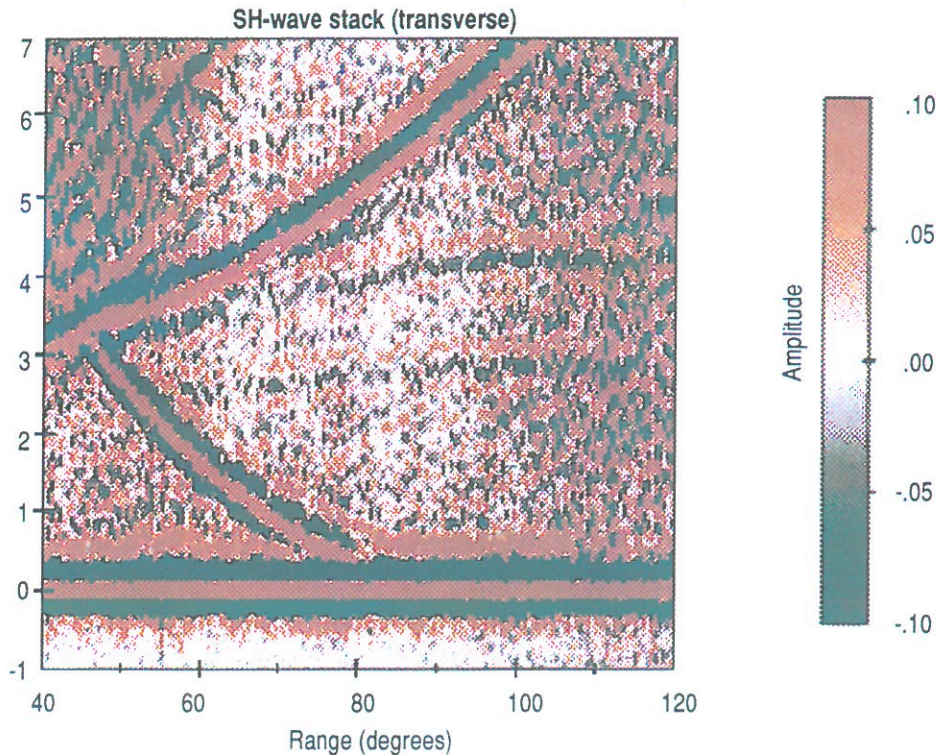
It should also be noted that seismic signals which sample the top 200km of the inner core are extremely strongly attenuated. Free-oscillation measurements seem to require a shear Q of about 150 while differential attenuation between PKP(BC) and PKP(DF) high frequency body waves indicates shear Q 's lower than about 50. The indication of strong frequency dependence of shear Q may be due to substantial partial melting in this region.

Our ability to resolve these issues depends on the availability of a global seismographic array with the bandwidth and dynamic range standards of the IRIS GSN. Most important would be a very large deep earthquake, such as last occurred in 1970 under Columbia. The relative rarity of such events argues for a speedy completion of the GSN. By maximizing the number of very low noise sites, several usable events per decade might be expected.

Widmer, R., G. Masters, and F. Gilbert (1990), Attenuation within the Earth from Normal Mode Data, Geophysical Journal International, accepted.



6. Globally Averaged Record Section (Stacking to Enhance Weak Events)



Problems of global Earth structure typically require thousands of station-event pairs. It is important that the needed seismograms can be extracted quickly and efficiently. In the past, the data was often distributed on dozens, or even hundreds, of computer tapes making the data collection a formidable task. The current use of optical storage devices promises to change this and make a large number of new experiments possible, including the stacking and automatic processing of data. Distribution of event data on CD-ROM will enable researchers with very modest computing equipment to have full access to the data.

For example, Shearer has stacked over 20,000 long period shallow focus seismograms from five years of GDSN data stored on CD-ROM. The resulting graphic display is a global record section which shows all of the major teleseismic signals, including "wrap-around" phases coming back from 180°, and a clear P diffraction visible well past 120°

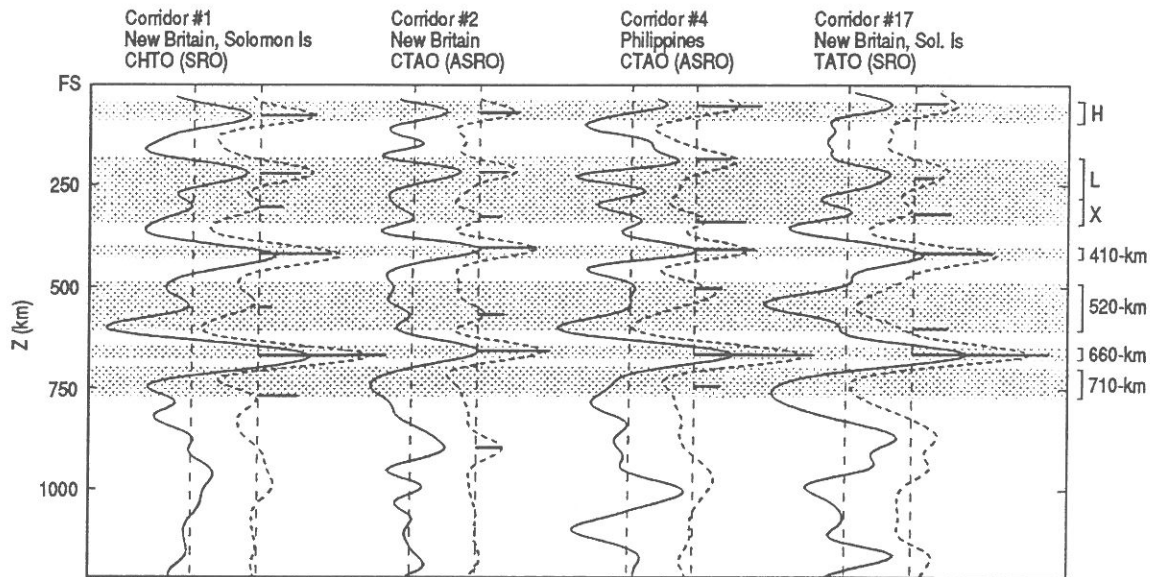
The averaging effects of stacking large seismic data sets minimize the effects of local structure, and enhance the visibility of weak phases. Recent stacks obtained by aligning a reference arrival clearly show numerous upper mantle discontinuity phases, some not previously observed. These images show travel time and amplitude relative to a reference seismic phase, which is aligned and normalized on all seismograms prior to stacking. The signals can be seen most clearly on a color display.

The color image above is stacked using SH as a reference phase. The core-reflected ScS phase as well as the surface reflected SS phase are clearly seen following SH. The blue streaks following SH by 2.5 to 4 minutes between 70° and 110° are topside reflections off upper mantle discontinuities. The positions of these phases indicate discontinuities at 410, 520, and 660 km depth. Nothing is seen which would correspond to a reflection from a 220 km discontinuity, suggesting that such a discontinuity cannot be a globally coherent feature. The apparent depths to the 410 and 660 km discontinuities seen on individual station data do not vary by more than about 20 km. These results are consistent with stacks using other reference phases, and with cross-correlation analyses of individual seismograms.

The new technology of the IRIS Global Seismic Network will greatly increase the bandwidth of the data, and the uniform global coverage and technical standards will facilitate construction of regionalized stacks. This will now advance the study of teleseismic phases to a point where it can consistently image backscattered and converted energy generated by regions of strong impedance gradients. In combination with tighter networks, such as the U.S. National Seismic Network and special deployments of Passcal broadband arrays, detailed structural images of the mantle and hopefully, of the core can be developed.

Shearer, P. M. (1990), Seismic Imaging of Upper-mantle Structure with New Evidence for a 520-km Discontinuity, Nature, 344, 121-126.

7. Regionally Averaged Upper Mantle Reflections (Stacking to Enhance Weak Events)



An interesting new technology using long-period and broadband digital recordings, is mantle discontinuity mapping with ScS reverberations. On an SH-polarized seismogram for epicentral distances on the order of a radian, a time interval starting with the passage of the fundamental Love wavetrain propagating along the minor arc is dominated by mantle reverberations, predominantly, the multiple ScS phases. These arrivals make multiple passes through the mantle along nearly vertical trajectories, and spawn reflections whenever they encounter abrupt variations in shear impedance. Using the multiple ScS (zeroth-order reverberations), and higher orders of internally reflected reverberations arriving within this portion of the seismogram, Revenaugh and Jordan have devised a hierarchical waveform inversion and migration scheme which produces maps of the path-averaged radial structure of high-wavenumber variation in shear impedance.

Several examples of these maps, referred to individually as reflectivity functions, are shown in the figure. Operationally, a reflectivity function corresponds to a low-passed version of the local SH reflection coefficient expressed as a function of depth. Included alongside each data profile is the best-fitting synthetic profile (dashed), computed from a discrete model of mantle reflectors, denoted by the spike series superimposed upon the synthetic reflectivity function.

The examples are taken from four seismic corridors with nearly coincident sampling of the tectonically complex regions around New Guinea and Borneo, which may be roughly characterized as an amalgam of continental margin and old-plate subduction zones. In all four cases the best fitting models are constructed of five upper-mantle and transition zone discontinuities.

Three discontinuities are ubiquitous, without regard to continental or oceanic nature of the path:

- the hitherto undetected 520 km discontinuity;
- the well-known 410 km discontinuity;
- the H discontinuity, interpreted as the spinel/garnet facies transition.

The remaining two discontinuities, however, display strong geographic and tectonic ties:

- The L is exclusively a continental feature, whose depth is greatest beneath stable cratons, and shallows toward margins. It may mark the asthenosphere-lithosphere transition.
- The X discontinuity has been seen only on paths crossing the Papua New Guinea-Borneo region.

One unique aspect of reverberation mapping is the ability to address mantle structure over its full depth range at short epicentral distances. This opens the possibility of mapping deep continental structure simultaneously with the shallow section, over a variety of length scales, maintaining good horizontal resolution all the while. A dense array of broadband, digital instruments would be the ideal tool.

Revenaugh, J., and T. H. Jordan (1989), A study of mantle layering beneath the Western Pacific, J. Geophys. Res., 94, 5787-5813.

Ibid. (1990a-d), Mantle layering from ScS reverberations, 1, Waveform inversion of zeroth-order reverberations; 2, The transition zone; 3, The upper mantle; 4, The lower mantle, D'', and the core-mantle boundary, J. Geophys. Res., submitted.

8. Portable Arrays for Teleseismic Recording: the Subcontinental Mantle

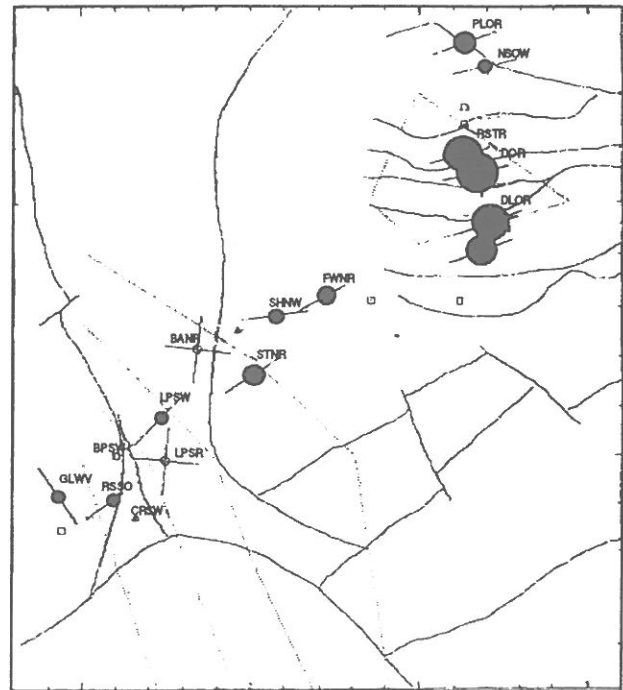


The portable broadband 3-component seismometers being developed under Passcal introduce a major new tool into studies of the Earth. By deployment of instrument arrays over hundreds to thousands of kilometers, it is possible to bridge the resolution gap between the 2000 km spacing of the GSN and the 100m spacing characteristic of crustal reflection surveys. This will be a principal tool in developing a dynamic geology for the whole Earth by focusing in detail on important targets.

In a critical demonstration experiment, workers from the Carnegie Institution of Washington and the University of Wisconsin, deployed an array of 22 portable 3-component teleseismic instruments along a 1500 km traverse in North America. They ranged from the Archean Superior Province of the Canadian Shield, across the Proterozoic Trans-Hudson Orogen, and onto the Archean Wyoming Craton. Ten of these instruments possess the initial prototype Passcal dataloggers, which were used for both prototype evaluation and for the scientific goals.

The array was designed by Silver and Chan to develop geographic detail with regard to a strong shear wave birefringence detected at two permanent stations along the traverse. It should also exploit additional opportunities for studying the mantle presented by the array geometry.

Birefringent splitting of the shear phase SKS appears as a separation of the time signal into two time-separated pulses. This occurs when the horizontal vector motion



is rotated into axes parallel and perpendicular to the principal direction. Differences of 0 to 0.5s are often seen, and range up to 1.8s.

[Right] The abrupt change in the birefringence along the array demonstrates that the anisotropy in the rock fabric which causes it, must lie beneath the array in the crust or upper mantle. The upper mantle is affected by the larger values, since it is hard to account for the observed splitting by plausible levels of anisotropy.

The size of the circles indicates the delay time: range .5 to 1.8s; the lines indicate the fast polarization direction. Open symbols indicate no splitting. The jump from strong to moderate splitting occurs across the Superior - Trans-Hudson boundary.

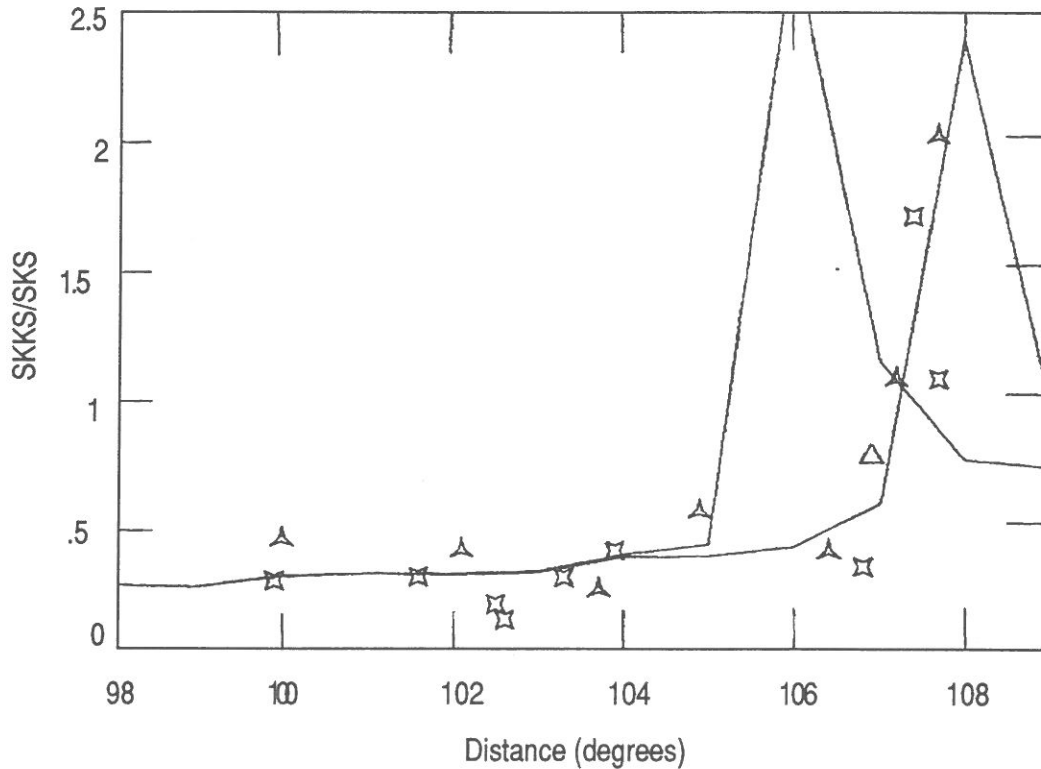
[Left] P delays from an intermediate focus event in South America show the same pattern. Larger symbols show faster paths; the range in delay times is about 3s.

Silver, Paul, and Winston Chan (1988), *Implications for Continental Structure and Evolution from Seismic Anisotropy*, *Nature*, 335, 34-39.

Silver, Paul, Robert P. Meyer, David E. James, and Timothy J. Clarke (1989), *A Portable Experiment to Determine the Properties of the Subcontinental Mantle: Preliminary Results*, *EOS*, 70, 1227.

Bokelmann, Gotz, Paul Silver, and Timothy J. Clarke (1990), *Multiple Travel Times for Portable Array Data*, *EOS*, 71, 562.

9. Portable Arrays for Teleseismic Recording: the Lower Mantle and Core



A teleseismic 3-component array can be used to examine other areas of the Earth. Body waves transmitted or reflected by the core are the only tools available for high resolution investigation at core depths, and require a closely spaced array of 1000km or more total aperture.

In the CIT/ UW demonstration experiment, the amplitude ratio of the core phases SKKS and SKS was used to examine properties near the core-mantle boundary. In the figure, three-sided stars are 5s seismometers, four-sided stars are 1s seismometers, and the triangle is RSTN station RSON.

The deep focus earthquake in the Solomon Islands (21 Aug 1989, $h=487\text{km}$) has provided data for the distance range 100° to 108° . The ratio is fairly constant from 100° to 107° in the range 0.1 to 0.5, but abruptly increases to the range 0.5 to 2 between 107° and 108° . The ray theoretical amplitudes predicted from PREM also exhibit this behavior, except that the rapid rise occurs between 105° and 106° , when the reflected phase ScP emerges from the core mantle boundary at grazing incidence. This causes a decrease in the SKS transmitted amplitude.

Assuming that the observed amplitude spike is caused by this phenomenon, three explanations may be considered for the 2° shift in distance relative to PREM:

- Perturbation in radial Earth structure. This can be done by increasing the P velocity at the base of the mantle by 2.5% or decrease the P velocity in the

outer core by about the same amount.

- Lateral heterogeneity. A dip in the core-mantle boundary or in the velocity isolines in the lower mantle could produce the shift.
- Non-ray theoretical effect. Diffraction effects may play a role near critical ray parameters. This is being studied using full wave theory modeling methods.

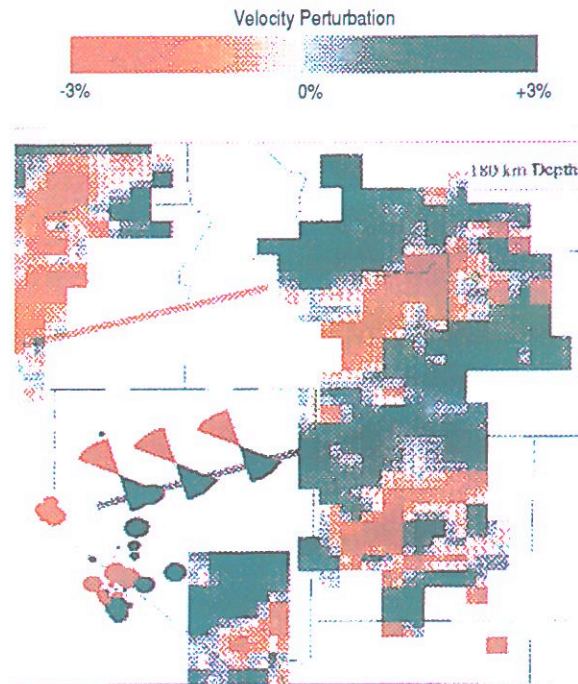
Detailed study of the core-mantle boundary region's vertical structure and its lateral variations is a high priority for students of the dynamics of the mantle and core. Heterogeneities indicated by global datasets must be studied using arrays of portable broadband seismometers. These have the spatial resolution, the bandwidth, and the dynamic range needed to fully characterize the body wave signals which have interacted with the core. Based on the results from this experiment, a recommended deployment might be 70 instruments spaced at 20 km intervals.

Other signals recorded by this demonstration experiment are planned for analysis, and illustrate the power of a teleseismic array:

- 2-D Shear wave velocity inversion along the transect using surface waves.
- 1-D inversions for crust/upper mantle structure using teleseismic receiver functions.

Silver, Paul, and Craig Bina (1990), An Anomaly in the Amplitude ratio of SKKS/SKS in the Range 100° - 108° from Portable Teleseismic Data. EOS. 71. 556.

10. Tomographic Image of the Upper Mantle Under the Great Basin



The 1500km extension of the Great Basin in the past 25 million years atop the hot East Pacific Rise mantle, is one of the most striking examples of the effects of mantle dynamics in driving continental evolution. Very little is known, however, about its internal structure there or about its actual dynamical state.

First arrival data from narrow-band regional monitoring networks have been analyzed by Dueker and Humphreys for variations in mantle compressional (P-wave) velocity. The figure shows relative P-wave velocity structure at 180 km depth, as determined by tomographic inversion of teleseismic residuals; red and blue represents low and high seismic velocity (V_p), respectively. In the western Great Basin, the average P-wave teleseismic residuals are represented with red and blue circles corresponding to late and early arrivals, respectively; largest diameter shows 0.7 seconds anomalous arrival with respect to the array mean. The pie shapes plotted in northern Nevada represent the ~ 1 sec variation in travel-time between early arrivals (blue) from SE sources, and late arrivals from NW sources (red). The red (slow) and blue (fast) lines represent the $\sim 6\%$ difference in S-wave velocities in the upper 200 km of the mantle as determined by the Rayleigh wave dispersion modeling.

The results suggest that the regional upper mantle velocity structure beneath the Great Basin consists of an alternating sequence of high- and low-velocity regions trending NE across the Great Basin. The low velocity mantle lies beneath the volcanic trends of the Snake River Plain and the St. George Volcanic lineament. These two trends are separated by high-velocity upper mantle extending from SW Wyoming into central Ne-

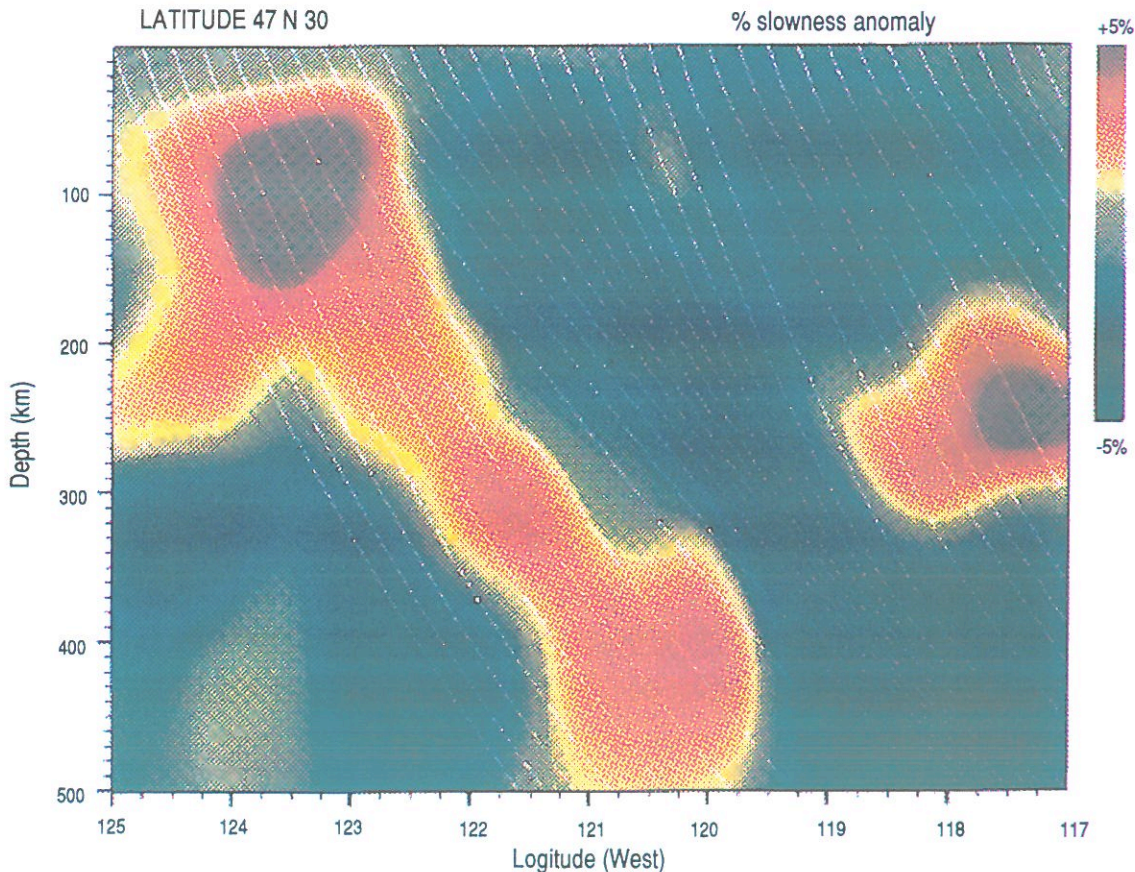
vada. Assuming a purely thermal origin for these velocity contrasts, and using a scaling relation of $1\% \Delta V_p = 160^\circ\text{C}$, the $6\% V_p$ velocity variations would require $\sim 1000^\circ$ temperature variations! Such temperature variations are unreasonably large. The presence of partial melt (perhaps 2-4%), as well as possible compositional variations (maximum of $\sim 1\% V_p$) seem to explain the velocity anomalies.

Dueker and Humphreys suggest that the origin of this velocity structure is temperature variations associated with regional impingement of "hot spot" material, and subsequent convective destabilization of the lower lithosphere. This model is supported by: (1) the discordant nature of these upper mantle trends with respect to the tectonic grain and Phanerozoic crustal structure; (2) the large magnitude of velocity perturbation at the 180 km depth, which requires large variations in the temperature and partial melt structure of the underlying mantle at this depth; and (3) the "sharpness" of the velocity contrasts, which suggests these features are thermally young (i.e. < 10 Ma).

While these compressional-wave data provide impressive first results, only when combined with broad-band shear-wave data will issues such as the percentage of partial melt, or the possibilities of chemical variation, be resolved. It will also be important to independently locate reflectors in this region with the help of portable arrays.

Dueker, Kenneth, and Eugene Humphreys (1990). Upper mantle velocity structure of the Great Basin. Geophys. Res. Lett., in press.

11. Tomographic Image of the Slab Under the Cascadia Subduction Zone



High performance digital arrays now available suggest the feasibility of imaging both currently active and fossil slabs in the upper mantle. This tomographic reconstruction of velocity anomalies under the Cascadia subduction zone shows that the velocity anomalies are quite large enough to yield invertible data.

The figure shows a vertical, E-W cross section, without vertical exaggeration, of compressional wave slowness. The model was obtained from a linear inversion of teleseismic travel times to about 100 local stations, and was parameterized at nodes with taut spline interpolation. Local station travel time static anomalies were determined and removed simultaneously in the inversion algorithm.

Blue indicates regions of anomalously high velocity, and is readily inferred to be the cold subducting Juan de Fuca plate of oceanic lithosphere. The slow material at 100 km depth and longitude 124 W lies beneath the Olympic Peninsula, while the fast material at 119 W is beneath the Columbia Plateau.

The rays (white) are traced to equally spaced positions along the surface. Where these are bunched at depth, indicates rays which are defocused at the surface, with consequently low amplitude. This amplitude reduction directly over the updip end of the slab is seen in signals arriving from the east and, as predicted, is not seen on signals arriving from the west.

For this case, the data consisted entirely of P-wave travel times....one data point per seismogram. For the future, the advent of high performance 3-component portable stations will permit a significantly enhanced detail in this kind of image reconstruction.

- Instrument arrays will permit detection and directional mapping of many wavefronts from each event.
- These will include converted and scattered wave groups which can be transformed into image elements at depth.
- These will provide a significantly larger tomographic data set, including in particular, shear waves.
- Station siting can be easily planned using modern resolution analysis, to focus closely on particular target areas.

Such improvements in resolution and robustness are going to be needed for sorting out structures which do not have the strikingly steep dip seen for this actively subducting slab.

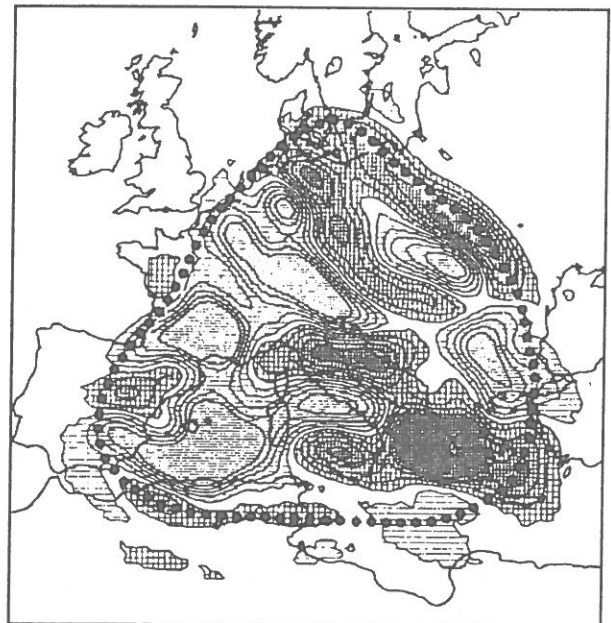
VanDecar, J. C., R. S. Crosson, and K. C. Creager (1990), *Teleseismic Arrivals Recorded over the Cascadia Subduction Zone: Amplitude Variation and Calibration of the Washington Regional Network*, *Seis. Res. Lett.*, 61, 32.

12. Surface Wave Tomography for Upper Mantle Structure

Source-receiver minor arcs.



5%  +5%
 $\delta\beta/\beta$ for 100 km. $z < 200$ km.



Arrays of instruments, either portable arrays, or regional networks, record surface wave trains over many different paths. If surface wave paths were able to cover a test region densely enough, then theoretically several different methods could reconstruct the 3-dimensional shear velocity structures.

Surface wave seismograms were recorded by the 14 station NARS array in western Europe. These were made from 5 earthquakes in southeast Europe studied by Snieder. Three different inversions were undertaken:

- Born scattering inversion of the surface wave coda;
- direct nonlinear inversion of the direct surface wave group;
- Born scattering inversion of the direct surface wave group.

The inversions were fairly low resolution, being based on a limited data set and a signal passband from .01 - 0.5 hz. The upper left figure shows the source-receiver minor arcs for the seismograms used.

The coda of the surface wave corresponds to the reflected wave train used in crustal body wave imaging, and should be usable to image heterogeneities by wavefield extrapolation. However, the coda data are currently too sparse and noisy to produce an accurate reconstruction of the lateral heterogeneity. It is dominated by artifacts due to undersampling, but gives some visual suggestion of the lateral resolution inherent in these signals.

Using the principal surface wave group resulted in a more successful inversion. A nonlinear inversion for a smooth reference model was followed by a Born itera-

tion for corrections to this model. The forward scattering geometry produced to a longer-scale, more stable inversion than the backscattering geometry of the coda inversion.

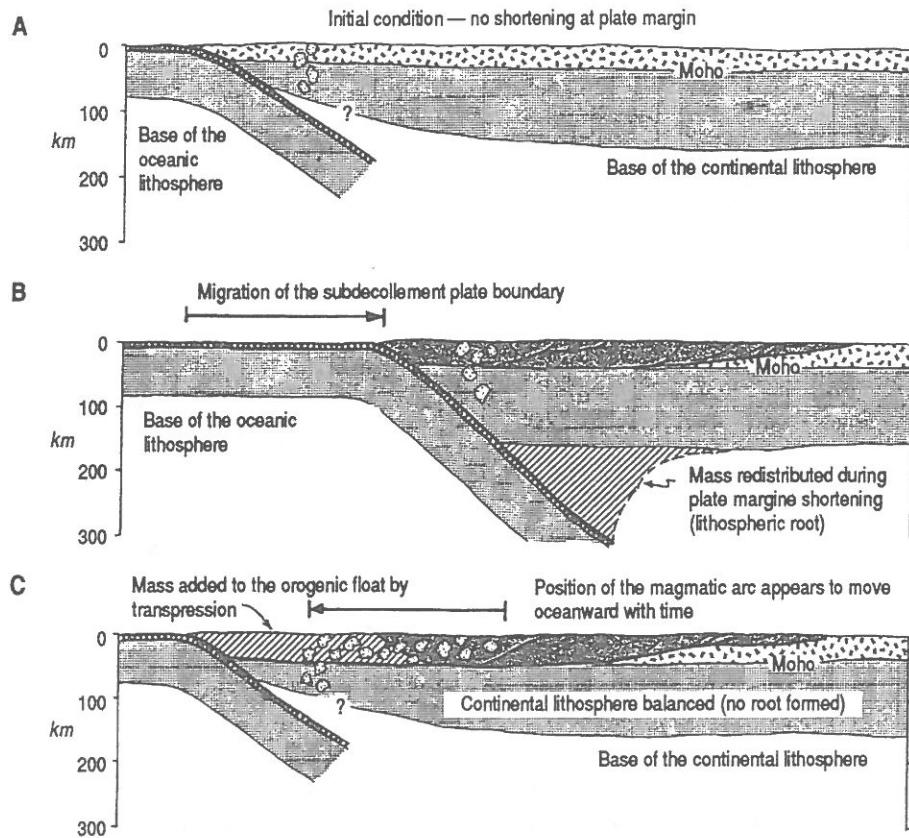
The right shows the result, in the form of an average relative shear velocity perturbation in the layer 100-200km. The dotted line defines an interior region within which resolution analysis indicates adequate data.

The most spectacular feature is the high-velocity anomaly running NW-SE through Eastern Europe. This is needed to produce the focusing of amplitudes seen in the northern station of the NARS array. It is not seen in the 0-100 km layer. Coinciding with the Tomquist-Tesseyre zone, the boundary between central Europe and the east European platform, this transition is also indicated by a travel time inversion for P times.

At present, the main limitation in using surface wave trains is imposed by the limited high-quality digital surface wave data. The deployment of US National Seismic Network stations should provide a growing base of broadband signals for an inversion of US crustal and upper mantle structure. At much smaller scales, surface waves recorded on portable arrays may be used to develop reconnaissance images of the near-subsurface, without the need for labor-intensive reflection profiling.

Snieder, Roel, (1988), Large-Scale Waveform Inversions for Lateral heterogeneity 2. Application to Surface Waves in Europe and the Mediterranean, J. Geophys. Res., 93, 12067-12080.

13. Mountain Belt Deep Structure Driven by Subduction and Delamination



The association of compressional mountain belts with plate collision and subduction at continental margins has been long recognized. In the top 15 km, the internal structure of these belts is readily shown from seismic reflection data, and from geological information and constraints. A complete dynamical understanding of mountain building requires determination of structure and physical properties in the lithospheric substrate (beneath the detached orogenic float which is seen at the surface).

Alternative models for the mass balance in a compressional orogen are illustrated here.

- A: Initial condition at convergent plate boundary without regional contraction
- B: Large-scale shortening and formation of orogenic float without addition of terranes to leading edge of upper continental plate. Shortening of sedimentary and crustal units overlying basal decollement requires comparable shortening in subdecollement lithosphere and migration of subdecollement plate boundary (to right). Area balance requirements call for development of lithospheric root.
- C: Shortening of sedimentary and crustal units originally overlying continental lithosphere is compensated by addition of terranes to leading edge of upper plate. Position of subdecollement plate boundary does not move; hence there is no necessity to form lithospheric root.

It is now important to know the lower crustal and mantle substrate of collisional orogens. It will require a significant extension of technique. It will challenge the multiple methods of generalized tomography and generalized reflection. It will entail most of the following:

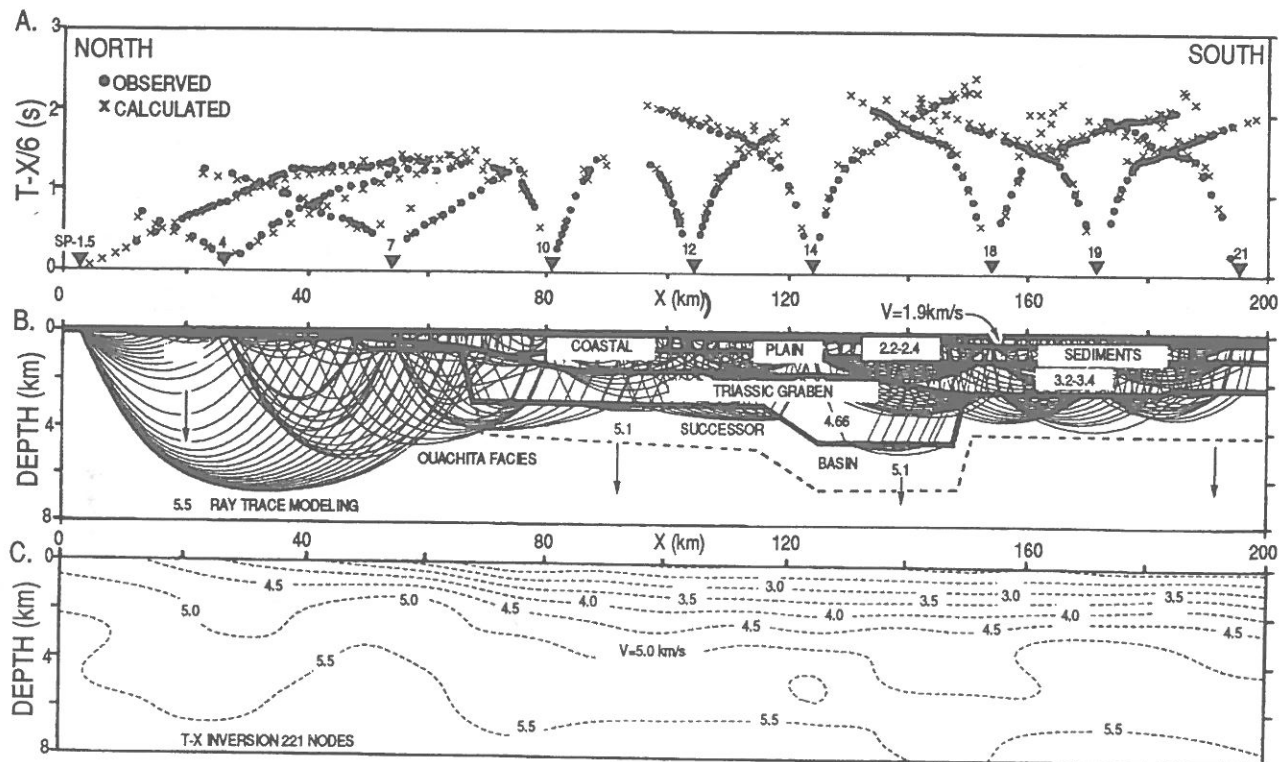
- use of numerous explosion sources (on land), and large marine airguns (where possible), to obtain relatively dense source spacing;
- dense arrays of 3-component sensors... typically 400 locations at 250m spacing;
- exploitation of signals from earthquakes, for both tomographic and P-SV conversion imaging.

The North American Cordillera offers a number of corridors where crustal structure has already been investigated (TACT transect, Brooks Range study, COCORP, Lithoprobe Vancouver Island study), where the extension to mantle structure would make sense. In addition, the well-studied Appalachians present the question of the mantle substrate for a Paleozoic mountain belt.

The powerful combination of large marine airguns with land-based, directionally sensitive arrays suggests international efforts directed at targets in the Mediterranean or Southeast Asia.

Oldow, John, S., Albert W. Bally, and Hans G. Ave Lallemand (1990), Transpression, orogenic float, and lithospheric balance, manuscript submitted to Tectonics.

14. Velocity and Structure of Paleozoic Orogenic Crust The PASSCAL Ouachita Experiment



The 1986 PASSCAL Ouachita Seismic Experiment was designed as a prototype for the type of high resolution crustal imaging envisioned for the new PASSCAL instruments. It featured close station spacing and multiple sources that allow for imaging by travel time, amplitude, and waveform techniques, using reflection and refraction information. Top priority was placed on obtaining enough resolution and reliability, so that the images could be geologically interpreted.

The north-south experiment corridor overlays the southern third of a COCORP reflection profile across the Ouachita Mountains and the Benton uplift in Arkansas. The geological goal was to study the late Paleozoic convergent margin, and to obtain detailed information about the southward transition from continental crust to former oceanic crust, now tectonically filled.

Four hundred instruments (vertical component Seismic Group Recorders) were deployed in two separate profiles each 100 km in length. The 21 explosive sources were at an average interval of 10 km along the profile, and allowed the recording of near-vertical offset information, as well as refracted and wide-angle reflected information.

An example of the shallow structural data and interpretations is given in the figure, in which velocity

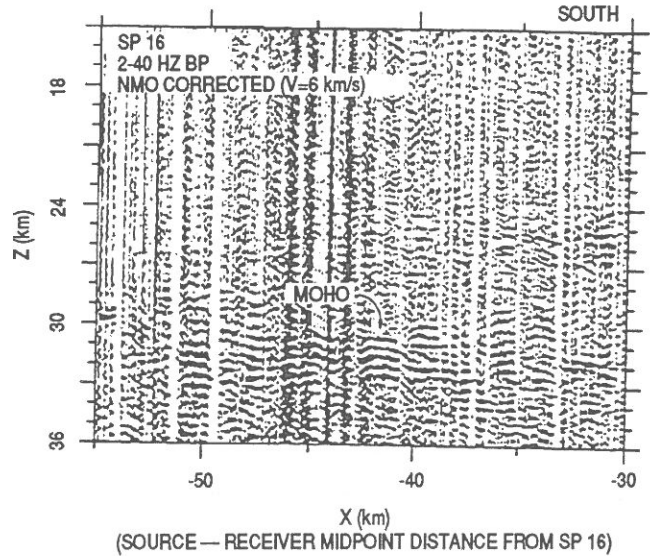
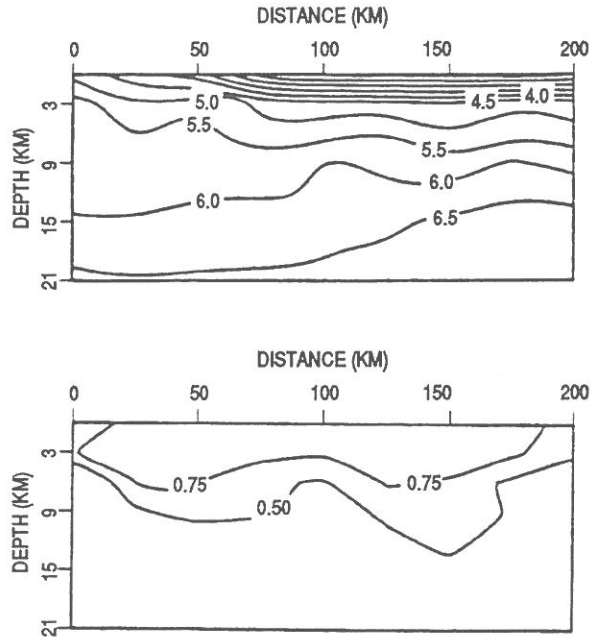
inversion and resolution estimates are based on first-arrival travel times. (A) Travel times, ray paths, and velocity structure for ray trace model (B), with comparison with travel time inversion (C) velocity structure. The ray paths show that multiple shots produce multiple rays through a given subsurface point.

Instrument spacings of 250m permitted the identification of first and later arrivals by intertrace coherency and apparent velocity. This greatly facilitated the use of reciprocity relationships to obtain travel time picks from noisy traces.

Braile, L. W., G. R. Keller, G. A. McMechan, W. J. Lutter, S. H. Harder, W. G. Jardine, J. Plappert, R. L. Nowack, W. A. Thomas, K. Mikus, and W. F. Wang (1990), The Passcal Ouachita Seismic Experiment: Observations, Data Analysis and Crustal Velocity Model, in press.

Keller, G. R., L. W. Braile, G. a. McMechan, W. A. Thomas, S. H. Harder, W. F. Chang, and W. G. Jardine (1989), The Paleozoic Continent-Ocean Transition in the Ouachita Mountains Imaged from PASSCAL Wide Angle Reflection-Refraction Data, Geology, 17, 119-122.

15. The PASSCAL Ouachita Experiment: Velocity Inversion



The reconstruction of the Ouachita velocity model by Lutter et al is a major step toward achieving robust 2-d inversion of wide angle profiles. Nonlinear inversion of the full set of travel times was iteratively done using partial derivatives for a splined interpolated velocity model. The methodology assesses the reliability of the solution in terms of resolution and model errors. The figure on the left shows the isovelocity contour diagram of the 90 node inversion using first arrival times (top), with the contoured diagonal elements of the model resolution. For the first arrival data, resolution greater than 0.5 could be achieved no deeper than 9 km.

To sample deeper into the crust, wide angle reflections need to be incorporated. An average one-dimensional velocity structure is first obtained by using wavefield extrapolation methods; this is possible only with the closely spaced data. Then the arrival times of the wide angle reflections are used to invert for the lateral structure of the reflectors, using a splined interface model. This velocity model can then be used for 2-dimensional imaging of the reflected wavefield by depth migration.

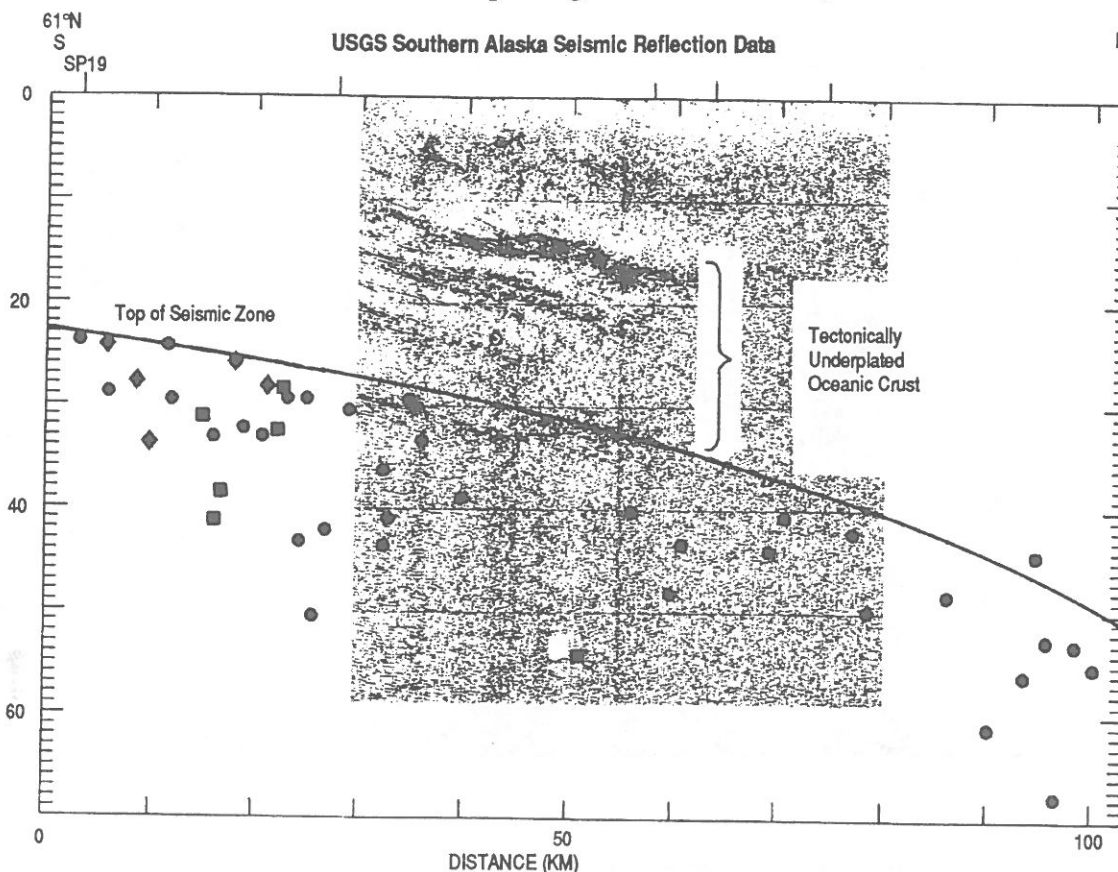
In the top right is given an NMO image of the Moho wide angle reflection beneath part of the profile.

Combination of these methods provides enough information to develop a geologically based crustal model. The final interpretation utilized COCORP reflections and Pascal CMP and NMO-corrected reflection data for imaging, and ray-trace inversion to determine the velocity distribution.

By adopting the sensor spacing and source spacing required to achieve a robust, well-resolved solution, this experiment produced geologically far more useful information than would have been possible otherwise. The methods available for assessment of inversion are also available to assess proposed experiments in advance of deployment. The maximum and probable resolution and errors could be achieved with any given deployment. Consequently, experimenters can be confident, knowing they will be getting valuable results.

Lutter, W.J., R.L. Nowack, and L.W. Braile (1990), Seismic Imaging of Upper Mantle Crustal Structure Using Travel Times From the PASSCAL Ouachita Experiment, J. Geophys. Res., 95, 4621-4631.

16. Tectonic Underplating of Oceanic Crust, Alaska



The Trans-Alaska Crustal Transect (TACT) has yielded significant results about crustal and mantle structure, in a region where continental accretion has been going on since Cretaceous time. This program, organized by the U. S. Geological Survey, and conducted by the Survey in collaboration with different University groups, is a model for the organization of a major cooperative program of geophysical investigation. It is composed of a number of individual field projects which, over several years, employ different methods in the same area.

The TACT route runs from the Beaufort Sea to the Aleutian Trench, including a significant offshore leg. Recent work in the area of the Chugach terrane has included seismic reflection profiling, local earthquake studies, refraction profiling, and geological field studies. The example shown here compares the reflection profile of Fisher et al with the seismicity cross section of Page et al.

The reflection section has been depth migrated using velocities from the refraction survey. Prominent bands of reflections are seen between 16 and 35 km. Seismicity defining the top of the Benioff zone is superimposed; tectonically underplated oceanic crust (and some uppermost mantle) has been identified above the Benioff zone, on the basis of seismic refraction velocities and geologic investigations. These results indicate that continental growth can occur by tectonic underplating of the oceanic lithosphere at active continental margins.

A combined onshore and offshore seismic reflection profiling the subducting Juan de Fuca plate under Vancouver Island, with magnetotelluric studies (Green et al; Hyndman et al), is extremely significant; it shows the power of applying modern multidisciplinary tools to a problem.

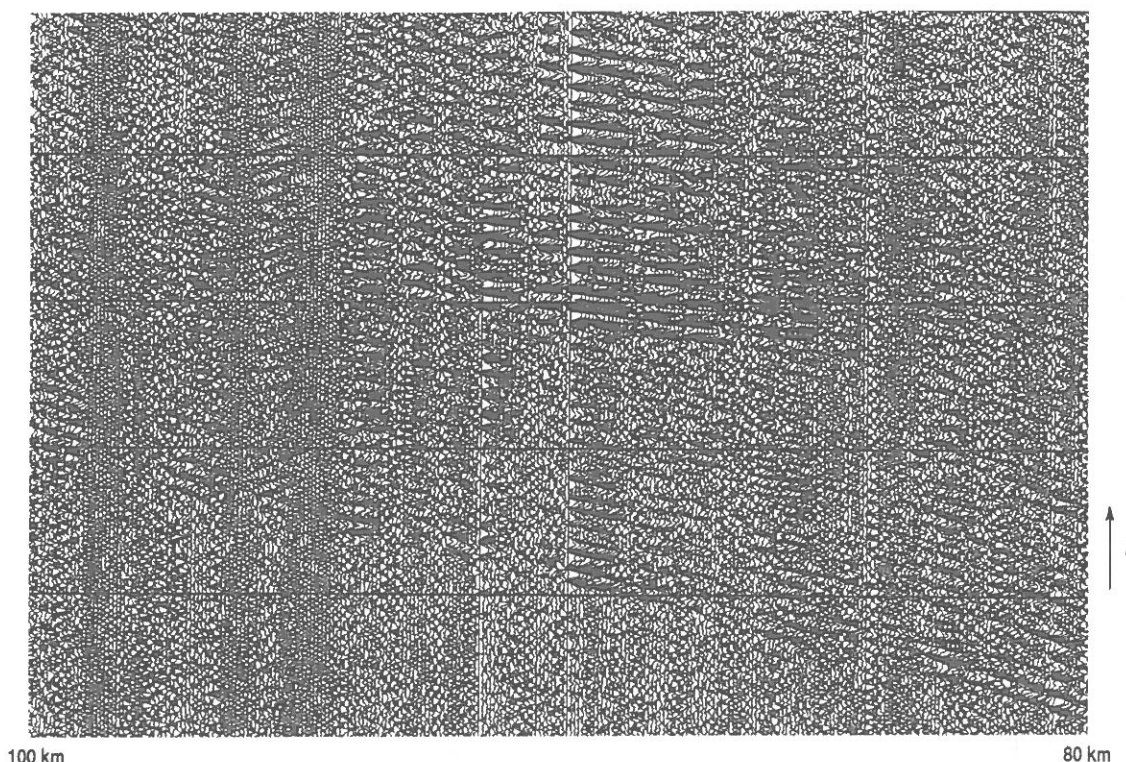
Page, R. A., C. D. Stephens, and J. C. Lahr (1989), *Seismicity of the Wrangell and Aleutian Wadati-Benioff Zones and the North American Plate along the Trans-Alaska Crustal Transect, Chugach Mountains and Copper River Basin, Southern Alaska*, *J. Geophys. Res.*, **94**, 16059-16082.

Fisher, M. A., T. M. Brocher, W. J. Nokleberg, G. Plafker, and G. L. Smith (1989), *Seismic Reflection Images of the Crust of the Northern Part of the Chugach Terrane, Alaska: Results of a Survey for the Trans-Alaska Crustal Transect (TACT)*, *J. Geophys. Res.* **94**, 4424-4440.

Green, A. G., R. M. Clowes, C. J. Yorath, C. P. Spencer, E. R. Kanasewich, M. T. Brandon, and A. Sutherland Brown (1986), *Seismic Reflection Imaging of the Subducting Juan de Fuca Plate*, *Nature* **319**, 210-213

Hyndman, R. D., C. J. Yorath, R. M. Clowes, and E. E. Davis (1990), *The Northern Cascadia subduction zone at Vancouver Island: Seismic Structure and Tectonic History*, submitted, *Can. J. Earth Sci.*

17. Airgun Sources for Imaging the Continental Margin



A recent two day onshore-offshore experiment near Oceanside, California, illuminates several issues. Eleven portable seismometers were deployed at 10 km intervals from Oceanside to Anza, on a line perpendicular to the coast. Six of these were the new PASSCAL instruments with 3-component 2-hz seismometers. A 2000 cu. in. marine airgun was fired at 20 sec (44m) intervals on a WSW extension of the receiver line offshore toward San Clemente Island. Data were continuously recorded on the hard disk packs of the instruments for the 8 hours of the experiment.

1. Within one day of the end of recording (9 May 1990), the data were dumped onto a workstation and plotted. Minus transit time, the delay between acquisition and availability for display and processing was perhaps 20 minutes.
2. Excellent wide angle Moho reflections were seen on the receiver gathers at distances of 80-120 km... both PmP and SmS. The figure shows a portion of a receiver gather at an offset range of 80-100 km (1 second time marks). With a current state-of-the-art airgun, one would expect a variety of sub-critical, near-critical, and post-critical reflection events from the continental margin structure, and be able to follow refractions out to beyond 200 km.
3. The onshore-offshore join used to be considered a problematic zone for acquisition of crustal reflection images. Now, the ease with which high capacity portable instruments can be deployed onshore, combined with the ability of the offshore airgun to generate a closely spaced line of strong shotpoints, makes this zone perhaps the most fa-

vorable place for gathering high quality deep data. The offshore ship can obtain a conventional CDP marine profile, and the onshore instruments can be deployed in a 2-D pattern, providing 3-d information on the subsurface under the margin. The marine community has become interested in developing an ocean bottom seismograph (OBS), for use in arrays in the near-shore environment, as a means of augmenting these capabilities.

A continued program to map the deep structure of the US coastal zone by onshore-offshore methods, could be a very productive and cost-effective effort. The utility of offshore profiling of continental margins has been exploited very successfully by the BIRPS consortium from the U. K. A similar effort in the U.S., the EDGE project, has acquired offshore CDP data on the Yakutat margin of Alaska, and has combined an offshore CDP program with onshore recordings across the Central California coastline (Levander and Putzig).

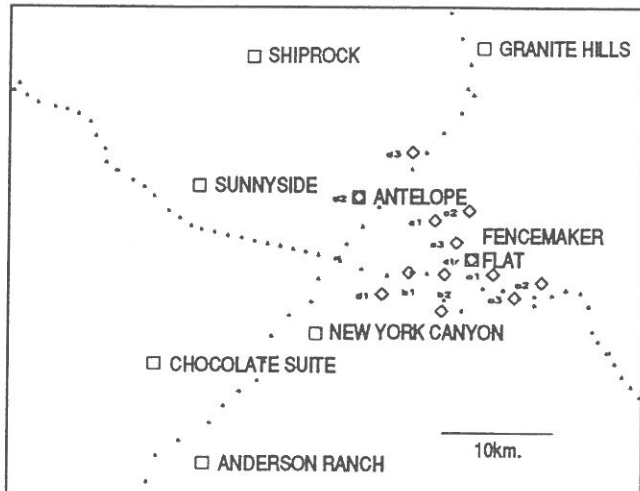
4. The lack of offshore static problems, and the further ability to generate local arrays of sensors on land, provides sufficient channel capacity to look for energy reflected from within the upper mantle, but buried in the crustal signal (by array beamforming).

Heney, Thomas Y. (1990), personal communication.

Levander, A. R., and N. E. Putzig (1987), Interpretation of a Continuous-Offset Seismic Profile in the Central California Margin, EOS, 68, 1366.

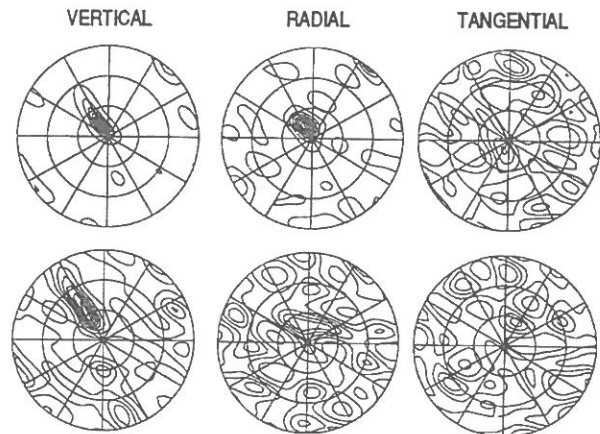
18. An Array for Crust and Mantle Imaging Using Converted Waves

40.25N 118.25W



39.9SN 117.75W

ARRAY PERFORMANCE VS FREQUENCY



P-waves incident on a structure from below generate converted shear waves by scattering into the forward direction from heterogeneities within the structure. Recording of this scattered wavefield by a surface array permits the application of established wavefield extrapolation methods of imaging, normally used in reflection profiling.

This has been the basis of the "Receiver function" method (Owens), in which the vertical component of a teleseismic P wave is regarded as the source function, and is used to deconvolve source effects from the radial component. The deconvolved radial then is an approximation to the forward scattered field of shear waves. This was developed as a single station method, although it can be applied separately for different event backazimuths, yielding a directionally dependent result. As an imaging tool, the single station method is equivalent to the 1-d deconvolution of reflection seismograms.

From August 1988 until May 1989, an array deployment was undertaken in north-central Nevada under the PASSCAL program. It was located in the vicinity of the 1986 PASSCAL active source experiment. Its purposes were to record teleseismic and other earthquake source records, to extend and apply receiver function techniques to an array, and to compare the results of these studies to the reflection and refraction profiles which had preceded.

Two arrays of 3-component instruments were utilized. A Large-aperture Array (LAA), consisting of 7 prototype PASSCAL recorders equipped with modestly broadband (intermediate period) seismometers, was

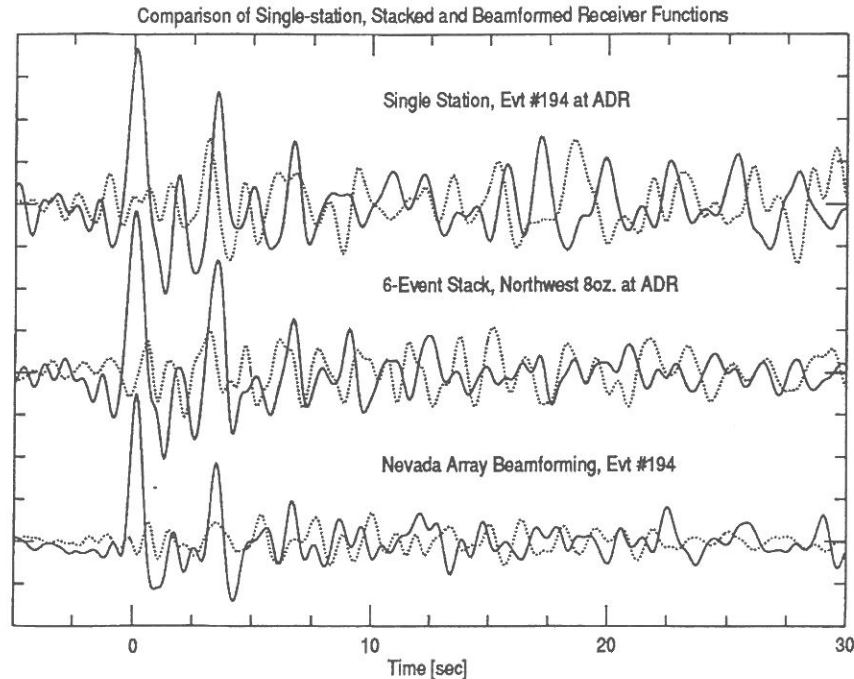
deployed with an average station spacing of about 8 km. A Small-Aperture Array (SAA) was used, consisting of 13 Reftek recorders and equipped with 3-component 1hz sensors. The LAA operated in an event triggered mode with a sampling rate of 20 s/sec for about 9 months, and was the first major experiment to utilize the new Passcal recorders. The SAA recorded continuously at 100 s/sec for about 3 months using the Lawrence Livermore Laboratory's configurable Seismic Monitoring System. The basemap (figure on left) shows the LAA sites (squares), the SAA sites (diamonds), and the receiver points for the 1986 active source experiment (triangles).

Analysis to date has clearly demonstrated the worth of this recording mode in passive-source lithospheric imaging experiments (Randall and Owens). For example, the figure on the right shows the benefits of broadband recording over narrow-band recording. For event #194 from Honshu, recorded by the LAA, the directionality of a 15 second signal window is given in wavenumber space: Top, for the actual broadband data; Bottom, filtered to simulate a 1 Hz instrument.

For the broadband data, the vertical and radial components of the P wave have well-resolved peaks. These indicate the dominance of on-azimuth arriving energy over scattered energy in the broadband teleseismic P-waveform. There is little coherent energy in the tangential component. In contrast, the simulated 1hz data shows a severely degraded radial component, proving that randomly polarized scattering at these wavelengths begins to dominate the waveforms. Broadband sensors will be essential for future application of these methods.

-continued-

18.(Cont.) An Array for Crust and Mantle Imaging Using Converted Waves



A significant increase in signal/noise ratio can be found with a modest array. Receiver functions should contain primarily P-to-S converted phases generated beneath the receiver. With a single station, receiver functions may be calculated for single events, or by stacking receiver functions from multiple events from similar source regions. With array deployments, a third approach is to use the entire array for beamforming prior to deconvolution.

These approaches are compared in the figure on the left. The radial (solid) and transverse (dotted) receiver functions are displayed. The third approach (beamform before deconvolution) yields the cleanest representation of the Ps radial component converted wave energy.

This important observation, from a minimal array, implies that we can expect dramatic improvements in signal-to-noise ratio with arrays of 20 to 25 broadband instruments over single-station data. This means, first, that we can expect to observe smaller amplitude arrivals generated from interfaces in the upper mantle and mantle lithosphere more easily. Second, a deployment of an array of instruments can now be expected to reduce the recording time of a teleseismic field experiment, by making smaller teleseisms usable.

Signal enhancement of converted phases by a very different approach was used by investigators from the Institute of Geology of the Soviet Academy of Sciences. This was used to establish crustal structure on long profiles in Kazakhstan. A linear array of 120 3-component 1 hz seismometers, with 250 m spacing, recorded

teleseismic P-waves. By lining up the radial component seismograms in a record section, the Ps Moho converted phase becomes visible by virtue of its multichannel coherence across the entire array. Long profiles of crustal structure were created by rolling this array along at suitable intervals.

The receiver function (deconvolved radial component) becomes an exact analog of a Born reflected wavefield in reflection seismology. This occurs if the deconvolution approach to receiver functions is combined with the linear array-record section. It may be migrated into an image of the subsurface.

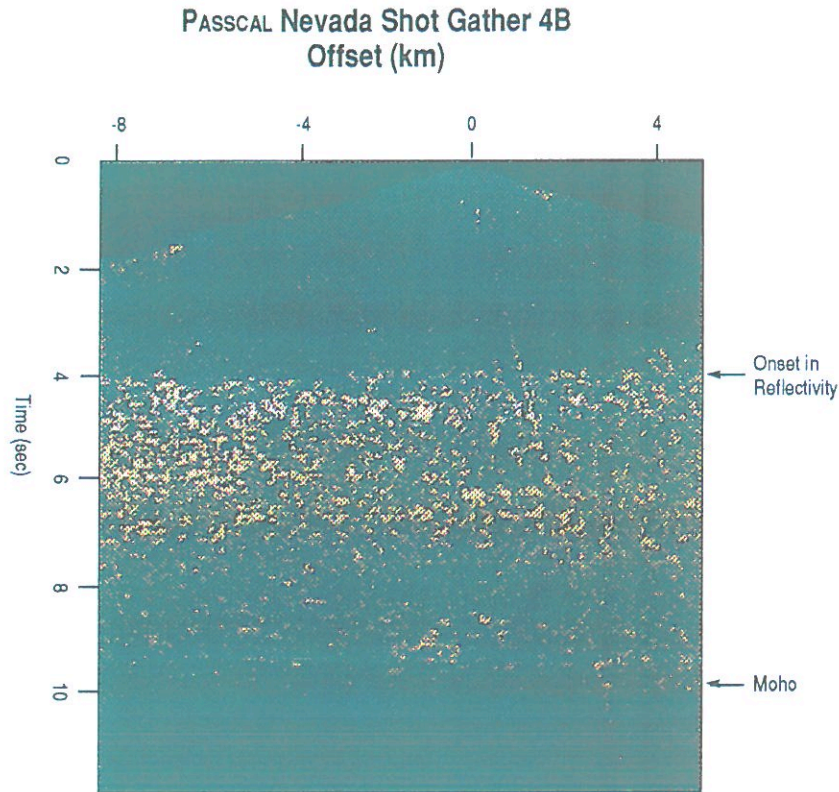
Developing these methods is particularly important because deeper targets, the Moho and deeper mantle interfaces, are impartially imaged by distant sources, without the geometrical signal decay suffered with artificial sources in reflection profiling. Such studies are now possible with PASSCAL instruments. The most obvious practical limitation is that only a few teleseisms have appreciable spectral energy above 2 hz.

Owens, T. J. (1987), *Crustal structure of the Adirondacks determined from broadband teleseismic waveform modeling*, *J. Geophys. Res.*, 92, 6391-6401.

Randall, G. E., and R. J. Owens (1990), *Array analysis of teleseismic P-waveforms from the 1988-89 PASSCAL Basin and Range Passive Source Seismic Experiment*, *EOS*, 71, 557.

Galperin, Y., (1989), *personal communication*.

19. Use of Explosive Sources for Crustal Reflection Imaging



More powerful sources than either explosions or earthquakes are needed to extend reflection imaging techniques either to the lower crust and mantle, or to reliable in situ estimation of physical properties. PASSCAL instrumentation for long, closely spaced receiver arrays makes possible explosion and earthquake data which can be treated as coherent wavefields.

In recent large-offset refraction studies in Nevada (PASSCAL), Arizona (PACE), and the Columbia River Plateau, university and USGS groups collaborated in the distribution of long reflection cables. These recorded the wavefields from explosions of 100-2000kg at different offsets. To much surprise, the images of the crust and upper mantle were shown to have a broad frequency bandwidth and are not severely contaminated by source-generated noise. Clear, high resolution images of the crust and upper mantle seem to be the rule, rather than the exception (Jarchow et al).

Many benefits are found by this approach:

- Much stronger signals provide good signal to noise ratio at upper mantle depths.
- Signal degradation due to vertical stacking of multiple vibrators and multiple sweeps is no longer an issue.
- At the normal shot depths, interfering ground roll occurs in a lower frequency band than the reflected signals, and can be removed by filtering.

- Good shear waves are excited, which can be analyzed with 3-component arrays.

In the figure above is part of an unstacked explosive shot gather collected in NW Nevada, showing the lamination characteristic of the lower crust in the Basin and Range, with the die-out of reflectivity at Moho depth. Instrument spacing is 67m.

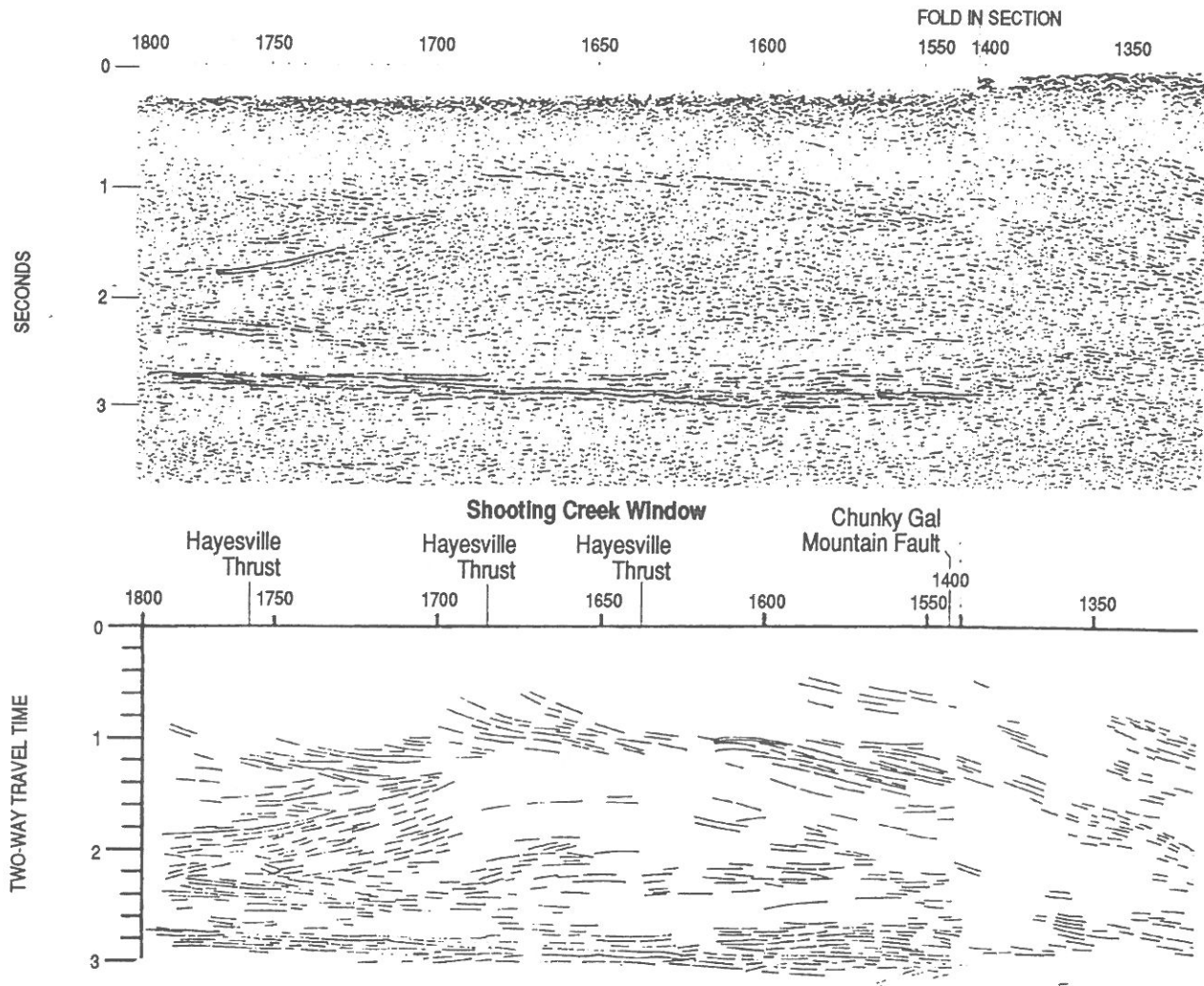
Direct comparison of dynamite data, with vibrator data under controlled conditions, was done by Brocher et al, in connection with seismic studies of the Yucca Mountain proposed waste repository. The mid-crustal images were nearly exactly the same, but explosions gave considerably better resolved, more impulse-like reflections, in the lower crust.

The same dynamite shots used for short-offset imaging are also recorded well at offsets up to 200km. They fit into an integrated strategy for crust/mantle imaging which uses both artificial sources and earthquakes.

Jarchow, Craig M., Erik B. Goodwin, and Rufus D. Catchings (1990), Are Large Explosive Sources Applicable to Resource Exploration?, The Leading Edge, 9, #1, 12-17.

Brocher, T.M., and P.E. Hart (1990), Do High Fold Vibroseis Methods Image the Lower Crust? Comparison of Vibroseis and Explosive Source Methods for Deep Crustal Seismic Reflection Profiling in the Basin and Range Province, manuscript.

20. Reflection Profile of the Southern Appalachian Thrust Sheet



The past five years have seen significant extensions to the CDP method: wide angle geometry, shear waves, and dynamite sources, to name a few. Narrow-angle, conventional CDP imaging, however, remains the baseline for studying much of the crust. This example, from the ADCOH Southern Appalachian project, shows that optimal choice of field and processing parameters can yield major improvements in quality.

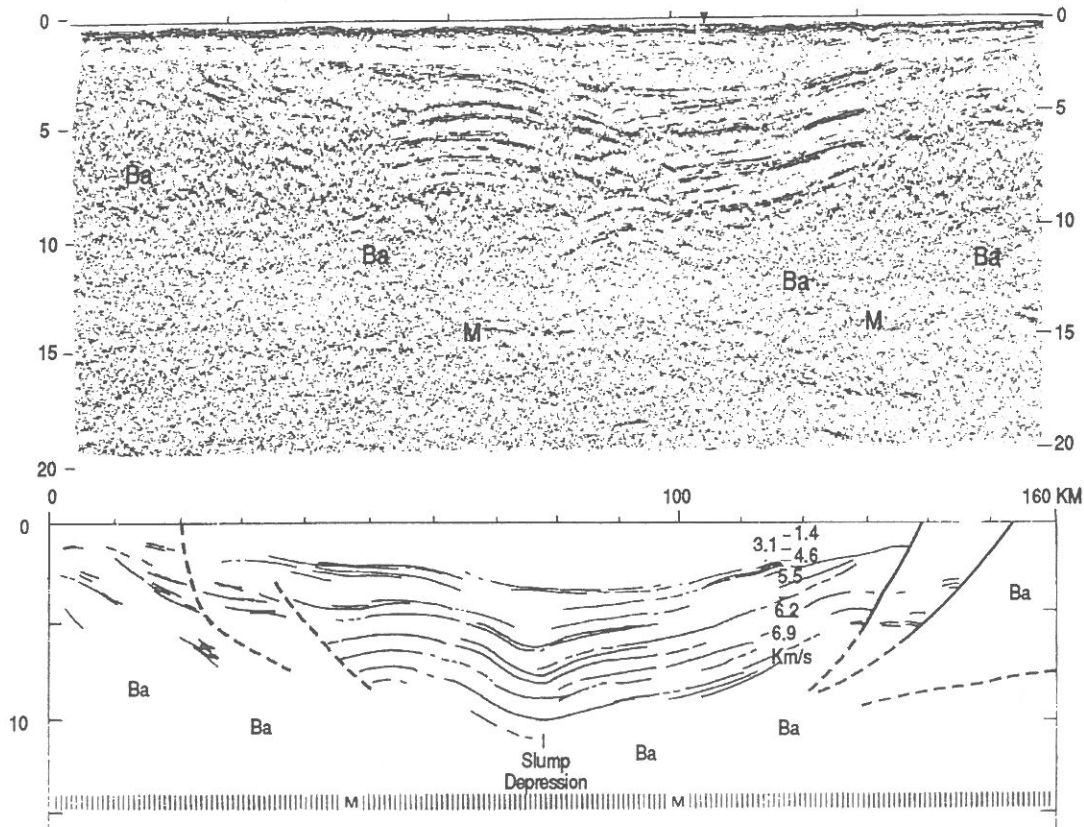
The target, in this case, was the crystalline thrust sheet of the eastern Blue Ridge in western North Carolina. The goal was to extract detailed information on the internal structure of the thrust, now about 10 km thick, with high grade crustal rocks at the surface. The stacked section (top), was obtained from 30 fold vibroseis data, using 4 vibrators and 120 receiver groups. Using an experiment design aimed at just the top 10 km, the investigators were able to image a number of internal

reflectors, including near-surface reflectors with steep dips.

The interpretation (bottom) shows the interior of the thrust sheet consisting, at that point, a massive antiform, interpreted as a duplex structure. Steeply dipping imbricates are draped over the duplex. The chance that the duplex may be constructed of sub-thrust platform sediments have suggested the axis be drilled to look for hydrocarbons. This reflection line has provided a basic explanation for the regional scale tectonic windows found in the crystalline Blue Ridge from Virginia south to Georgia.

Coruh, C., J. K. Costain, R. D. Hatcher, Jr., T. L. Pratt, R. T. Williams, and R. A. Phinney (1987), Results from Regional Vibroseis Profiling: Appalachian Ultra-deep Core Hole Site Study, Geophys. J., 89, 147-156.

21. "GLIMPCE Profiling of Precambrian Crust"



These images of the Keewenaw Rift underlying Lake Superior are produced by the GLIMPCE experiment (Behrendt et al). They are a particularly striking success for reflection profiling. The collaboration between the Geological Survey of Canada, the U. S. Geological Survey, and many University investigators, was built upon a marine multichannel airgun reflection survey in Lake Superior. "Piggyback" portable 3-component instruments on shore and on islands in the lake made it possible to map transverse variations in the structure, and to invert for seismic P and S velocities.

The section shows the rift-filling volcanics and sediments extending nearly to the present-day Moho. The velocities are well enough resolved that the sediment-dominated upper section and the volcanic-dominated lower section can be quantitatively modeled.

On a GLIMPCE multichannel reflection line in Georgian Bay, the Canadian Lithoprobe team imaged the crustal cross-section at the Grenville Front, in which Grenville rocks are tectonically thrust west and up over older Precambrian crust. At depth, the Grenville Front is a thick imbricated stack of highly reflective, deformed high grade basement, dipping uniformly $\sim 35^\circ$ SE., through the entire crustal thickness.

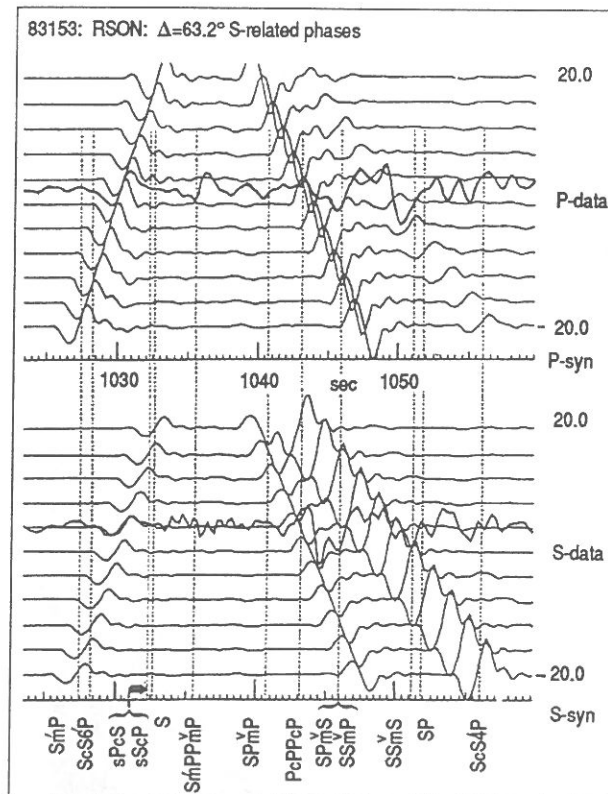
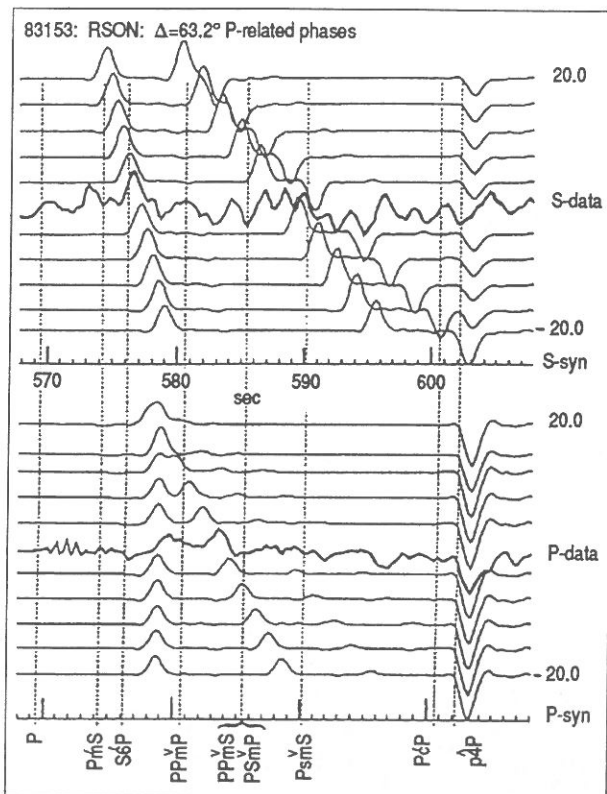
Lithoprobe profiling across the Kapuskasing uplift northeast of Lake Superior (Geis et al) recently imaged a major set of SE verging low-angle thrusts, along which the mid- and lower-crustal rocks of the uplift were brought to the surface.

Thus, major Proterozoic crustal dislocations are now readily imaged. Within the Archean, however, the standard imaging methods have not yielded particularly clear images. These oldest of crustal sections will require specialized experiments aimed at high resolution imaging of steeply dipping, complex structures.

Behrendt, J. C., A. G. Green, W. F. Cannon, D. R. Hutchinson, M. W. Lee, B. Milkereit, W. F. Agara, and C. Spencer (1988), Crustal Structure of the Midcontinent Rift System: Results from GLIMPCE Deep Seismic Profiles, *Geology*, **16**, 81-85

Geis, Wayne T., F. A. Cook, A. G. Green, B. Milkereit, J. A. Percival, and G. F. West (1990), Thin thrust sheet formation of the Kapuskasing structural zone revealed by Lithoprobe seismic reflection data, *Geology*, **18**, 513-516.

22. Imaging the Continental Lithosphere: New Body Wave Techniques



Teleseismic body waves represent a natural tool for the investigation of Earth structure. Until recently, the limitations both of data, and of analysis techniques, have kept inquiry to only a very small part of the available information, such as the first arriving P wave, or a narrow band of surface waves. The availability of high quality, broad-band three-component digital data has prompted the development of interpretation methods, which make full use of these signals.

Clarke and Silver have shown how to invert for crustal and upper mantle structure using full waveform 3-component data. By exploiting the partition of energy between large main phases associated with smooth structure and families of smaller "boundary interaction phases" associated with discontinuities, specific features of the Earth's velocity structure can be targeted. The tool which makes this possible is a new technique for calculating synthetic seismograms. These "Complete Ordered Ray Expansion" (CORE) seismograms are both *complete*, in the sense of containing all significant energy contributions, and *interpretable*, in the sense that all such contributions can be explicitly identified.

One of this technique's applications is the study of the Moho. By using interaction phases associated with either the direct P or S wave (or other main phases), estimates of the crustal thickness under a station can be had using a single deep focus earthquake. In addition, combining P- and S-related phases will eliminate the trade-off between crustal velocities and Moho depth, and produce reliable measurements of Poisson's ratio for the crust.

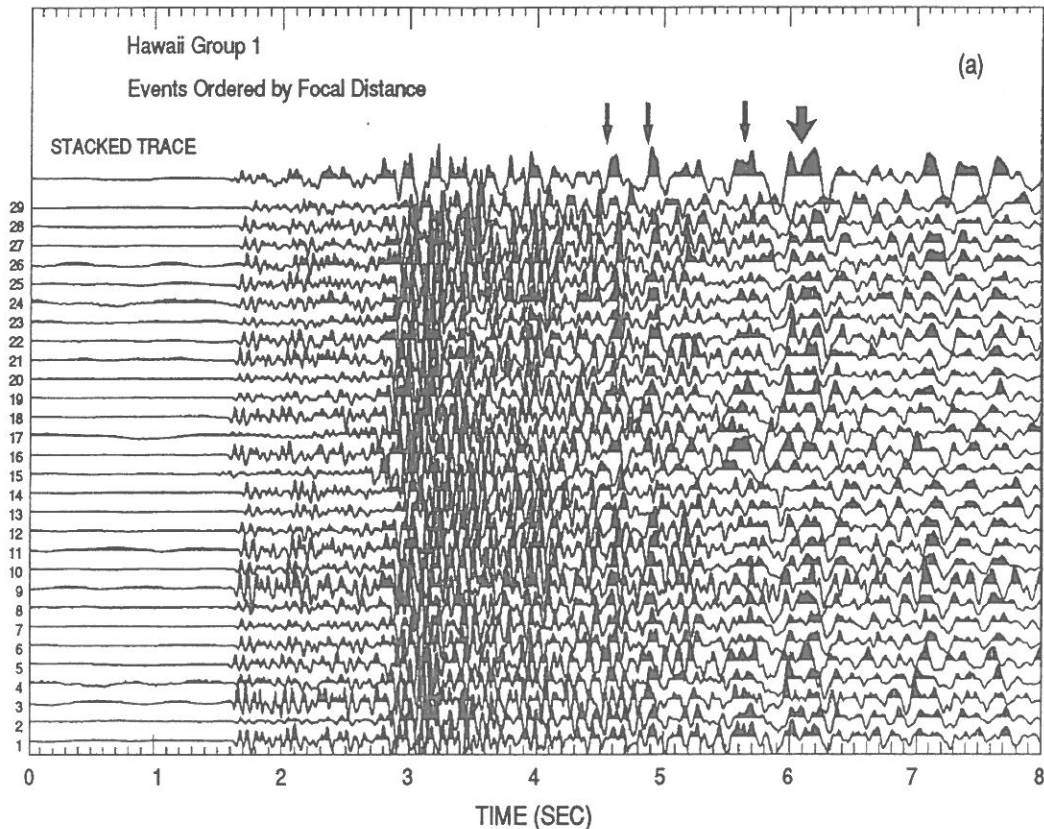
P-related Moho interaction phases for a deep focus South American event were recorded at station RSON in Ontario (left). The deconvolved data have been rotated into P (bottom) and SV (top) directions, and the direct P wave subtracted from both data and synthetics. Synthetic seismograms are shown for a number of Moho depths, for perturbations between +20 and -20 km about a reference of 40 km, and with the data traces plotted at the value giving the best fit (0 km in this case). In addition to the Moho related phases shown, an S-P conversion is also seen around 578 seconds on the P component.

The S-related arrivals (right) need reliable identification, since many unrelated phases occur in this time window. The precursor SmP, and other Moho phases, are seen clearly, as well as other Moho phases. These include a larger than predicted SmPPmP on the P component. The minimum residual occurs at a perturbation of 2 km, giving a Moho depth of 38 km. The P and S information can be combined to invert for Poisson's ratio for the crust beneath RSON, giving a value of 0.255.

Such results show important seismological constraints on crustal composition beneath a station, using a few three-component records. By applying the same technique to deeper structure, mantle and transition zone discontinuity structure can be constrained.

Clarke, T., and P. G. Silver (1990), *A Procedure for the Systematic Interpretation of Body Wave Seismograms - 1: Application to Moho Depth and Crustal Properties*, *Geophys. J. Int.*, in press.

23. Structure and Dynamics of the Hawaiian Hot Spot



Hawaii is a classic laboratory for studying hot spot dynamics interacting with oceanic crust. The intracrustal seismicity directly indicates magmatic movement upward as well as sources for tracking fault geometry, and imaging crustal and upper mantle structure.

James and Savage have treated a cluster of shallow earthquakes as a source array, and, after careful processing, produced a record section showing shear wave reflections from within the crust (S_2 and small arrow), and from the Moho (large arrow). This is the best demonstration to date of how earthquakes can be used as sources for seismic reflection images.

In a summer of 1990 experiment, a group from Wisconsin, Santa Barbara, and Stony Brook, plans to deploy three 6-station arrays of PASSCAL instruments on the southeast flank of Mauna Loa volcano. Data from shallow and deep local earthquakes and teleseisms will be exploited. The major interfaces beneath the volcano's flank will be mapped with reflected and converted waves. One target interface is a basal layer presumed to be marine sediment mixed with volcanic debris lying beneath the volcanic edifice and atop the underlying ocean crust. This interface appears to serve as a major detachment fault, giving rise to large earthquakes such as 1975 Kalapana (M 7.2) and 1868 Kau (M 8?). The other target is the crust-mantle boundary (Moho).

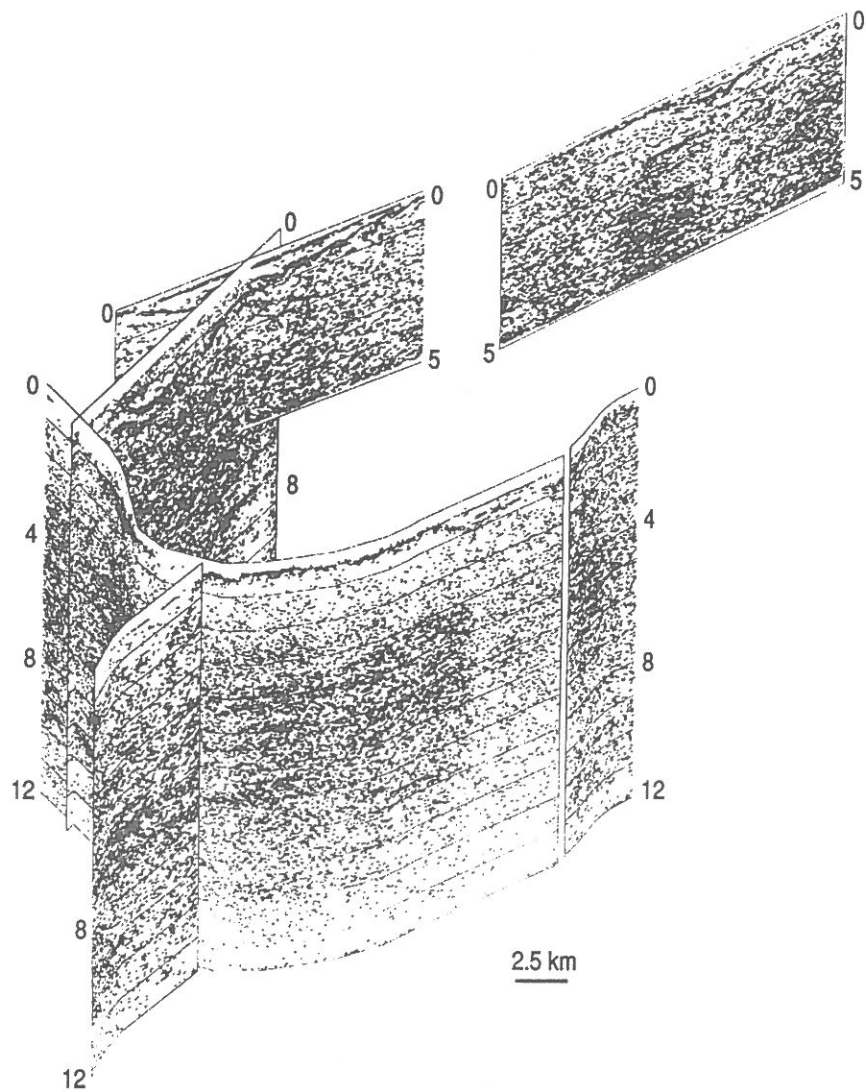
Mapping the Moho depth and crustal thickness variations will provide direct information on the flexural deformation of the lithosphere beneath Hawaii. This will hopefully resolve the bent versus broken plate controversy, constrain estimates of elastic lithosphere thickness, and evaluate the extent of crustal underplating or thinning beneath the young volcanic centers of southern Hawaii. Future goals are to resolve the debate over the deep structure of the volcanic rift zones of Kilauea and Mauna Loa (a possible "deep" magma zone), and eventually to image the mantle beneath the island, in search of the mantle "plume".

The James and Savage results suggest that the new study, which will employ tight receiver arrays with beamforming capabilities, should produce some very clean image information. It also illustrates very well how 3-component digital instruments enable study shear waves, both velocities and images, in a way comparable to the established methods for using compressional waves.

James, David E., and Martha Savage (1990), A Search for Seismic Reflections from the Top of the Oceanic Crust beneath Hawaii, Bull. Seis. Soc. Amer., 80, 675-701.

Thurber, Clifford T., (1990) personal communication.

24. Reflection Imaging of Extensional Crust: the Whipple Mountains



The crystalline continental basement shows a complex history of deformation, recrystallization, and melting. Reflection profiling has, since the COCORP profiles of the late 1970's, been a principal tool in understanding the way the crust deforms, and its characteristic structures. The importance of low angle detachments, now acknowledged, marks a major breakthrough in the past decade.

The CALCRUST program of profiling on the Whipple Mountains of California southeast was directed at imaging the characteristic mid-crustal detachment found in the extensional Basin and Range. It was also aimed at finding its extrapolation from the surface outcrop, and at determining the characteristic appearance of the principal mylonite zone in reflection images. This is an important step towards developing reliable interpretations of deep crustal images for which no correlative surface outcrop exists.

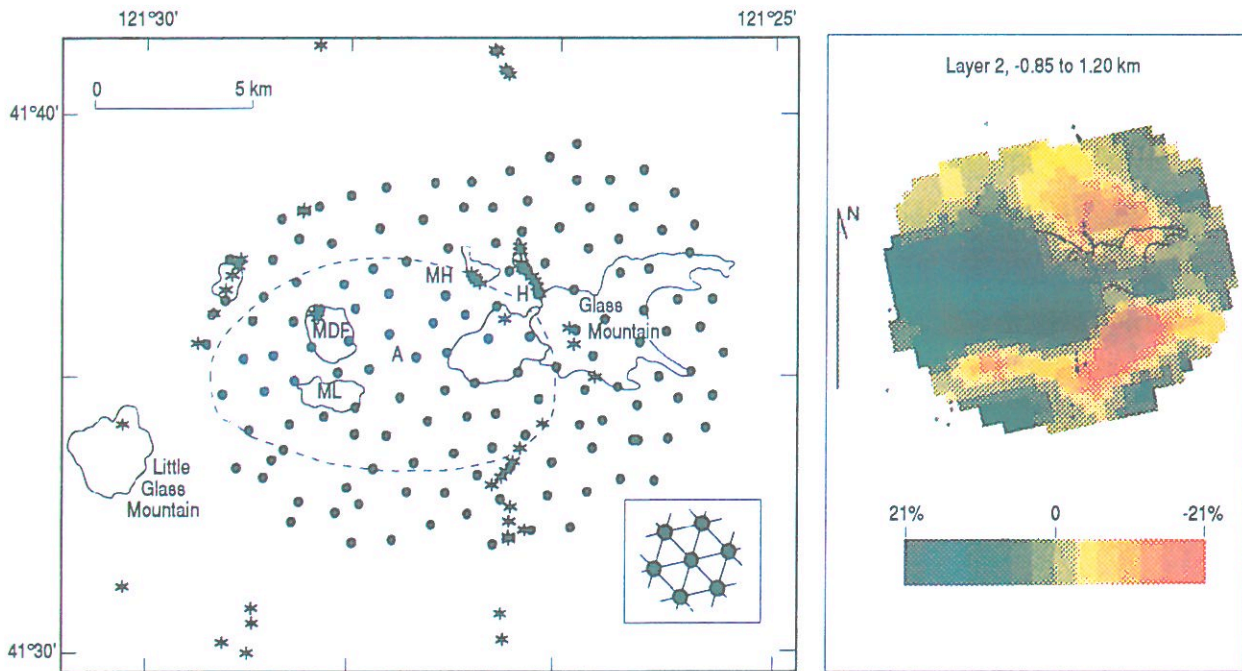
The figure shows an oblique perspective fence diagram of five Calcrust and two industry profiles. Significant mid-crustal reflectivity exists from 3 to 7 seconds

throughout the region and rises towards the observed Whipple and Chemehuevi metamorphic core complexes (lower plate mylonites). These reflections are seen to be caused by the mid-Tertiary extensional mylonite fabric. Low angle detachment faults are common through the region, and are the brittle upper plate expression of the extension which formed the mid-crustal mylonites.

Imaging of structures in the near subsurface is a current frontier, because sources, recording geometries, and processing have to be customized to detect and resolve complex, steeply dipping features in the near-field of the experiment. Flexible, high performance portable instrumentation is critical in developing such capabilities, whether for applied hydrological studies, or for basic continental dynamics studies.

Okaya, D., E. Frost, G. Davis, and T. Henyey (1990), CALCRUST Seismic Profiling in the Whipple Mountains Detachment Terrane - Part II: Evidence for Distributed mid-Tertiary Extension, (in preparation).....

25. Tomographic Image, Medicine Lake Volcano



Tomographic methods may be applied at any scale. Although not widely tried for smaller scale crustal features, they are in some ways less complicated than regional or global scale efforts. The edifice and underpinnings of a volcano represent the kind of geological feature which can be targeted with portable instruments in a limited-scale deployment.

Evans and Zucca selected the summit caldera of the Medicine Lake, California, volcano (map above), as a target for a small-scale tomographic experiment which relied upon dynamite shots fired outside the target zone at different azimuths. 140 mostly vertical sensors were deployed in a 12x16km oval array, and eight explosive sources (1360-1810 kg) were at 50 km distance. First arrival signal propagation was via a 6.3 km/sec refractor at about 5 km depth, thus limiting the target zone to shallower depths.

The geometry is intermediate between local earthquake tomography and teleseismic tomography. First arrival wave groups were analyzed for travel time anomalies, and for differential attenuation t^* by spectral ratios. Imaging was done by dividing the target volume into cells, and applying a damped least squares inversion.

The structure of this edifice is sufficiently complex that the input data set was just adequate to define the major anomalous features. Numerous artifacts of the experiment geometry and complexity had to be sorted out, by testing several alternative approaches to the reduction and inversion of the data.

The color figure above shows the most striking features in the final inversion. For the depth range -0.85 to 1.20 km (with the surface at -2 km), a major high velocity plug is found in the western portion of the caldera. In the context of other geological and geophysical information, this is seen as an intrusive mass of sills and dikes of the same composition as the observed extrusives.

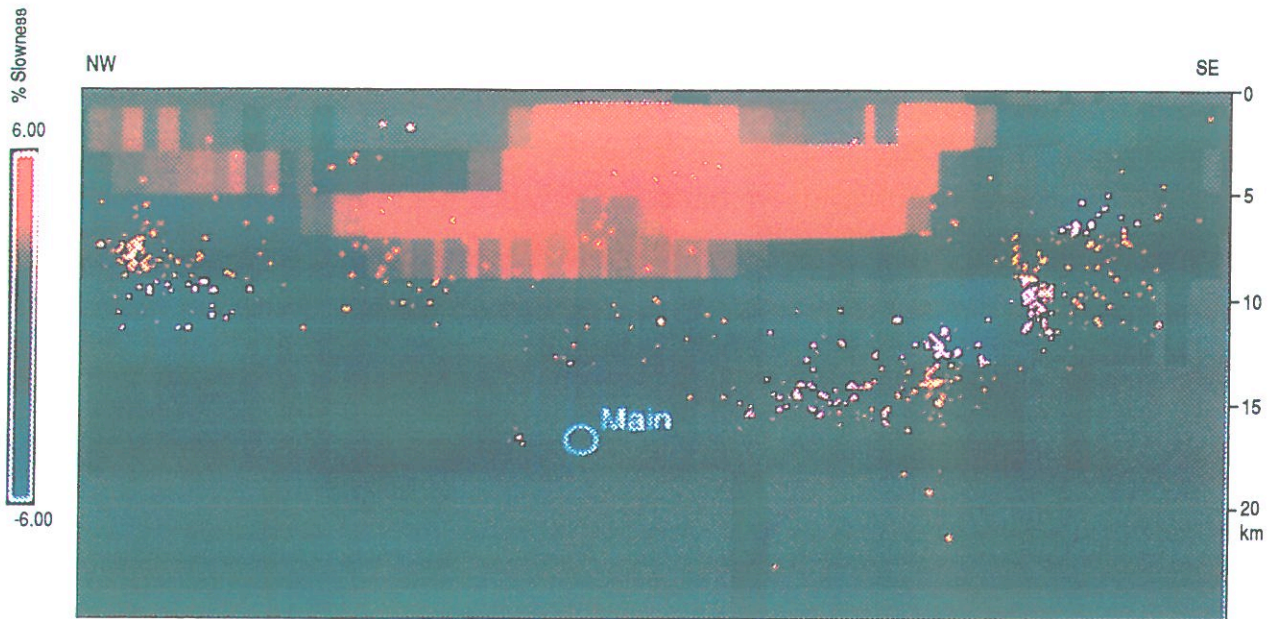
The low velocities (yellow to red) form a ring around the outside of the caldera, and are interpreted as due to the load of low velocity extrusives and sediments banked on the outside perimeter of the caldera.

A significant low velocity nexus is imaged in the northeast corner of the caldera at depths of 1.2 to 3.25 km (not shown above), and is proposed to be the site of a long-persisting, but small magma chamber.

This study is similar to the very long scale images obtained for the lower mantle. As in these geologically significant anomalous zones can be clearly detected, but further information is unobtainable from the baseline travel time data. To proceed, it will be necessary to exploit the full recorded waveform data, with local 3-component arrays. These are a basis for identifying and imaging discontinuities within the structure.

Evans, John R., and John J. Zucca (1988), Active High-Resolution Seismic Tomography of Compressional Wave Velocity and Attenuation Structure at Medicine Lake Volcano, Northern California Cascade Range, J. Geophys. Res., 93, 15016-15036.

26. Loma Prieta Velocity Structure: Correlation with Aftershock Distribution



This tomographic reconstruction of P-wave velocity anomalies along the San Andreas Fault in the Santa Cruz Mountains, was generated from over 500 aftershocks recorded on nearby USGS Calnet stations after the October 17, 1989 Loma Prieta earthquake (Lees).

The earthquakes were relocated using a layered, two sided fault model (with no ray bending at the fault). The tomographic inversion was done using Lee's and Crosson's method (1989). The colors depict velocity deviations from the baseline layered model, ranging from 6% fast (blue), through 0 (black), to 6% slow (red),

Note the correlation of the earthquakes with the faster velocities, the aseismic zone around the fast hypocenter of the October event, and the slow, aseismic zone above the rupture. A similar study along the Parkfield segment of the San Andreas Fault, using downhole instruments with a low magnitude detection capability, also supports this correlation (Lees and Malin).

Based on these results we would propose the following model:

- Portions of the fault subject to seismic (brittle) failure are fast.
- Events of a wide range of magnitudes occur by release of stress on asperities which form a mosaic of widely varying sizes.

- Large earthquakes are to be anticipated where the medium is fast, and the local seismicity appears to be depressed relative to other fast regions.
- The slow regions with low seismicity, are identified with less competent rock, incapable of supporting appreciable stress, although in the brittle regime.

These results suggest a possible strategy for monitoring a segment of the San Andreas Fault for earthquake forecasting. A real-time network of high sensitivity down-hole seismometers (3-component) should be designed with the capability of detecting and locating all events above magnitude 0. In addition to monitoring the seismicity and focal mechanisms, the velocity model should be monitored as a function of time by having a number of controlled source points; times for such controlled events can be used to calibrate the velocity model determined from natural events.

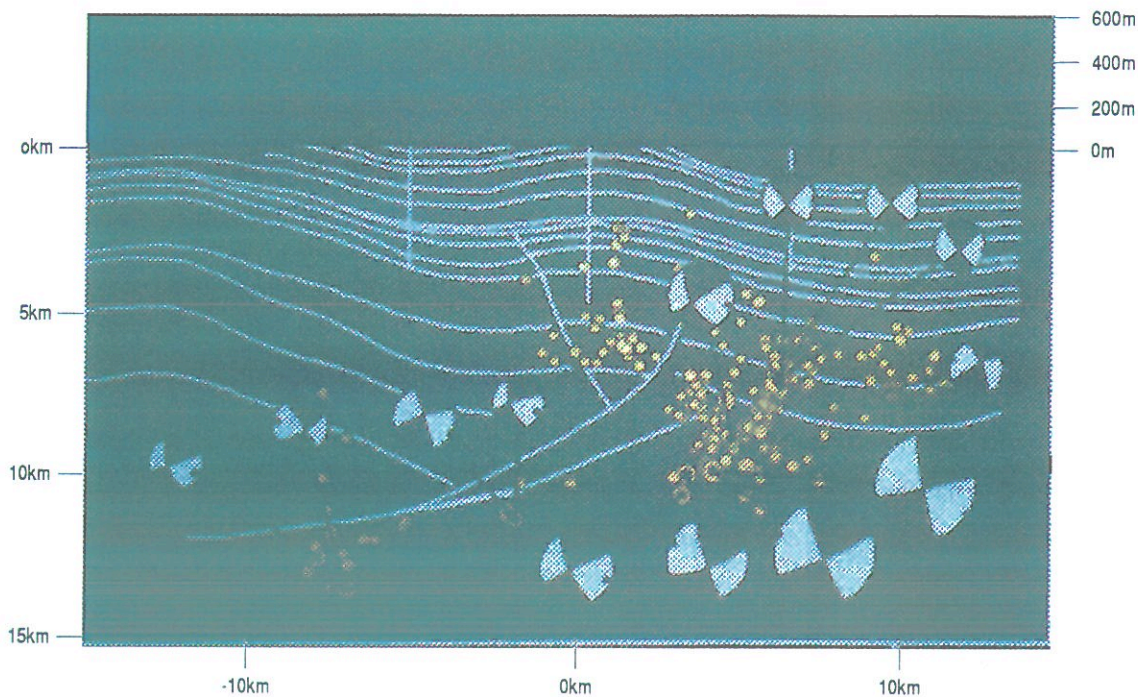
Technically, this level of capability requires high capability instruments, low noise borehole sites, rapid playback and data processing. These are all elements of the IRIS/PASSCAL effort.

Contributed by Peter Malin

Lees, J. M., and P. E. Malin (1990), Tomographic Images of P-Wave Velocity Variation at Parkfield, California, J. Geophys. Res., in press.

27. Earthquake Hazard and Subsurface Structure: the Kettleman Hills Anticline

Cross section at 36° 5.4' N, 120°10.8' W
Azimuth: 308°
Depth of field: -8km to 2km



Only recently has the scientific community recognized the importance, to California geology, of anticlines cored by blind thrusts. These structures contain a good fraction of the state's hydrocarbon reservoirs, and present a significant public hazard as major earthquakes. Recent work has just begun to clarify the relationship between microearthquake locations and mechanisms, and the geometry of the fault propagation fold.

The special earthquake hazard is caused by the entire land surface area over the blind thrust moving vertically during a large slip event. Thus everyone is "near the fault".

Traditionally, seismic reflection crews running rollalong vibroseis surveys imaged the structure, and earthquake recording networks located and characterized the earthquakes. The advent of broadband digital portable arrays for earthquake studies now makes it possible to investigate individual events in some detail. Using downhole sensors increases the sensitivity and number of events which can be studied by an order of magnitude.

The figure is a cross section of the subsurface structure of Kettleman Hills anticline, central California, from seismic reflection data. It shows Kettleman Hills earthquake locations. Northeast is to the right. The foreshock and mainshock are shown as filled hexagons. Focal

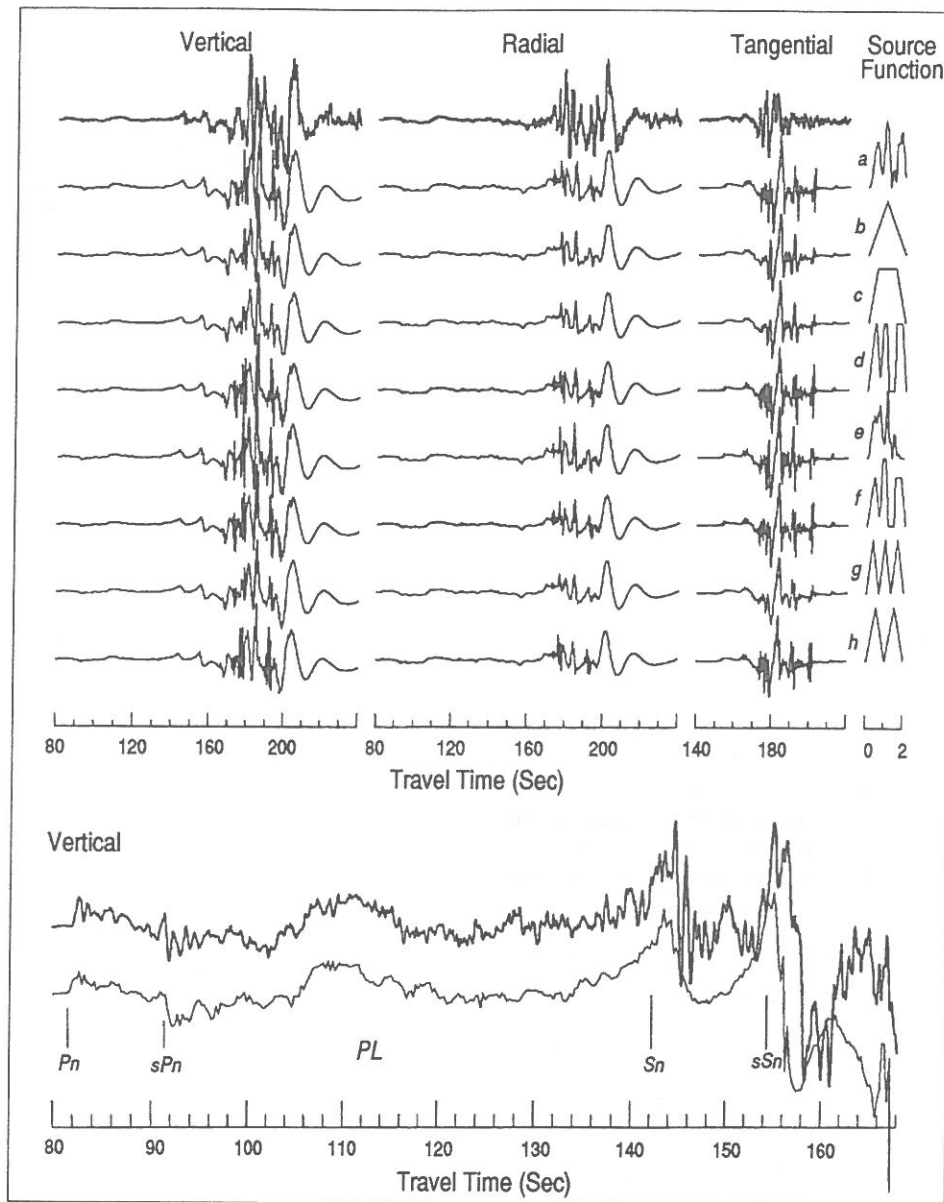
mechanisms are back hemisphere projections. The main shock appears to have occurred on a subhorizontal fault, while aftershocks show the development of more steeply dipping thrust faults. The discrepancy between the location of the mainshock and the interpreted fault surface, probably results from the different velocity models used to process the seismic data and locate the earthquakes. The reflection interpretation is from Meltzer (1988); the tectonic interpretation and earthquake locations are from Ekstrom, et al (1990).

Detailed monitoring of active blind thrusts by high sensitivity downhole digital arrays is of paramount concern to new earthquake monitoring efforts. At these sensitivities, earthquakes smaller than $m=0$ can be seen, providing a look at the small magnitude cutoff region as a function of time. Combined with modern geodetic and strain monitoring, close observation can be made of the status of displacements, fault slip, and stress within the active volume.

Meltzer, A.S. (1988), Crustal structure and tectonic evolution, central California, Ph.D. thesis, Rice University.

Ekstrom, G., R.S. Stein, J.P. Eaton, and D. Eberhart-Phillips (1990), Seismicity and geometry of a 110-km long blind fault, 1: the 1985 Kettleman hills, California, earthquake, J. Geophys. Research, submitted.

28. Very Broad Band Study of an Intraplate Earthquake



The $M = 6$ Saguenay earthquake, 640 km from the IRIS VBB station at Harvard, MA, was the first large cratonic earthquake recorded at regional distance by a high dynamic range broadband instrument. The top panel shows the observed record (top trace) and a sequence of synthetic records for different source time functions (right). This display is scaled to show the surface waves clearly.

The lower panel displays a blow-up of the first 80 seconds of the vertical trace, indicating the dynamic range required to study body waves and surface waves along the same path, and for the same event. The bottom trace uses synthetic record *e*.

The synthetic traces are computed using a transitional upper-mantle model crossing an old suture zone, with a source depth of 28 km. Complex source histories *a* and *e*, which were derived from a few strong-motion

observations fit the data best, indicating that IRIS stations are capable of assessing asperity content and related hazards of such earthquakes. Note that strong motion estimation in the western United States is possible, based on our ability to instrument active fault zones. This is not the situation in most intraplate environments, where active faults are not recognized at the surface. Consequently, the estimation of future strong motion for east-coast events is subject to large uncertainties.

Our knowledge of the source process for intraplate events should be substantially enhanced by increasing the number of such stations in the eastern and central U.S.

Zhao, L. S. and D. V. Helmberger (1990), Broadband modeling of the 25 November 1989, Saguenay Earthquake at Regional Distances, submitted, BSSA.

29. Loma Prieta Focal Mechanism from Global Seismic Network

The M_s 7.1 Loma Prieta earthquake of October 17, 1989 demonstrated the use of digital global seismic stations to determine a focal mechanism. Within hours of the event, several investigators had retrieved waveform data from the IRIS Data Management Center and made provisional determination of the focal plane, slip direction, and time behavior of the slip.

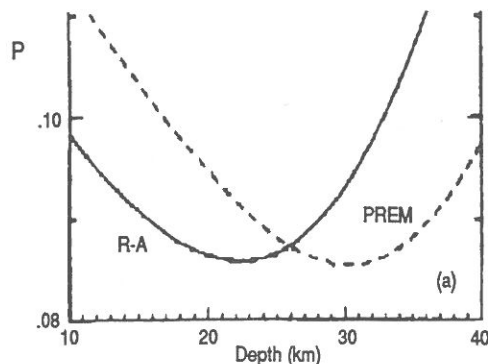
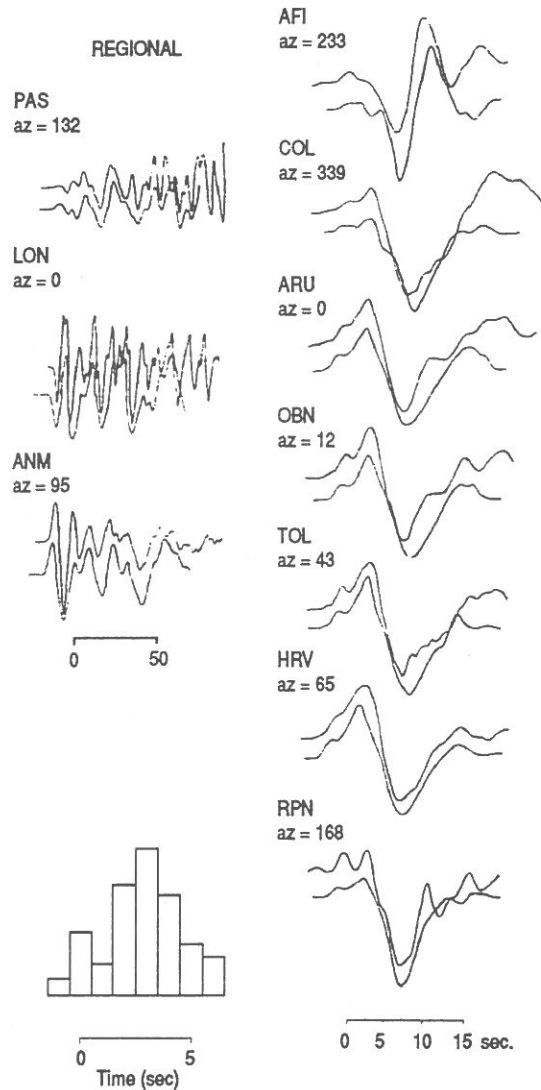
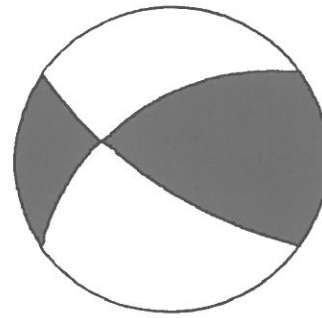
The body waveforms at regional ($1^\circ - 13^\circ$) and teleseismic distances are the product of source and propagation effects. If the effects of the travel path are known, then it is possible to recover seismic source processes such as fault orientation, fault displacement history and stress drop. Generalized Least Squares inversions for the seismic source based on minimizing the differences between observed and synthetic waveforms have become routine. High quality digital data yields much more detail about the faulting process than was possible with analog, band-limited WWSSN and early GDSN seismograms.

Shown to the right is the focal mechanism and the waveform fits for the Loma Prieta earthquake. The mechanism is an oblique thrust; the strike is consistent with the local trend of the San Andreas Fault, although the dip and reverse motion are somewhat of a surprise. The inversion is based on 3 regional distance stations, 7 teleseismic P waves, and 4 SH waves. The time behavior of the seismic moment release is shown below the regional distance records, with two discrete episodes of moment release separated by about 3.5 sec. On the basis of these waveforms, it is also possible to tell that the fault ruptured updip. The event nucleated at ~ 17 km and ruptured through an asperity at 12 km depth. These depths are extremely unusual for San Andreas seismicity, usually about 8 km deep. Shown at the bottom right is a depth resolution kernel determined from the long-period surface waves. Earth model R-A gives a hypocentral depth in good agreement with the body wave analysis.

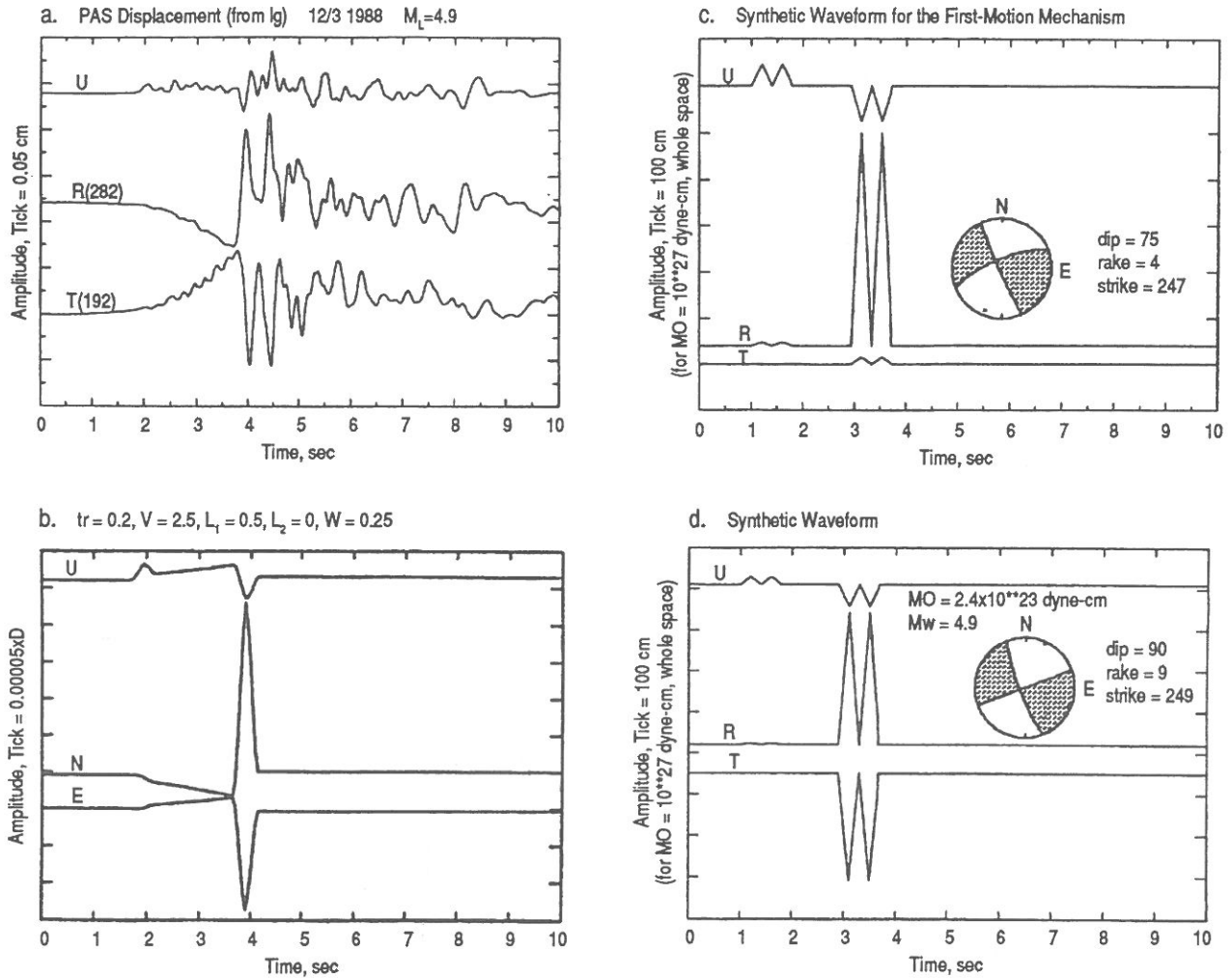
Immediately after a major earthquake, local authorities need reliable information on where to expect the most severe damage. A teleseismic source solution can be obtained within an hour of the event, and can predict the expected intensity of shaking as a function of location throughout the affected region.

Retrospective analysis of focal mechanisms is fundamental to picking apart the process by which two plate boundaries move relative to each other in a seismogenic region. Forecasting of future events depends on establishing a detailed model for the seismicity of events spanning a wide magnitude range.

Contributed by Terry Wallace



30. Very Broad Band Study of a Local Earthquake Asperities and Stress Drop



One of the proofs of the high dynamic range VBB IRIS instrumentation capability occurred recently in Pasadena, with an event occurring at an epicentral distance of 4 km. This was the 12/2/1988 magnitude 5 Pasadena earthquake. Panel *a* of the figure shows displacement records from the IRIS instrument.

This event triggered many strong motion instruments, including one co-located with the IRIS station in Pasadena, which produced nearly identical records to those displayed in the figure. Both the near-field, slow drift downward on the radial channel, and the far-field, sharp spikes near 4 seconds, are clearly recorded.

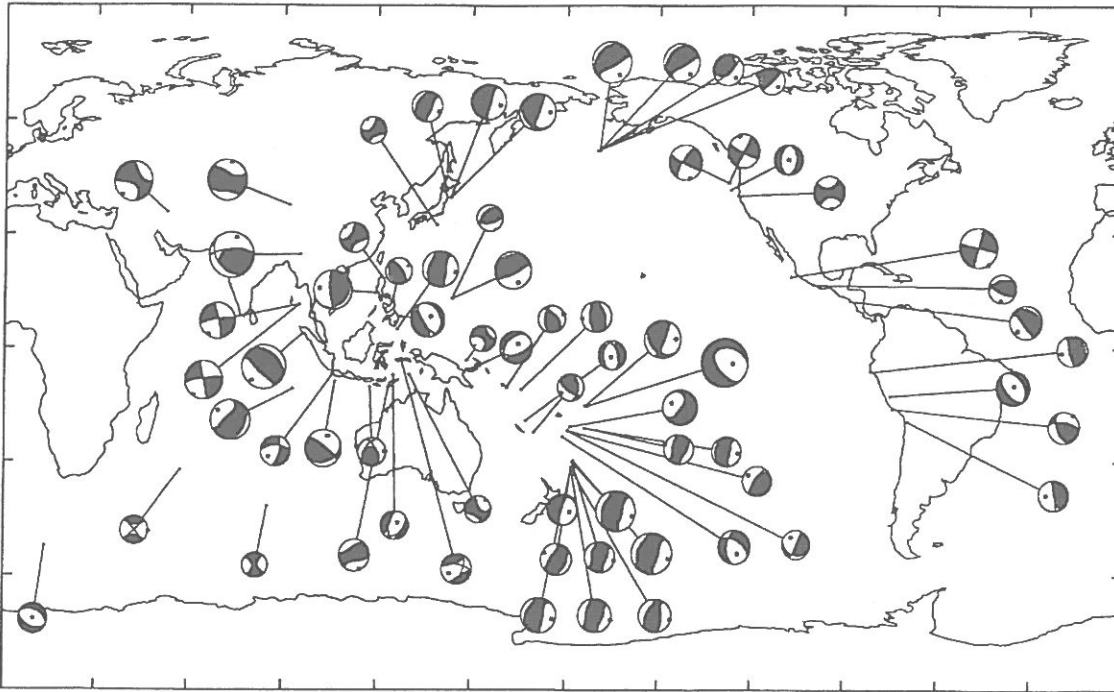
Inversion of the far-field waveforms yields a model with 2 high stress release asperities (roughly 2 kb), displayed in panels (c) and (d). A calculation for a smooth finite fault of area .5km x 2.5km, including the

near-field, is given in panel (b), and reproduces the ramp-like behavior of the horizontal components.

This example shows that a single high performance station can determine as much, if not more information than a conventional network of stations measuring arrival times and first motions. In pursuit of this idea, institutions in southern California, led by Caltech, are planning the installation of a regional network of stations (TERRASCOPE) which match the IRIS GSN specifications. IRIS and Caltech, using the facilities of the IRIS Data Management System, have made agreements to support this effort.

Kanamori, H., J. Mori, and T. H. Heaton (1990), The December 1989, Pasadena Earthquake ($M = 4.9$) Recorded with the Very Broadband System in Pasadena, Bull. Seis. Soc. Amer., 80, 483-487.

31. Rapid Determination of Earthquake Mechanisms from Global Digital Data Networks



The development of global digital networks permits routine and accurate estimates of average source parameters in near real time. Centroid moment tensor (CMT) solutions correspond to a relatively low level of parameterization of the seismic source. They are now a standard component of the information available to every seismologist after the occurrence of an earthquake of magnitude 5 or greater.

Systematic analysis of world-wide seismicity using global digital networks (GDSN and IDA) began at Harvard in 1981. With the extension to early 1977, it now covers a period of over 13 years, with a uniform detection threshold of magnitude 5. The 8,500 solutions in this database are used widely by the Earth science community, including non-seismologists. Two examples are the new model of plate velocities constructed by tectonophysicists at Northwestern University and the World Stress Map compiled under the auspices of the International Lithosphere Project. The solutions are sent monthly to the National Earthquake Information Center for inclusion in the *Monthly Listings of PDE*. They are also published on a quarterly basis in *Physics of the Earth and Planetary Interiors*.

The figure shows CMT solutions for 65 earthquakes that occurred during January, 1990. The size of a "beach-ball" is a linear function of magnitude; the largest event has moment magnitude M_w of 6.5, the smallest is 5.1. Equal area projection is used to map the forces acting at the source. The shaded areas correspond to tension at the source, and blank represents compression. The dot is the lower hemisphere projection of the compression axis. Solid lines represent the "best double-

couple" solution, meaning that the trace and one of the eigenvalues of the moment tensor are equal to zero.

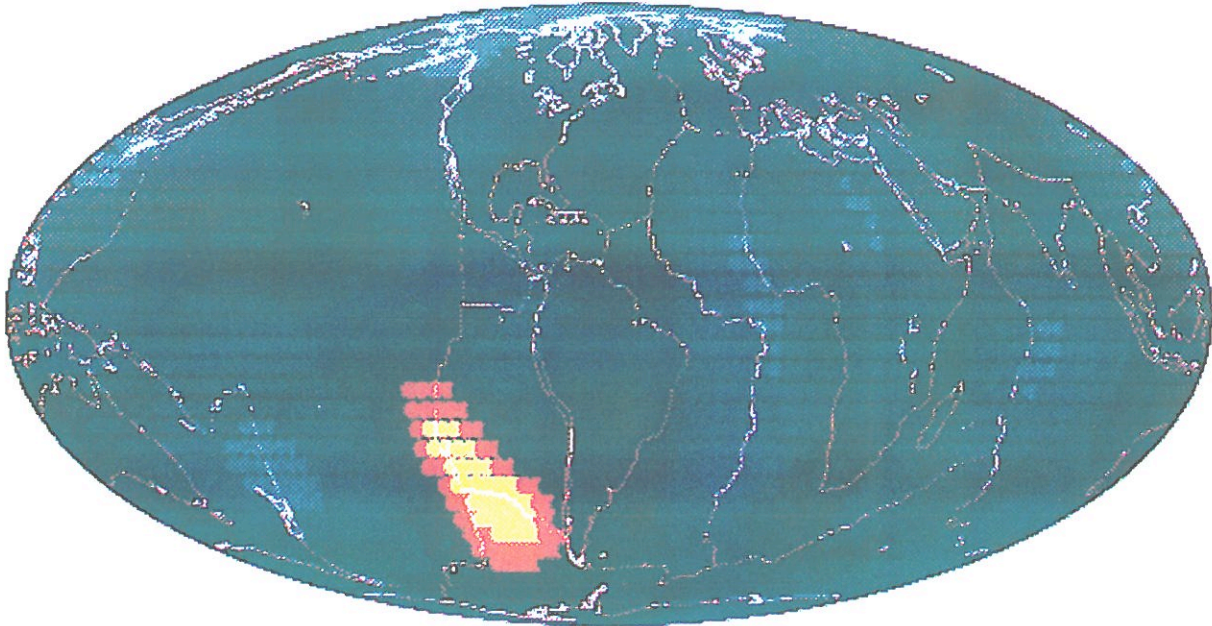
Now that IRIS stations offer telephone dial-up capability, it is feasible to obtain CMT solutions in nearly real time. For example, the solution for the Romanian earthquake of May 30, 1990, was obtained within hours of its occurrence, and the result was posted at the meeting of the American Geophysical Meeting then in progress.

While great strides have been made in understanding large earthquakes, the CMT gives only "average" properties of the source. Much more information is needed about individual events before seismologists can fully understand how faults rupture, and how the rupture process might be related to heterogeneity within the fault zone. This has implications not only for fundamental understanding of the earthquake process, but for the inter-quake interval and earthquake forecasting. For example, the spatial patterns of aftershocks, and the spatial variation of their source mechanisms, provide important clues in the dissection of the main rupture.

The planned station density, and low noise performance of the Global Seismic Network, will bring the magnitude threshold down substantially. It will also add to the data set an order of magnitude increase in the number of events. The retrieval of individual source histories is particularly dependent on the increased dynamic range of the network.

Contributed by Adam Dziewonski

32. "Slow" Seismic Events From a Decade of Continuous Normal-Mode Data



Analyzing continuous long-period data for signs of background free oscillation activity is an exciting new area of seismology. Beroza and Jordan have developed a method that uses the globally yet thinly distributed, continuously-recording IDA network. With these they detected excitation of the Earth's free oscillations. They applied the method to a ten-year (1978-1987) record of IDA data to obtain a new catalog of the Earth's normal-mode activity. By associating individual mode-excitation events in this catalog with earthquakes in the ISC and CMT catalogs, they were able to search systematically for anomalous events.

Over this period 1503 distinct, mode-excitation events were registered. Of these, 1339 could be plausibly associated with earthquakes in the ISC or CMT catalogs. A subset of these events shows an anomalously strong excitation of the Earth's free oscillations. Further analysis indicates that these were slow earthquakes with unusually low characteristic velocities. Many of these slow earthquakes occurred on oceanic transform faults.

Over the 10-year period, 29 false positive detections were expected to register. However, Beroza and Jordan found 164 mode-excitation events that were not associated with cataloged seismicity of sufficient size. It is not yet certain precisely what these anomalous excitations represent. Theoretical and empirical estimates of the detection threshold fluctuate about an average level of $M_w \sim 6.0$, which argues against the possibility that the excitations were due to regular earthquakes with fast seismic rupture that were not located by the ISC. A more likely explanation is that they were caused by slow seismic rupture. Either they were slow events with very low instrumental magnitudes, or slip events with large

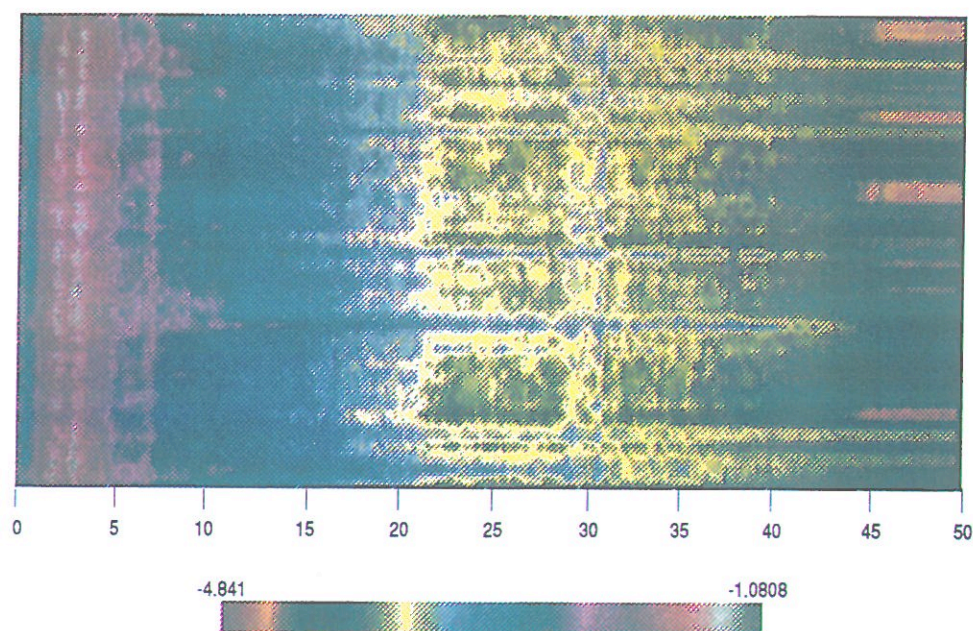
seismic moment and very low characteristic velocities, lower than for typical slow earthquakes.

For studying these anomalously quiet earthquakes, a low-frequency (<5 mHz) earthquake location algorithm has been developed. The procedure assumes that the source phase is constant over the 1-5 mHz band. This is a reasonable approximation for shallow earthquakes, and it determines the origin time and epicentral coordinates most consistent with the observations at all stations in the network. The results for the October 22, 1980 excitation are shown in the figure above. Although the excitation is attributed to a small event in Borneo ($m_b=5.0$), analyzed in the Harvard CMT catalog, it appears to be generated by a slow earthquake on the Chile Rise that occurs at 23:00 GMT, which was located by the ISC, but not analyzed by Harvard due to its low magnitude ($m_b=4.8$, $M_s=5.6$). By applying these techniques to the anomalous excitations identified for the period 1978-1987, it should be possible to identify the sources of these events.

This work offers a novel and potentially significant line of inquiry in understanding the dynamics of plate interactions. It is critically dependent on the planned Global Seismic Network. High dynamic range and low noise levels for high quality sites are required for extending these studies down to smaller magnitudes, and many more events. Greater station density will be important in improving the accuracy of event location.

Beroza, G. C., and T. H. Jordan (1990), Searching for slow and silent earthquakes using free oscillations, J. Geophys. Res., 95, 2485-2510.

33. Field Determination of Earthquake Site Amplification



The most extreme earthquake shaking occurs on unconsolidated muds, which amplify the earthquake signal by factors of 5 or more. The combination of portable digital seismometers, and modern methods of seismic signal analysis and inversion, makes it possible to rapidly access the structure, bulk physical properties, and predicted amplification.

Thirty minutes of ambient noise were recorded on the Quinnipiac River muds in New Haven, CO. This was done with PASCAL instruments and provided excellent information on sediment thickness, physical properties (Hajnal).

This figure shows a sonogram (log velocity spectrum) of the EW component computed with 30 second time windows over the band 0.2 - 50 Hz. [Clock time: y axis; Frequency: x-axis].

Vertical features in the color plot are persistent and spectral, either local minima or maxima. The local maxima are suspected sediment resonances: roughly 2.3Hz, 3.5Hz, 7Hz and 10.5 Hz. Using the simple 1-D model of a soft layer over a relatively rigid halfspace, trapped waves should follow the 'quarter-wavelength' rule. Waves are trapped at $1/4$, $3/4$, $5/4$, and $7/4$ times the natural shear-wave wavelength, so that the period of the first overtone should be three times that of the fundamental oscillation. The spectra are more complicated than this, suggesting (1) either two 'fundamental' trapped resonances (with associated overtones) in a 1-D model with two major impedance contrasts, or (2) 2-D and 3-D effects.

The former hypothesis is supported by borehole logs from the initial engineering study for the freeway bridge, which was performed in the mid-1950's. This suggested a significant change in shear modulus near 20m depth.

Two persistent spectral peaks can be discerned between 2-4Hz in all data save that recorded on the hard rock control site. These frequencies vary across the array, but are too weak to be interpreted as a simple consequence of depth-to-bedrock variations.

Overall amplification scales with depth-to-bedrock. Preliminary polarization analysis permits separation of spectral features by characteristic polarization; whether this is due to distinct noise sources, or to characteristic mode polarization is now under study.

Reconnaissance studies of the site-dependent hazard from earthquakes can be done routinely by a small crew, with a few instruments. With appropriate specialized software, the features observed in this brief study could quickly yield useful estimates of physical properties and linear site amplification.

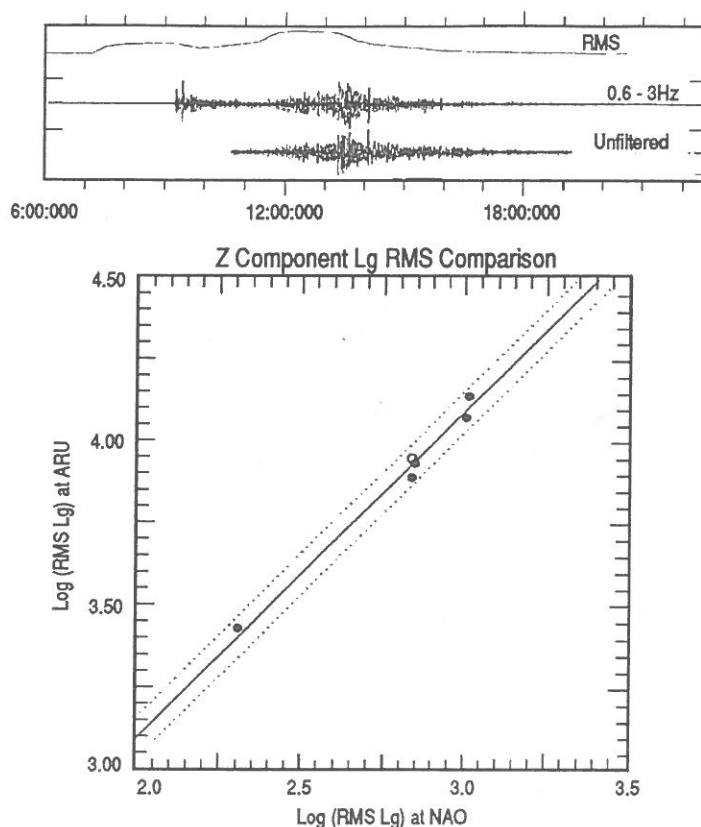
The relation between the linear and the actual large-amplitude nonlinear response is critical to the prediction of site hazard (Jarpe *et al*). Using high performance portable instruments for in situ determination of this phenomenon, at well studied sites over a wide range of amplitudes, is a critical next step.

Hajnal, Z., Jr., *Ambient Noise and Potential Earthquake Hazard (1990)*, Bachelor's Thesis, Yale University.

Hajnal, Z., Jr., J. Park, and S. Hough (1990), *Site Amplification and Ambient Noise Measurements in New Haven, Connecticut*, manuscript in preparation.

Jarpe, S. P., L. J. Hutchings, and J. J. Litehiser (1990), *A Study of Seismic Site Response Using Loma Prieta Main Shock and Aftershock Data*, *Seis. Res. Letters*, 61, 50.

34. Yield Estimation of Underground Nuclear Explosions



The IRIS stations in the USSR have observed nuclear explosions at the Shagan River Test Site in Kazakhstan since 1988. The reverberative Lg wavetrain trapped in the crust, shows an unexpected stability in total power making it an important quantitative tool for estimating the yields of underground nuclear explosions from this region. This result is now an unprecedented capability for precisely measuring the relative size of a set of earthquakes in the same general location.

[Top] The IRIS/USSR station ARU (top) shows 18 minutes from a large Shagan River explosion. Three traces are shown for the vertical component: the unfiltered trace (bottom); the trace filtered in the band 0.6 - 3.0 hz, favorable for signal-to-noise enhancement of Lg (middle); and a moving window (120 sec) RMS measure (top). The largest signal amplitude on each trace comes in the Lg wavetrain.

[Bottom] At bottom comparison is made of log RMS Lg measured at the in-country IRIS/USSR station ARU ($D=1400$ km), with log RMS Lg at the NORSAR array in Norway ($D=4200$ km) for six events at Shagan River. The dotted lines correspond to $\pm 2s$ for the five solid points. The open circle was added later for an explosion in October 1989, and it is gratifying to see how well it fits the line obtained from earlier events. The correlation coefficient is 0.994, and the orthogonal RMS misfit is 0.02-0.03 magnitude units. In contrast, the misfit using P-wave estimators of magnitude is well above 0.1 magnitude units. The capability to make precise mea-

surements of RMS Lg may also make accurate yield estimates possible, once these signals are calibrated by information on Soviet yields. This is anticipated as an outcome of the new verification protocol (signed June 1, 1990) for the Threshold Test Ban Treaty.

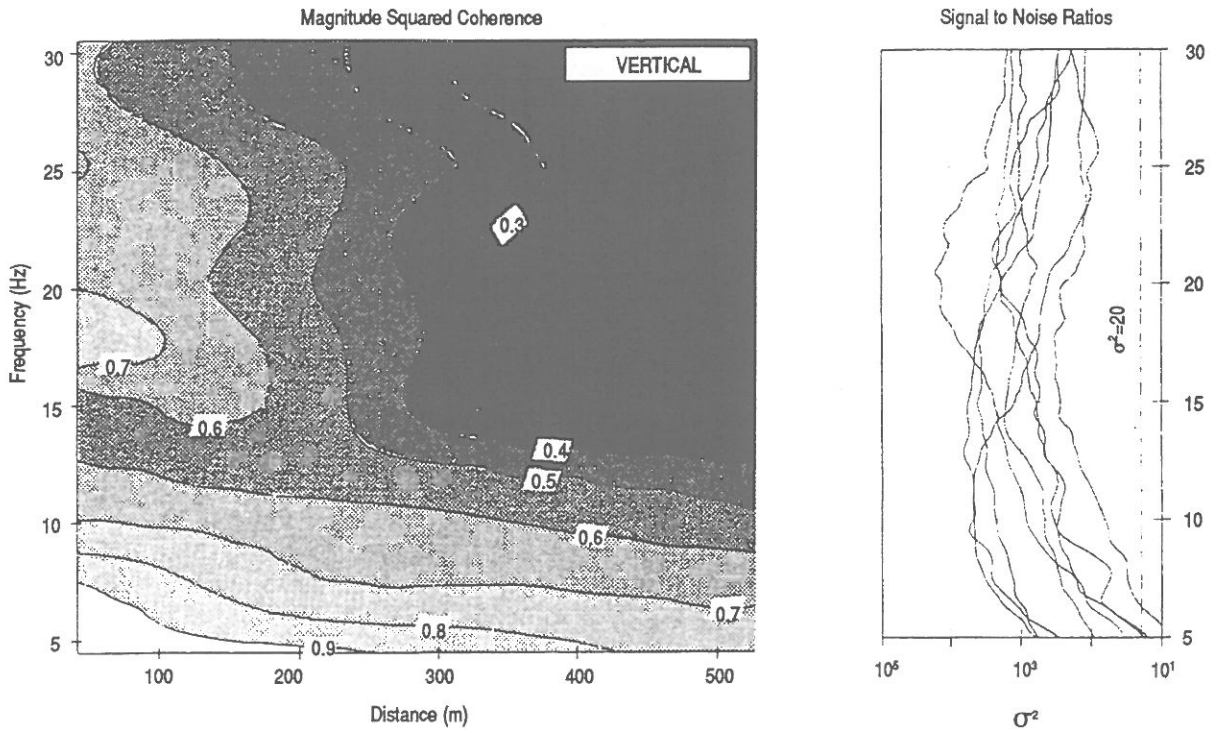
In addition to the precision of the Lg magnitude estimates, use of the in-country location lowers the threshold for yield determination by 1.5 to 2.0 magnitude units, and below 1 kiloton for typical coupling.

Lg is a complex statistical mixture of S and P waves, trapped by total reflection in the continental crust. Many early studies of Lg demonstrated the sensitivity of this signal to major lateral discontinuities in the crust. Indeed, the presence or absence of Lg is often used as an indicator of whether the path is purely continental or not. This is at odds with the quantitative stability of RMS Lg, and is probably explained by consideration of the raypath averaging inherent in the RMS statistic. These issues are to be addressed by IRIS university science teams, through the deployment of small PASSCAL arrays in Soviet Kirghizia and Northern Caucasus in 1990-1991.

Hansen, Roger A., Frode Ringdal, and Paul G. Richards (1990), The stability of RMS Lg measurements, and their potential for accurate estimation of the yields of Soviet underground nuclear explosions, Bull. Seis. Soc. Amer., in press.

35. Coherence of Seismic Body Waves from Local Events as Measured by a Small Aperture Array

Compressional Waves



The most common technique used to study local earthquake sources involves deploying a network of seismic stations around a known region of active seismicity. Portable recorders are located in the aftershock area of a large earthquake, or a permanent array can be set up that encompasses an active fault zone. The signals observed at these seismic stations typically have strikingly different waveforms for each event. This variability can be caused by the seismic radiation originating preferentially from different parts of the focal sphere, by the scattering of seismic waves through a complicated geological structure, or by localized site and topographic effects. In both types of experiments, the station separations range from one to several tens of kilometers. Even at this close spacing and in a geologically simple region, these separations correspond to many spatial wavelengths for those frequencies above a few hertz. This makes it hard to resolve differences between source and path effects.

It is assumed for measurements of local earthquakes, with small source for small perturbations of take-off angles. As the signals propagate through the Earth they become less coherent due to scattering, but the coherent frequency bands should contain significant information about the seismic source. In recent years there has been considerable interest in the variation of seismic waveforms measured at interstation spacings of tens to hundreds of meters. This information is important in understanding the causes and scale lengths of scattering mechanisms in the crust.

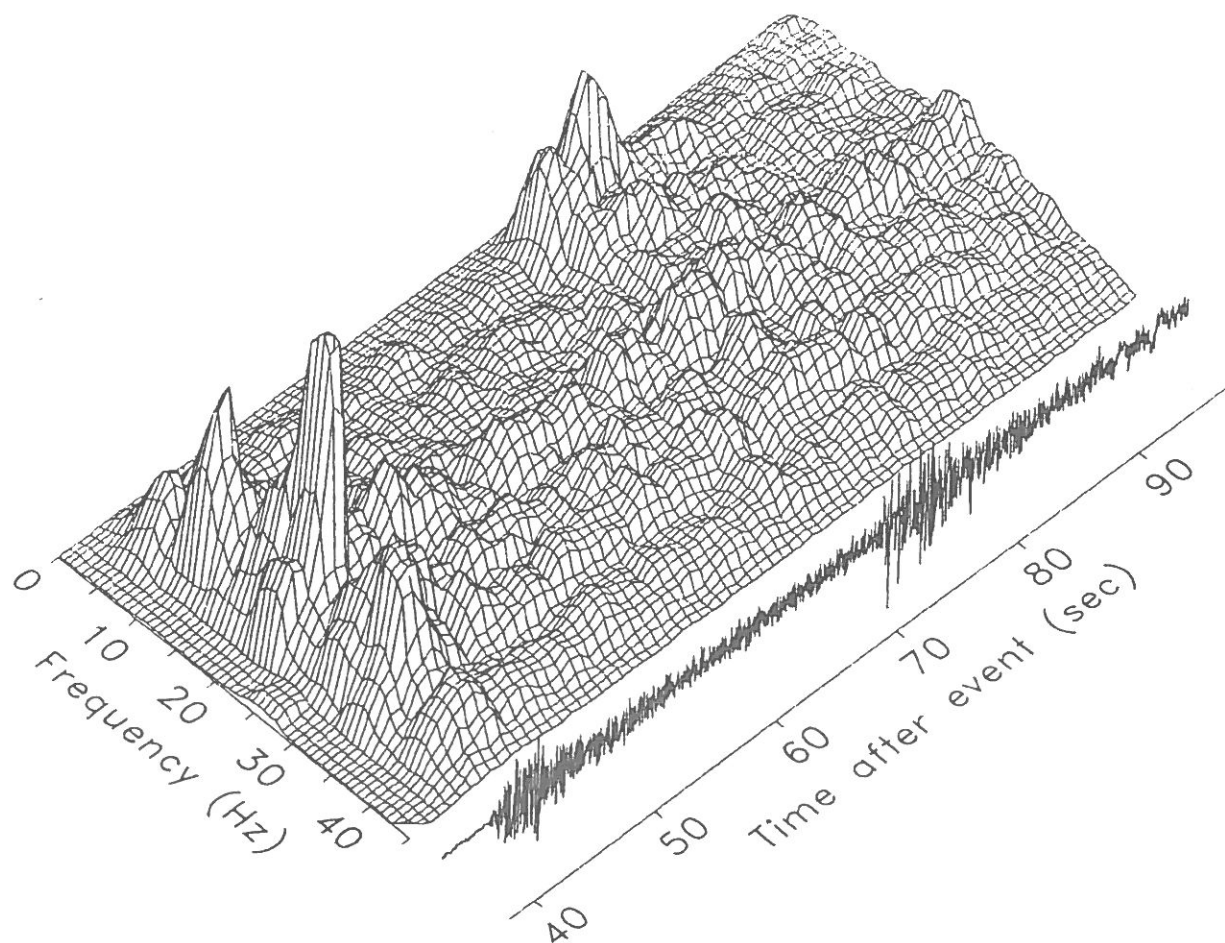
The illustration above is from a study of the variability of seismic spectra, and the spatial coherence of the

seismic wavefields over horizontal distances of 50 to 500 miles. These data were recorded on a nine-station seismic array operated on a fairly level granitic terrain for eight months in 1985. Eight well recorded events with magnitudes between 3.0 and 4.0 were analyzed. These had epicentral distances between 14 and 40 km. The plot shows an average value of magnitude squared coherence as a function of frequency and distance for the compressional wave as measured by vertical seismometers. The graph at the right side of each contour plot gives the signal-to-noise ratio for each of the eight events.

The recent development availability of IRIS/PASSCAL equipment allows the extension of the above techniques to study the coherence of the seismic wavefield with unprecedented dynamic range, bandwidth (both frequency and spatial). During a current experiment, using PASSCAL instruments in conjunction with the IRIS Eurasian Seismic Studies Program (ESSP), a 60 element 250 meter aperture array recorded 370 events during a two month interval. This unique dataset will provide the most detailed observations of the seismic wavefield to date for local and regional events. The next step is to acquire measurements with broadband instrument sorganized in two-dimensional arrays with interstation spacings from .1 to 10 km. These data will yield considerable improvement to our understanding of seismic wave propagation, velocity structure, and source properties.

Frank L. Vernon, Jon Fletcher, Linda Carroll, Alan Chave, and Eugene Sembera submitted to JGR 4/90.

36. Using Seismic Data to Discriminate Between Nuclear and Engineering Explosions



In recent years there has been greater interest in discriminating between nuclear and engineering (mining) explosions. A reduced "Threshold Test Ban Treaty," or TTBT, may bring the size of the largest allowed nuclear events down to that of large engineering explosions (called "quarry blasts"). Currently available high-frequency seismic data can discriminate between these two types of events.

A technique used in mining practice, known as ripple firing, involves the detonation of sub-explosions offset from each other by small distances and times. This procedure is intended to enhance fracturing of the rock and reduce ground motion in areas proximal to the mine. The interaction of the time-offset wavefields produced by the staggered sub-explosions can yield seismic coda possessing highly colored spectra. The regular repetition and superposition of similar seismic motions in the time domain leads to regular amplification and suppression of power in the frequency domain.

As has been demonstrated by Hedlin et al (1989), this spectral modulation can persist after the onset of the seismic energy and is generally independent of time in

the seismic coda. The figure above illustrates this point. The frequency-time display has been computed from a recording of a quarry blast detonated in the Soviet republic of Kazakhstan, near the Semipalatinsk nuclear test site. In this figure the amplitude of acceleration is displayed on a linear scale. The one minute window displayed encompasses both the compressional and shear onsets, as well as the bulk of the coda. The time independent character, with a spacing in frequency of roughly 7 Hz, is clearly present in this coda, and extends from the onset to the end of the window. It has been attributed to source multiplicity.

It is this time-independent spectral character, which is generally absent from the coda of nuclear events, that can be effectively used to discriminate between nuclear and engineering explosions.

Hedlin, M.A.H., Minster, J.B. and Orcutt, J.A., 1989, The time-frequency characteristics of quarry blasts and calibration explosions recorded in Kazakhstan USSR, Geophysical J., 99, 109-121.

III. New Possibilities

Selected Examples

The best way to illustrate the opportunities springing from the new digital seismic technologies, is to show some of the initiatives, proposals, and ideas currently being promoted within the earth science community. Some of these represent full-scaled national initiatives. Others are pending proposals, and others still have the status of germinating ideas. In every case, however, they represent the current thinking and efforts of the earth science community.

These examples run the gamut from experimental methods to geological targets. They depict ways of looking into the earth which, until quite recently, were beyond the realm of possibility. They meld together different experimental genres in untraditional fashion—onshore and offshore, reflection and refraction, active source and earthquake source. They depend on the global network stations and portable array instrumentation developed by IRIS.

1. Imaging Dynamical Processes in the Mantle and Core Performance of a Full Global Seismographic Network

A principal objective of the 128 station Global Seismographic Network is resolving discontinuities and physical properties in the mantle and core with enough resolution to show the characteristic effects of whole Earth dynamical processes. The methods used are described in the essays II.2-7. In every case, the results to date are merely suggestive, and lack resolution and geographical coverage.

The GSN serves as a global imaging experiment. It is designed with new capabilities which make this possible:

1. High dynamic range, bandwidth, and linearity.
2. Broad geographical coverage, including oceanic areas, the southern hemisphere, the polar regions, and previously inaccessible portions of Eurasia.

The characteristics of the GSN VBB instruments greatly increase the number of usable signals per station per year. All portions of the signal can be utilized for a given earthquake, including all body waves and their multiples, surface wave groups, and normal modes. Low noise sites run at full 24 bit gain can record large numbers of smaller events while maintaining the ability to accurately retain signals from the largest earthquakes.

The station distribution, with spacing ~2000 km, does not appear to sample the Earth with high resolution. However, when combined with the global distribution of earthquakes, the 128 station GSN is capable of obtaining multiple signals which sample each sub-surface target volume with enough redundancy to permit an inversion of the image. The construction of uniformly valid images of dynamic significance requires very large data quantities. Tomographic imaging requires multiple paths through each volume (multiply the number of volumes to be resolved by the number of paths needed, say a minimum of 10). Reflection imaging requires a multiplicity of reflection paths reflected by a given surface element of each discontinuity. Finally, inversion by nonlocal methods, such as free oscillation splitting, is an inherently global process, and can achieve high spatial resolution only by having a very large number of measurements. Many of these will come from precise measurements of multiplet shape at the multiplicity of GSN stations.

As designed, the GSN will function as an integral experiment for imaging the core and most of the mantle.

For the upper mantle, broadband stations deployed in national networks will yield increased resolution. Some are now being put in place in the US, Canada, and Australia. PASSCAL arrays of 50-100 portable broadband instruments provide the means of targeting specific (subcontinental) portions of the upper mantle, with linear arrays or area networks. It is estimated that US experiments alone will have at least 100 instruments continuously recording earthquakes: in effect, a doubling of the data volume of the GSN.

What are the targets which we are trying to resolve?

1. The inner core: discernable heterogeneity or irregularity of the surface; confirmation and spatial resolution of the reported anisotropy.
2. The core-mantle boundary: nature and distribution of heterogeneities; detection and resolution of "continents" accreted along the boundary.
3. The lower mantle: broad-scale anomalies which make sense in terms of convection; small-scale tracks made by plumes; interfaces or boundaries which might be detected by stacking and array methods. Are there indications that former slabs are collecting or accreting in certain areas?
4. The upper mantle: establishing which of the discontinuities are global, and which are associated with the roots of continents; production of global maps of the discontinuities, including a characterization of the physical parameters; establishing the relationship of the upper mantle discontinuities with mantle convection, such as sinking slabs and rising convection limbs and plumes; establishing and mapping anisotropy.

The GSN array's integral nature as an imaging system, and the nature of the imaging problem, will lead to development of closely coordinated mechanisms for managing the full data set, and the full arsenal of computational tools needed for the imaging process.

Meeting these goals strongly depends on achieving the original design specifications, with the degree of global coverage implied by a 128 station network. The functionality of the GSN as an integral network can only be achieved if the deployment time is short enough that the installed technology is uniformly maintainable.

2. Upper Mantle Continental Dynamics A North American Transect

Of all the continents, North America arguably offers the widest variety of tectonic settings. It is here that the role of the mantle is most clearly evident. Even before plate tectonics, the great variations in heat flow, seismicity, volcanism, and mean crustal elevation from province to province required a role for the mantle. Today, dynamical processes in the upper mantle are known to drive the continent and determine the surface tectonic styles.

At the largest scale, the rising mantle convection element seen as the East Pacific Rise, is recognized as generating the high heat flow and tensional forces which are disaggregating the Basin and Range. Recognition that this disaggregation is proceeding through the development of detachments and major horizontal shears in the mid-crust and at the Moho has not revealed what is happening in the directly subjacent mantle to drive these processes. Teleseismic body wave tomography (*Dueker and Humphreys, Figure II.10*) shows lateral structures below the Moho which strongly suggest small-scale convection, and could be driven by small-scale sinkers of high density crustal material.

The role of ocean-continental collision, and the subduction of the Juan de Fuca plate under the Pacific Northwest, has been recognized for 20 years; but it is only recently that subsurface geophysical evidence has confirmed this (*Vandecar, Crosson, and Creager, Figure II.11*; also the EMSLAB electromagnetic profiling).

In central and southern California the signs of a transcurrent-transpressional relative plate motion in the upper crust are becoming understood. However, for lack of data, the mechanism of mantle-crust coupling, the role of regional detachment along the Moho, and the relevance of vertical mantle motions are not known. Local tomographic studies have shown the existence of probable high density sinkers in the upper mantle, but their connection to the larger-scale plate motions is not understood.

It is well established that a low velocity mantle body beneath the Yellowstone region exists, and that it is the mantle source of the Yellowstone volcanism. On a more regional scale, the relation of this body to the upper mantle remains poorly understood.

Although not currently active, the Colorado Plateau and Rocky Mountain provinces remain at anomalous elevations. The pronounced discontinuity at the Rocky

Mountain Front has hardly been studied geophysically, and although its origin in mantle processes is recognized, the actual causes remain conjectural.

In the stable portion of the continent the relationship of crustal morphology to the mantle is perhaps less dynamic. Nonetheless, the unusually thick crust under the high plains, the long-term subsidence of the Williston Basin, the seismicity associated with the Mississippi embayment, are all elements involving the upper mantle.

The community is now considering a continental dynamics geophysical transect across the major provinces of North America. This transect's most fundamental goal would be to establish the geological structure and physical properties of the upper mantle along the corridor, down to the 670 km discontinuity. The program would require a decade or more, and would need a number of complementary multidisciplinary geophysical studies. The PASSCAL array facilities would be central to most projects, for deployment in multi-method imaging of the upper mantle.

The goals of the Continental Dynamics transect would be:

1. Image velocities, Q , and anisotropy throughout the upper mantle. Establish the characteristics and extent of the continental root (tectosphere). Establish the vertical and horizontal extent of the 100km scale velocity anomalies seen by Dueker and Humphreys.
2. Develop and exploit techniques for imaging the upper mantle discontinuities. Track these discontinuities across province boundaries, and determine the characteristic suite of discontinuities as a function of province.
3. Characterize the geological nature of the subsurface based on these results. This includes the identification (where possible) of a lithosphere-asthenosphere boundary, the identification of other boundaries characterized by major shear/detachment, the identification of old slab fragments, the identification of thermal anomalies.
4. Explain the Rocky Mountain Front, by looking for the relevant mantle structures.
5. Explain the Sierra Nevada uplift, the Death Valley extension (see *III.3*).
6. Look for evidence of vertical convective motions by examination of the topography on the major discontinuities.

2. Upper Mantle Continental Dynamics (continued) Seismological Imaging Techniques

The purpose of The Continental Dynamics transect across North America is to establish detailed, geologically useful images of structure and physical properties down to the 670km discontinuity. This requires the extension of many known seismological techniques into a new regime. The key tool which makes this possible is the PASSCAL arrays. These can be deployed in long lines without spatial aliasing, simultaneously acquiring explosion and earthquake data, and matching 3-component systems. In most cases, the imaging will be based on treating the data as multichannel array data.

Most deployment plans permit the simultaneous acquisition of information of several kinds, such as refraction shot gathers and teleseismic body waves. An example of a specific experiment is given in III.3, a planned program for studying the dynamics of the Sierra Nevada - Death Valley corridor. We review here the methods which can be applied, and indicate the kinds of deployment

In general, each of these methods requires a major demonstration to establish expectations and procedures.

Integrated refraction-reflection profile: Requires a line of 3-component receivers 400 km or more in length, spaced at 250m, with large explosions along line. The search for reflections from the mantle would require the use of coherent subarrays for beamforming, if the available equipment is insufficient for an uninterrupted line at 250m spacing. The dataset can be significantly expanded if a regional earthquake occurs during the dynamite work's deployment .

Imaging by use of converted waves: The same line used for the explosion profiling can record teleseismic P-waveforms in 3-components. After minor deconvolution, the radial component represents the Born (forward) scattered shear energy from the crust and upper mantle. This has worked well for identification of the Moho, and in principle could work for upper mantle boundaries as well, if the array design is able to reject interfering energy (*see II.18*).

Teleseismic P and S travel times for tomography: A regional deployment of portable instruments can be used to record teleseisms for extracting P and S travel time anomalies. This will yield a tomographic velocity image of the region (*see II.10*).

Detection and inversion of shear wave birefringence: Any of the deployments will yield measurements of the splitting of purely polarized shear waves, like SKS, with determination of principal directions. At low resolution, these are merely integral estimates of the

S anisotropy in the upper mantle; at high resolution (enough stations and events), this information could be tomographically inverted in the same fashion as the travel-time anomalies.

Surface Wave Propagation: Surface waves from teleseisms and large regional earthquakes, suffer phase delays and mode-coupling due to lateral variations in the basic waveguide. Signals from .01 to .2 hz propagate as fundamental or low higher mode energy in the waveguide, which includes the crust and upper mantle. The general idea is to put out a network of 3-component instruments and to collect surface wave data from different azimuths. Velocity structure is obtained by a generalized inversion of the phase delay data.

This experiment has not yet been done, so that the optimum deployment scheme is not worked out. A tomographic deployment puts instruments in a ring around the region to be studied. A less idealistic approach would involve adding instruments to the interior of the region. If simple fundamental mode energy were being studied, single instruments would suffice. Multi-mode energy from regional earthquakes would require subarrays, to permit the independent extraction of wavenumber information from the data.

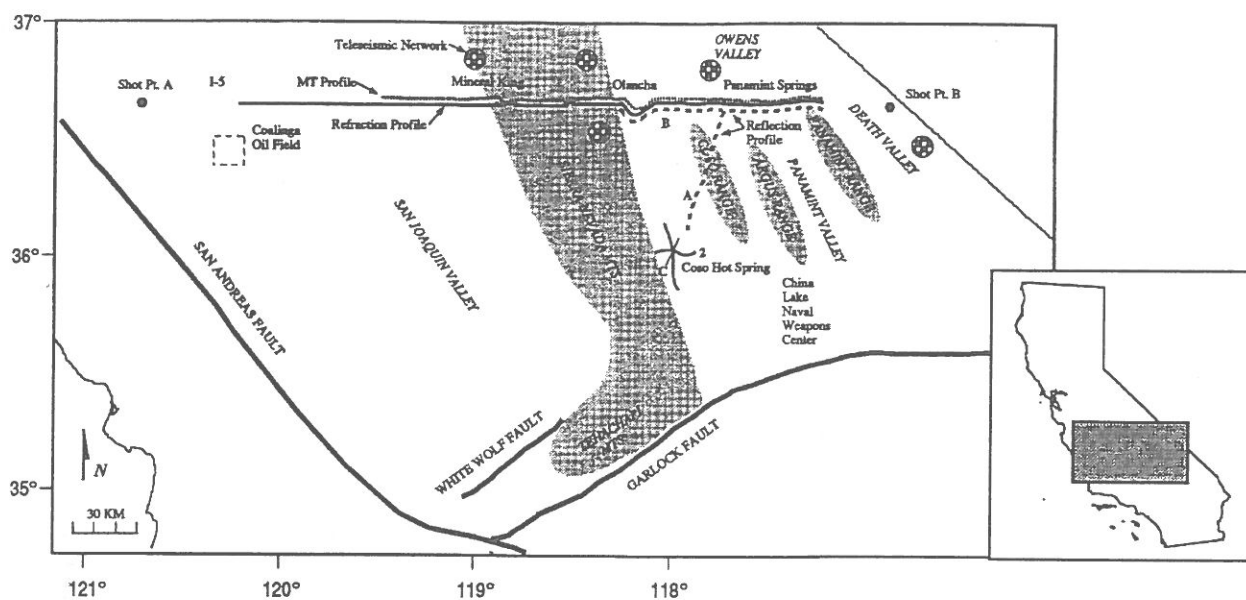
Surface waves provide perhaps the best return for the effort in reconnaissance information about a large region. On the transect of North America, a grouping of 8 subarrays on a 2-d swath (100km x 300km) could collect enough earthquake data in a few weeks, and move on.

Long-line profiling using earthquake signals: The transect should ideally be spanned by a long array of instruments, along which broad-band propagating signals from regional earthquakes would be inverted (full waveform inversion) for velocities. Such an array would also provide a reconnaissance look at P delays, birefringence, and converted phases. A possible deployment would be a line 2000 km long, with 50 instruments at 40 km intervals.

The long-line array also provides teleseismic body wave data which can address the structure of the core and lower mantle (*see III.4*).

The actual implementation of the transect is a matter of many individual experiments and deployments. It will require collaboration at the national level, and will demand the development of data processing tools capable of handling and inverting such large quantities of data.

3. Structure and Dynamics of the Southern Sierra Nevada



A planned 3-year multidisciplinary geophysical transect across the southern Sierra Nevada uplift, and the Death Valley extensional province, is to address the dynamical factors which continue to produce the uplift and extension. A cooperative effort will involve teleseismic studies, seismic refraction and reflection lines, structural geology, local earthquake seismology, and magnetotelluric soundings.

Existing geophysical data have suggested a thick crustal root under the Sierra Nevada, and alternately no root, with a flat Moho and a slow subcrustal asthenosphere. The Death Valley extension exposes mid-crustal metamorphic rocks, yet seems to have again a flat Moho. The continuous imaging of reflective horizons and seismic velocities along the transect shown in the figure, combined with the other geophysical and geological studies, should settle a number of longstanding problems. The geometric constraints could be adequate to determine whether the lower crust under Death Valley is receiving mass input by lateral ductile flow of lower crustal material, or from the input of mantle magmas.

The specific goals of this program are:

1. Constrain the seismic velocities of the crust and uppermost mantle from: (a) a reversed seismic refraction profile with simultaneous recording of teleseismic and regional earthquakes and (b) several tightly clustered networks of seismometers for recording teleseisms.
2. Image structures either accommodating transport of lower crustal material, or associated with large-scale intrusion of the crust to the east of the Sierra

Nevada with coincident seismic reflection, refraction, and magnetotelluric surveys.

3. Determine relief on the top of the asthenosphere with teleseismic and MT studies.
4. Study active faulting with the distributed seismometer arrays.

To accomplish this, a series of interrelated field experiments is planned over a two year period:

- A. A 45 km 2048 channel industry multichannel profile from Coso Springs to Darwin (year 1); A 90 km 4096 channel profile EW from Olancho to Death Valley. Vibrator sources, supplemented by dynamite.
- B. 3 100km long EW deployments of 3-component PASSCAL instruments spaced at 250m, for refraction/reflection profiling with dynamite. Also collection of triggered teleseismic signals for converted-wave imaging.
- C. A Magnetotelluric profile along the line of the refraction profile.
- D. 4 ten element tight 2D arrays with portable broadband sensors, for detailed velocity structure using teleseismic signals. A sparse aerial deployment in the region to determine travel-time anomalies.
- E. Temporary networks for locating local earthquakes: 30 3-component seismometers on the corridor east of the Sierra Nevada crest.

From a pending proposal by: P.E. Malin, R. W. Clayton, C. Jones, B. Wernicke, R. Phinney, S. Roecker, and S. Park.

4. Core-Mantle Boundary Structure from Regional Portable Arrays

The core mantle boundary (CMB), and the mantle just above, have been demonstrated to have heterogeneities at scales ranging from tens to thousands of kilometers. The importance of this region as a dynamic boundary layer, similar to the lithosphere and continents, requires that imaging resolution be pushed to the limit. Body wave phases such as PKIKP and related scattered energy potentially provide this resolution.

At conventional station spacing, regional networks and GDSN stations have observed small, incoherent, scattered precursors to PKIKP (PKP_{DF}). Modeling shows that these must originate in first-order scattering by heterogeneities in D'' or bumps in the CMB. From the principles of wavelet interference, these signals must have a spatially coherent structure which could be exploited in reconstructing the scatterer distribution. However, existing data have had neither the bandwidth nor the spatial density to properly characterize these signals. Moreover, the fortuitous distribution of good records has not permitted any attempt to correlate the

behavior of this precursor with models derived from large-scale tomographic inversion of global data.

Targeted deployments of portable broad-band seismometer arrays could break new ground in characterization of CMB properties. Siting of a few tight 2-dimensional subarrays over a 1000 km baseline in the northeastern US, would provide detailed information about the patch of the CMB illuminated by earthquakes from the southwest Pacific. Reconnaissance results would lead to a strategy for redeployment of these arrays over a period of several years, as the structure of the CMB becomes clarified.

This is a particularly striking example of how the PASSCAL and GSN programs could work together to improve our understanding of Earth structure. For while the PASSCAL arrays could provide maps of small patches of the CMB with unprecedented detail, it is only with the guidance of global studies that targets could be selected, and the results given a global perspective.

Contributed by Art Lerner-Lam

5. EDGE: Onshore-offshore Studies of Passive Margins

Onshore-offshore seismic experiments are crucial to our understanding of divergent continental margins, and the continental rifting process which formed them. In almost all cases, the coastline at divergent margins lies over crust affected by rifting. The difficulty of matching up geology and seismic results across a coastline makes it an artificial boundary. However, onshore-offshore experiments offer the promise of bridging the gap in imaging and understanding basin and crustal structures produced by continental rifting and ocean formation. By undershooting the coastline, we achieve deep penetration into the most critical transition region of the margin.

Some of the issues pertaining to divergent continental margins addressable with onshore-offshore experiments include:

- What is the distribution of crustal extension and thinning across divergent margins?
- Is the apparent lower crustal layering more or less pronounced at divergent margins where crustal extension and shearing have undoubtedly occurred?
- What is the distribution and volume of magma underplated to the crust during the continental rifting process?

Onshore-offshore experiments also combine the best aspects of marine and land seismic acquisition: marine

airgun sources, and arrays of 3-component portable seismometers. Marine airgun sources are reasonably powerful, very repeatable, and can be fired frequently, inexpensively, and safely. Arrays of portable seismometers can be deployed inexpensively at arbitrary, dense spacing on land. These contrast with land explosive shots and ocean bottom instruments which are more difficult to deploy.

Particularly valuable would be marine reflection seismic profiles that end close to shore, or pass islands, where individual or arrays of portable seismometers are deployed. The land instruments record all the shot records, which are then interpreted with the reflection profiles.

The concept has been field tested on the California coast by EDGE in 1987, and on the West Greenland Archean by the University of Wyoming in 1989, both times with PASSCAL instruments (see also *Figure II.17*). It is to be applied on a divergent margin, in conjunction with the EDGE offshore profiling on the US Atlantic margin near Chesapeake Bay (1990), in the Gulf of Mexico (1991), and in the Woodlark Basin in the western Pacific (1991).

Contributed by Dale Sawyer

6. Dynamic Study of an Active Blind Thrust

Earthquake hazard in Southern California is particularly associated with blind thrust structures developed in the general transpressional setting of the San Andreas Fault. The example from the Kettleman Hills Anticline (Figure II.27) shows the importance of combining structural imaging with monitoring of microearthquakes in such structures, where surface faulting may be obscure, or lacking entirely. The example from the Loma Prieta aftershocks (Figure II.26) illustrates that near-real-time monitoring of small events can be connected with the evolving dynamics of a fault segment. The downhole array at Parkfield demonstrates that microearthquakes of magnitude 0 or less can be detected and mapped. A particularly important experiment would now demonstrate the instrumentation of an active blind thrust in Southern California.

The object of such a program would be to maintain a near-real-time monitoring of the structure's dynamics. It would start with seismic reflection profiling for establishing the structure. The monitoring instruments would be based on an array of about 20 downhole 3-component seismometers, with a central station consisting of a low noise VBB instrument. Auxiliary instrumentation might include downhole strainmeters and hydrologic pressure monitors. A program of differential GPS position measurements would provide im-

portant integral information about the growth of the structure. Real-time data collection and processing would be a critical element of the program.

In Southern California, many structures of interest have been exhaustively explored by industry for hydrocarbons. Consequently, a large number of unused holes might be utilized for the instrumentation. Many of these penetrate well into the active core of the anticline. Instruments at these depths will lower the detection threshold, and improve the location accuracy significantly.

Such an experiment would represent a major step forward in determining the time and space history of a seismogenic structure, on scales of great interest in earthquake hazards research. With the capability of determining moments and mechanisms for many small events, it will be possible to test in detail different aspects of the asperity model for larger earthquakes.

Contributed by Tom Henyey. Based on a program proposed for the Southern California Earthquake Center to the NSF.

7. Dynamics and Structure of the Tien Shan-Pami Collision Zone

We know little about the nature of the lower crust and upper mantle in areas of continental collision. With improving relations between the U.S. and U.S.S.R., an interesting opportunity exists in Central Asia to learn about how the lower crust and upper mantle are affected by the continental collision.

A unique feature of central Asia is the prolific source region of intermediate depth earthquakes from the Pamir-Hindu Kush region. An average of 2 to 3 earthquakes with magnitude 3 or greater occur there every day. An interesting prospect exists for using a portable, broadband array to image converted phases from boundaries within the crust and upper mantle. The principal idea here is the same as that used for teleseismic receiver functions. Because the sources are deep, the angles of incidence are comparable to more distant earthquakes that are normally used for this technique. The difference is that the source is at regional, not teleseismic distances, and consequently would be much richer in higher frequencies.

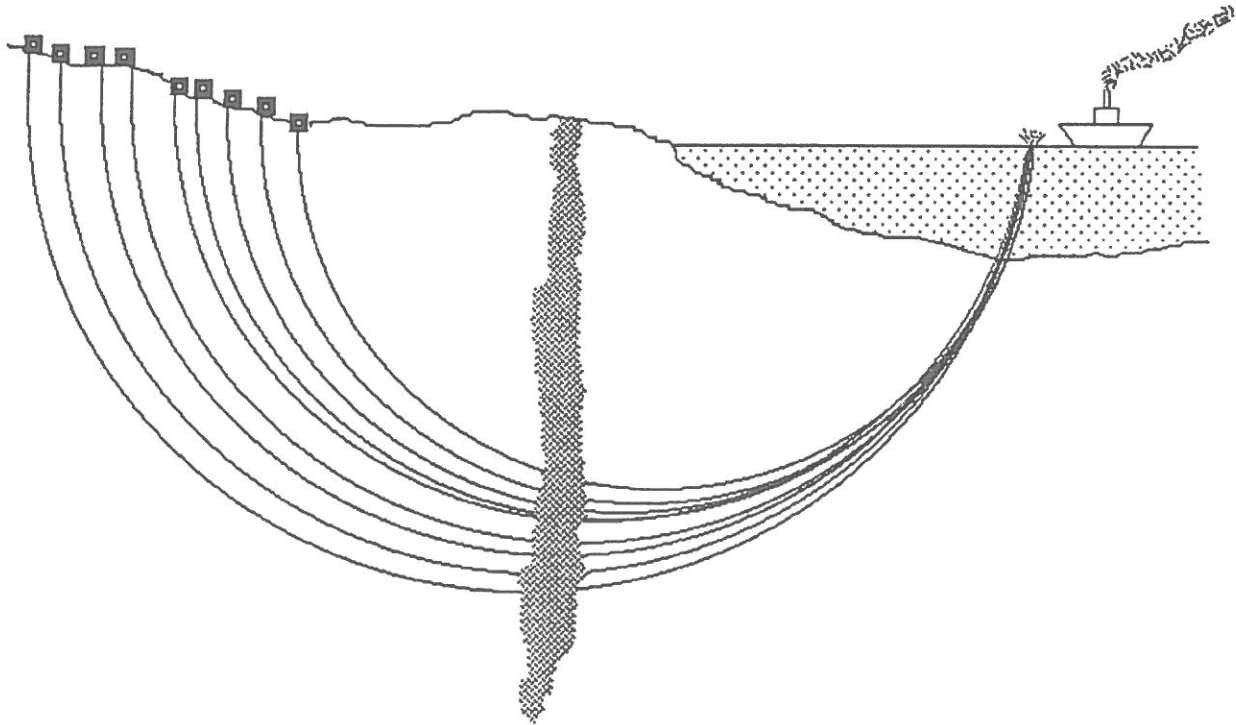
An idealized program would consist of a profile running from the Pamir range northward to across the Fergana Valley, the Tien Shan range, and onto the stable

craton in Kazakstan. The profile would be made by a series of deployments using a small, broadband array capable of beamforming. An initial experiment could be viewed as a reconnaissance. This would consist of a series of deployments of the array spaced at intervals of 50 to 100 km along the axis of the profile. A reasonable amount of data could probably be gathered at each site in a span of only about two weeks. Later, the profile could be filled in with more closely spaced deployments to outline transitional regions identified in the reconnaissance survey.

The portable broad-band sensors are also able to deduce detailed source mechanisms, as a function of space and time, for many events in this complex, inaccessible region. The intermediate depth earthquakes are a manifestation in the mantle of the continent-continent collision. Obtaining a systematic set of source mechanisms with the new instrumentation will go a long way to unraveling the dynamics of this unique region.

Contributed by Gary Pavlis. Based on the regional network and portable array which are to be installed in the Kirghiz Republic, in connection with the IRIS Eurasian Seismic Studies Program.

8. Imaging the Loma Prieta Fault Zone Using a Marine Airgun



The marine airgun source can be used in a number of novel geometries. The figure shows an experiment to study the Loma Prieta earthquake source volume.

The geology in this area is very complex, and this complexity clearly extends into the seismogenic crust, as shown by 3-D models developed from aftershock data. The physical properties of the fault zone are thought to be quite different from the surrounding crust. The extension of the fault zone to depth is difficult to image using conventional methods; this is well-known from seismic reflection data.

Consider, instead, a 2-D surface array placed to record rays that bottom in the fault zone. As the wavefield passes through the fault zone, it will be modified in two ways: (1) by the time delays and attenuation in the primary wave and (2) by the generation of converted waves. By recording with subarrays which recover an unaliased wavefield, it would be possible to use wavefield

continuation methods to image internal discontinuities from the converted waves and to infer compressional and shear velocities in the fault zone.

In a typical experiment, recording sites would be situated at intervals of 2 km in a loose 2-D grid. Each site would be occupied by an L-shaped subarray of 10 3-component instruments with spacing of about 30 meters. A high performance marine airgun array in Monterey Bay would shoot along several crossing tracks, into the instrument arrays.

The experiment follows the tradition of seismic reflection profiling, as practiced by industry, in terms of the quantity of data, and the dependence on technology for both acquisition and processing. Field work might last four days (1 for acquisition), resulting in about 10^6 seismic traces, or about 10^{10} bytes of storage.

Contributed by William Ellsworth

9. Interdisciplinary Crustal Experiment: Terrane Accretion in Southeast Alaska

Terrane accretion in southeast Alaska has differed from that of the well-studied trans-Alaska (TACT) transect. Convergence directions during accretion were oblique to the continental margin. Deep levels of the plate boundaries have been exhumed and are exposed at the surface. The region is not affected by present-day subduction as is south-central Alaska, which is currently being underthrust by the Pacific plate, or British Columbia south of the Queen Charlotte islands, which is being underthrust by the Juan de Fuca plate. Thus, Late Cretaceous and early Tertiary accretional events have been preserved and exposed.

Waterways that are suitable for marine geophysical transects cross all major geologic boundaries, and have nearby surface geologic control.

Much of the accretional history has been inferred from surface geology. But the processes are not well understood by which separate lithospheric units in the lower crust and upper mantle merge to form North American continental crust. In the study area are surface exposures of the deeper, more ductile and magma permeated middle and lower crust of the orogen. Tracing these features to greater depths, and the imaging of the lower crustal structure, the Moho, and the upper mantle, will help constrain models for terrane accretion.

Scientific Questions:

- How does magma interact with the lower crust?
- Did magmatic activity and ductile deformation in the lower crust overprint pre-existing structures and serve to homogenize the crustal section?
- Do the ductile fabrics exposed at the surface extend to depth, or are they truncated by later fabrics?

- Do the shear zones formed during early head-on collision penetrate into the mantle lithosphere?
- What role do the different structures play in the production of magma and its transport into the crust?
- What is the nature of the Moho? How and when did it form? Are there relict Mohos? Has magmatic activity modified the character or location of the Moho?

These problems require a multidisciplinary effort with geophysical studies imaging the orogen at depth. The waterways and intervening land masses provide opportunities for 3-dimensional imaging. The range in post-accretion uplift along strike allows choice in finding features for detailed study. Fjords and deep-water inlets permit marine multichannel profiling throughout the area, and the marine airgun to be used as a source for land-based seismic instruments.

The area lends itself particularly to the onshore-offshore experiment, based on the marine airgun and onshore arrays of 3-component portable seismic instruments. With the capability of detecting wide angle reflections at distances of 100km or more, reliable velocity models should be obtainable. The experiment would be a pioneer in 3-dimensional imaging, and in the long-vexing issue of following surface geology downward into the seismic section.

Based on a workshop proposal by Lincoln Hollister and Maria Luisa Crawford.

10. Subducting Ocean Crust beneath the Oregon Continental Margin

The offshore accretionary wedge complex and the onshore Cascade volcanic arc demonstrate that the Oregon-Washington continental margin is a zone of active subduction between the Juan de Fuca and North American plates. However, the anomalously low seismicity is an enigma, despite geologic evidence that the coastline has undergone abrupt episodes of subsidence.

In spite of much recent effort, data on the structure of the crust beneath, and within, the accretionary prism remain extremely sparse. A composite of information in the literature permits the inference that the base of the subducting slab dips around 8°-11°, but the conclusion is highly underconstrained, with no information at all over a critical 120 km stretch crossing the Oregon coast.

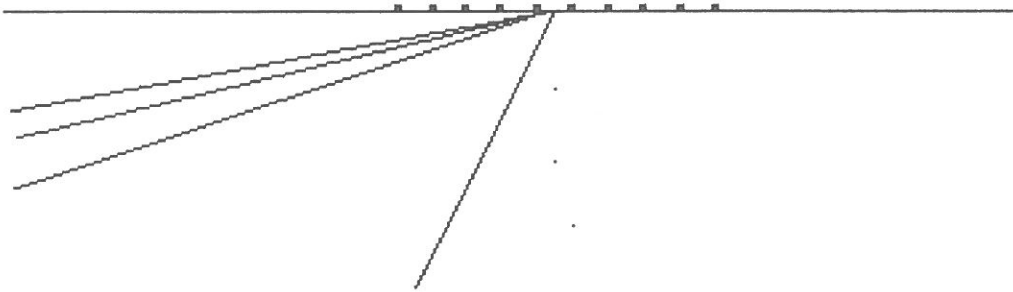
Current imaging technology makes it possible to design an experiment to image this critical structure. A

120km long marine multichannel reflection profile will be shot perpendicular to the coast using a large volume airgun array. High-resolution, large-offset data can be recorded at 6-8 ocean bottom seismometers and a like number of onshore stations. These will be based on PASSCAL instruments, and configured in small arrays at each station location. This will permit the identification of arrivals by their apparent velocities, and the reduction of noise.

With the onshore stations extending to 50 km inland, the signal paths for wide angle reflection will nicely image the critical volume where the downgoing plate, the accretionary wedge, and the continental rocks interact.

Contributed by Anne Trehu, based on a recent proposal.

11. Beamforming of Portable Array Data for Imaging Mantle Discontinuities



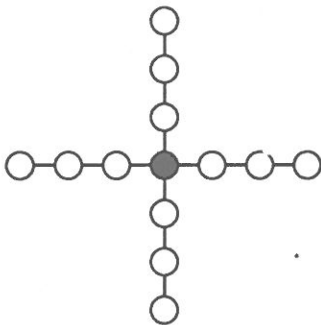
Arrays of high dynamic range digital instruments can detect weak mantle-reflected signals in the presence of strong crustal arrivals. For a large artificial explosion or regional earthquake observed at 200–400km offset, the interval between Pn and Sn is dominated by crustal P reverberations of the group Pg. Within the same time window are the expected arrivals of weak reflections from discontinuities within the upper mantle. These may be extracted from the Pg background by using a short linear array of sensors in place of a single sensor, and summing the outputs with appropriate time delays to produce a directional output, pointed in any desired direction.

For example, if the principal signal band is between 5 and 10 hz, we can try to enhance a mantle reflection

with a slowness of .05 sec/km, and reject crustal reverberations with slownesses between .12 and .20 sec/km. A linear array of total length 2km, with about 12–20 elements should be adequate.

This approach is precisely that used in exploration seismology to reject “ground roll”, or surface waves traveling in the low velocity surface layers, and to enhance reflections from the target zone. If it succeeds in detecting upper mantle reflections, then experiments can be planned which can precisely image upper mantle discontinuities. Furthermore, a large offset experiment could be conducted by using the available instruments in subarrays having beamforming capability, rather than disposing them uniformly.

12. Undergraduate Field Camp: Detect and Locate Small Earthquakes



A small cross-array of 4.5 hz geophones, 500m in diameter, could be used for student projects in areas having local microearthquakes. Students can play back triggered events on a daily basis, and make an estimate of depth, location, and magnitude. A number of areas, along the San Andreas Fault or the Sierra Nevada front, have enough seismicity to conduct this exercise.

At the center of the array is a 3-component 4.5 hz geophone. Each arm consists of 3 vertical geophones spaced 80m, and cabled to the center. The 3-component set and each arm are recorded by a PASSCAL 3-channel simple instrument; the 5 instruments are bunched at the center, and the trigger from the 3-component set turns on the other instruments.

The 15 channels displayed as a record section are sufficient for students to locate nearby microearthquakes. The delays along the arms of the array are used to compute a direction to the event. The 3-component instrument gives a clear S wave, permitting use of S-P to estimate the distance of the event along the arriving ray.

This geometry may also have advantages for rapid deployment when earthquake aftershocks are being monitored, or for exploratory deployments in poorly instrumented areas.

13. Rapid Earthquake Response Experiment

IRIS is organizing the capability to mobilize an array of portable 3-component instruments in the aftershock region of a major earthquake or in response to an earthquake forecast, within a fraction of a day of notification. This is to be implemented during the next year.

An instrument center designated for this task always has a complement of instruments which can be mobilized on short notice, whether instruments which are kept on stock, or, more likely, instruments whose status in the field designates them for service. Approximately 12 instruments are designated for immediate service, to be installed the first day, and another 20 are designated for installation on subsequent days.

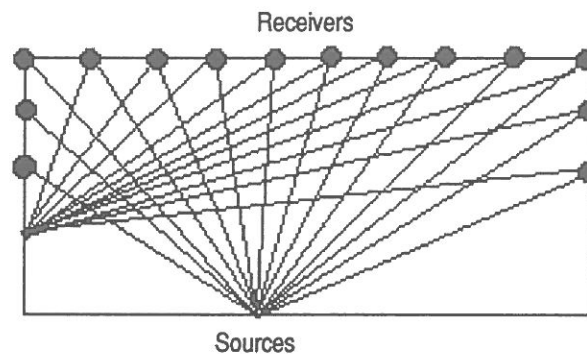
The instrument center is trained to transport, install, and operate the instruments. In each area where an alert may occur, the IC has an agreement with local University personnel who are prepared to provide local guidance in site selection, who can provide a host facility for the

computer, and who will take over operation of the instruments for the duration of the deployment.

The planned hardware complement would consist of at least 5 broadband sensors to facilitate focal mechanism determination, with L22's for the remainder. Timing would be with GPS equipment. The field computer would be equipped for communications with NEIS and other USGS information sources. Substantial effort is under way to provide the computer with near-real time analysis capability. A future upgrade would take advantage of low data rate satellite services to transmit state of health and a report of triggers, including P-picks, to the field computer site.

Coordinated with the portable instrument effort would be the use of the GOPHER capability to download waveform data from some of the GSN stations. Before the actual field deployment begins, the field team would have available a focal mechanism and moment estimate to help guide operations.

14. Reconnaissance for Shallow Anomalies: Hazardous Waste Site



Standardized portable 3-component instruments, combined with field computer support for rapid analysis and display provide tools for engineering needs. In the scenario which we outline here, an area of several square km needs to be screened for hazardous waste deposits which are no longer documented. The target zone is about 100 feet deep.

Conventional reflection profiling with hammer or weight drop is far too labor intensive for use in a large area reconnaissance. Instead, we describe an effort in which artificial or small explosive sources generate surface waves which are recorded on an array of portable instruments. Each test area, about 500m or 1000m on

a side, is studied by illuminating it with a large number of surface wave paths at different azimuths. Forty instruments at 25 m spacing along one side of the area record energy from about 50 source points around the rest of the perimeter.

This approach's usefulness requires that the data be processed and displayed in real time. At the scale of the experiment, UHF radio telemetry would provide real-time data at the field computer. The computer software would then need to extract an attribute from the 3-component waveform, and build a tomographic reconstruction on the spot.

