Antarctic Array: A Unique Perspective on the Changing Earth

Report from the ***Structure and Evolution of the Antarctic Plate 2003 Workshop***

March 3 - 5, 2003
Boulder, Colorado

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www.antarcticarray.org

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Outline

Executive Summary

Antarctica sits at the very center of the Antarctic lithospheric plate, one of only eight major plates that form the rigid outer shell of our planet. Because Antarctica is 99% ice covered, and access to a major proportion of the oceanic lithosphere of the Antarctic Plate is hampered by high seas and sea ice, seismology on the Antarctic continent is critical to knowledge of the structure and evolution of the Antarctic Plate. Beyond contributing to a comprehensive understanding of the Earth's continents and plates, this knowledge is important for Earth system science as Antarctica is the only continent fully covered by ice, and is therefore a critical component of Earth's hydrologic and climatic systems. The continent's location over the South Polar spin axis additionally affords a unique vantage point to observe the very deep Earth.

In March 2003, a community workshop was held in Boulder, Colorado entitled *Structure and Evolution of the Antarctic Plate* (SEAP2003). The purpose of the SEAP2003 workshop was to lay the scientific foundation for a long-term plan to improve the understanding of the structure and evolution of the Antarctic Plate, with particular emphasis on the solid earth and its coupling to ice sheets, ice streams, subglacial lakes, oceans, and atmosphere. The workshop was attended by more than 100 scientists from around the world. The workshop had several major goals:

- Highlight the science that can be done with improved seismic observing capabilities on the Antarctic continent.
- Discuss the scientific justification and technical requirements of the observing system.
- Develop a plan for the observational components of the system.

What emerged is an ambitious plan to apply modern observational, analytical and telecommunications technologies to investigate the structure of the Antarctic continent, the physical processes that govern its evolution, and the linkage between the solid earth and global change that may be most profound in polar regions. This undertaking is particularly timely in light of the impending International Polar Year (IPY), scheduled to occur between 2007 and 2009.

The scientific opportunities that Antarctica has in common with other continents relate to its age, growth, and evolution and the processes that have shaped its lithosphere (crust and uppermost mantle). Its ice cover and its location also present unique scientific opportunities. First, Antarctica is seismically very quiet, it provides a unique perspective on the Earth, and is an ideal location to study the deep Earth. Second, as the center of Gondwana and now surrounded by remnants of continental rifting that occurred over the past 200 Ma, Antarctica has played a unique role in the tectonic history of the Earth. Third, Antarctica is the only ice covered continent and, therefore, provides a link between the deformation of the solid Earth to climate change and sea level fluctuations.

To capitalize on the scientific opportunities that Antarctica presents requires a five component seismic system referred to as AntarcticArray.

- **Antarctic Backbone Network.** The permanent, internationally operated broad-band seismic network on Antarctica should be expanded from about 10 to more than 20 stations. This includes remote stations that require autonomous operation during winter months.
- **SPRESSO (South Pole Remote Earth Science and Seismological Observatory).** This site of particularly high quality year-round observations is envisioned as the center of US seismic activities in the deep continental interior.
- **Local and Regional Array Seismology on Antarctica (TELLUSCOPE).** Broad-band array installations are needed to improve resolution to length scales of tectonic relevance. Evolving Regional Arrays of 10 - 30 instruments moved around the continent in a "Pinwheel" configuration would be particularly effective.

- **Process-Oriented PASSCAL-like experiments.** These PI-driven experiments, several of which have already occurred within Antarctica, will provide much of the scientific product from AntarcticArray.
- **Active-Source System.** This system provides the most direct link between seismic observations and glacial processes by constraining icestream and icesheet bedding conditions, subsurface structure, and ice rheology.

AntarcticArray requires synergism with other observing capabilities. Co-location of seismic stations with GPS installations improves information return from either observing system independently. Coordination with initiatives in aero-geophysics, electro-magnetic methods, as well as on-shore and off-shore drilling is also needed.

International collaboration is an essential ingredient of AntarcticArray. As the interior encompasses multi-national domains of interest, the development of the Backbone Network and the Evolving Regional Arrays will be particularly dependent on international partnerships and collaborations, particularly in East Antarctica. Moreover, utilizing international facilities and logistical support is crucial for the successful development of AntarcticArray, as is intellectual collaborations with scientists from around the globe.

Along with the unique scientific opportunities that Antarctica presents come unique challenges posed by extreme weather conditions and the sheer remoteness of much of the continent. Much progress has already been made in Antarctic seismometry, but continued innovations are needed in power systems, communications, and seismic componentry. In particular, power at remote sites in winter months is problematic. Currently, remote systems return 6-8 months of data per year, which sets the baseline for autonomous systems within AntarcticArray. Parts of AntarcticArray are seen as permanent or long-term, and continued operation and maintenance of these aspects of the system must be addressed in collaboration with IRIS, the USGS, and international partnerships (e.g., GEOSCOPE, GEOFON). Data archival and distribution will be coordinated through the IRIS Data Management System.

Antarctica, as the most remote place on the planet and because of its many unearthly physical attributes, holds a unique fascination and potential for advancing science education and outreach (E&O). Because of its continent-scale focus, AntarcticArray will provide an exceptional opportunity for hands-on educator/scientist partnerships. The recent initiation of the EarthScope facility and science program in the U.S. is catalyzing a new level of ambitious planning in advancing public awareness of the solid Earth sciences. Association with EarthScope, the IRIS Education and Outreach program, the USGS, and participating institutions, will strengthen public knowledge and appreciation for the role of Antarctica in system Earth.

SEAP2003 was a scientific workshop. This report summarizes the vision for seismology on Antarctica in the upcoming decade. It lays the foundation for an AntarcticArray Implementation Plan, which should follow.

1. Overview

In March 2003, a community workshop supported by the US National Science Foundation Office of Polar Programs was held in Boulder, Colorado entitled *Structure and Evolution of the Antarctic Plate* (SEAP2003). The purpose of the SEAP2003 workshop was to lay the scientific foundation for a long-term plan to improve the understanding of the structure and evolution of the Antarctic Plate, with particular emphasis on the solid earth and its coupling to ice sheets, ice streams, subglacial lakes, oceans, and atmosphere. The workshop was attended by more than 100 scientists from around the world. The participants are listed in Appendix A and the agenda in Appendix B. Links to the participants and the talks delivered at the workshop can be found at:

http://www.antarcticarray.org/seap2003

The presentations and discussion at the workshop summarized how Antarctica's location and geological history provide profound and unique scientific opportunities.

This document emerged from the SEAP2003 Workshop. It discusses the scientific opportunities and technical challenges and presents a vision for the development of the next generation of seismological observing capabilities on Antarctica. These capabilities will be aimed at complementing initiatives based on other observables (e.g., airborne geophysics, geodetic measurements, measurements of the sedimentary record, etc.). This document advocates an ambitious undertaking to apply modern observational, analytical and telecommunications technologies to investigate the structure of the Antarctic continent, the physical processes that govern its evolution, and the linkage between the solid earth and global change that may be most profound in polar regions. This undertaking is particularly timely in light of the impending International Polar Year (IPY), scheduled to occur between 2007 and 2009.

We refer to the plan for the seismic observing system as AntarcticArray. Further developments in the planning and implementation of AntarcticArray may be tracked at:

http://www.antarcticarray.org

2. Scientific Opportunities

Antarctica is one of six continental landmasses on Earth. It is at the center of the Antarctic lithospheric plate, one of only eight major plates that form the rigid shell of our planet. Full understanding of Earth's kinematics and dynamics, and of Earth system processes, can only be achieved with data from all the continents and plates. Because Antarctica is 99% ice covered, and access to a major proportion of the oceanic lithosphere of the Antarctic plate is hampered by sea ice, seismology is critical to knowledge of the Antarctic crust and mantle. Beyond contributing to a comprehensive coverage of the continents and plates, this knowledge is particularly important for Earth system science as Antarctica is the only continent fully covered by ice, and is therefore a critical component of Earth's hydrologic and climatic systems. Moreover, the continent's location over the South Polar spin axis affords a unique opportunity to gain knowledge of the planet's core and the critical core-mantle boundary region.

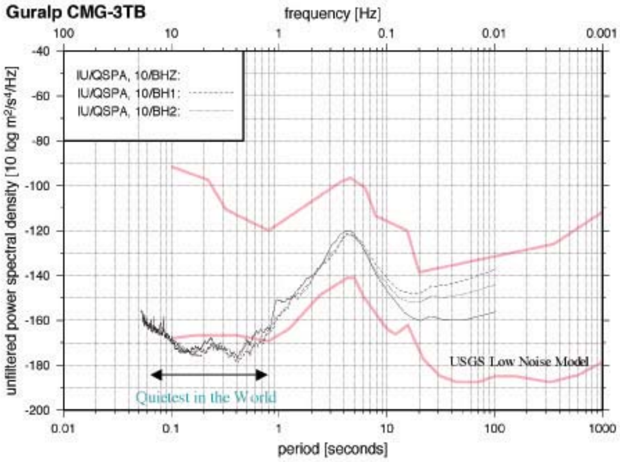

Figure 1: **The quiet Antarctic interior is ideal for seismic observations.** Seismic noise observed at the recently installed borehole instrument (QSPA) near South Pole Base across the seismic frequency band. The red lines bracket noise observed elsewhere in the world, so that at frequencies above 1 Hz QSPA is the quietest site in the world. (Courtesy of Rhett Butler).

Antarctic scientific opportunities fall into two principal categories: those opportunities that Antarctica presents in common with other continents and those that are unique to Antarctica, deriving from its place on the globe, its role in global tectonic history, or its ice-covered environment.

The scientific opportunities that Antarctica has in common with other continents relate to the age, growth, and evolution of the continent and the processes that have shaped its lithosphere (crust and uppermost mantle). These problems, together with seismic hazard, are the motivation, for example, for the EarthScope program, a bold observational initiative to improve the understanding of the solid earth beneath the US. Lessons learned in devising and now implementing the seismological component of EarthScope (USArray) are incorporated into the design of AntarcticArray.

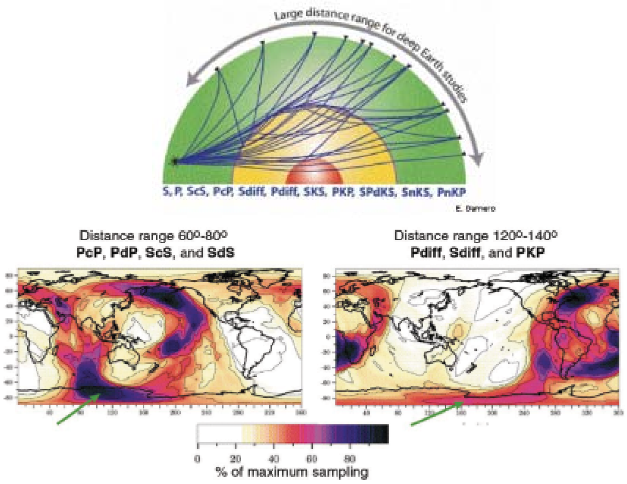

Figure 2: **Antarctica is ideally located for observations of the deep Earth.** Various seismic body wave phases that sample the core-mantle boundary region would be well-observed from Antarctic stations, given the worldwide distribution of earthquakes. (Courtesy of Michael Wysession.)

Perhaps more interesting are the scientific opportunities that could emerge from seismology that are unique to Antarctica. These fall into three main categories.

- **Antarctica provides a unique perspective on the Earth.** Antarctica is the seismically quietest location on the Earth (Fig. 1), except near anthropogenic noise sources and near the coast. Seismic waves emerging from beneath Antarctica cross regions within Earth that have been sampled earlier only poorly (Fig. 2) and its proximity to the polar rotation axis makes it an ideal location to study Earth's core. Antarctica provides a unique observational platform for studying the Earth on a global scale. It remains, however, sparsely covered by seismic instruments (Fig. 3).

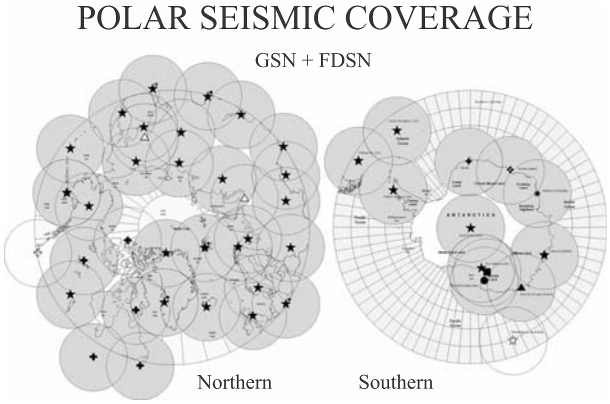

Figure 3: **Seismic instrumentation on Antarctica remains sparse.** Comparison between permanent seismic instrumentation in high northern and southern hemispheres, demonstrating that Antarctic station coverage does not satisfy the rather modest 1 station per 10° standard set for the Global Seismic Network (GSN) even when non-US stations are included (FDSN – international Federation of Digital Seismic Networks). (Courtesy of Rhett Butler.)

- **Antarctica has played a unique role in the tectonic history of the Earth.** Antarctica was the center of Gondwana and is surrounded by regions that have undergone previous events of rifting. The nature and extent of this rifting is important to global plate reconstructions and to an understanding of the thermal state of the lithosphere.

- **Antarctica is the only ice covered continent.** It, therefore, provides a link between the deformation of the solid earth with climate change and sea level fluctuations. Ice couples the deformation of the solid earth to more rapid processes that occur near to the surface; for example, in the oceans and atmosphere. Heat flowing from the solid earth and the ways in which the solid earth deforms in response to changes in ice loading may contribute to the dynamics of ice sheets and global change. Dramatic differences in mantle temperatures between East and West Antarctica (Fig. 4) profoundly affect surface heat flux (Fig. 5), the response of the solid earth to episodes of glacial loading and unloading (Fig. 6), and the distribution and extent of melting beneath the icesheets (Fig. 7). Bedding conditions (Fig. 8) also strongly affect the dynamics of icesheets and icestreams. Knowledge of mantle temperatures, rheology, heat flux, and bedding conditions remains crude, however, across most of Antarctica and models of how these variables may affect global change continue to be in their formative stages.

3. Observational Components: Current and Future Capabilities

A major goal of the SDEAP2003 workshop was to define the observational components needed to address the scientific opportunities that seismology on Antarctica presents. What emerges is a five component system which together compose AntarcticArray. International collaboration is essential in every component.

- **Antarctic Backbone Network.**
- **SPRESSO (South Pole Remote Earth Science and Seismological Observatory).**
- **Local and Regional Array Seismology on Antarctica (TELLUSCOPE).**
- **Process-Oriented PASSCAL-like experiments.**
- **Active-Source System.**

The nucleus of AntarcticArray is the permanent Backbone Network. The purpose of the Backbone Network is to provide information about crustal and lithospheric structure on a continental scale and about Earth's deep interior. The network is also needed to guide installation of more focused experiments (e.g., TELLUSCOPE, Process-Oriented Experiments). In general, Antarctic stations are extremely valuable for monitoring and studying seismic events in Antarctica and in the relatively sparsely instrumented southern hemisphere. The US and other countries currently operate year-round broad-band stations in Antarctica. The US stations are part of IRIS's Global Seismic Network (GSN) and most of the international stations are part of the Federation of Dig-

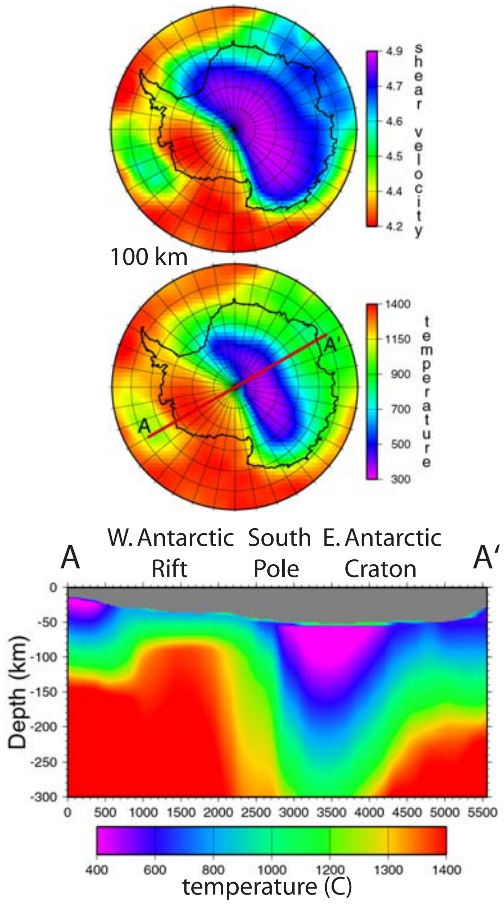

Figure 4: **Temperature contrast between East and West Antarctica.** Maps at top show shear wave speed and temperature ($^\circ C$), and the lower panel shows a vertical cross-section of temperature crossing W. Antarctica and E. Antarctica. The temperature contrast across the Transantarctic Mountains is among the world's strongest large-scale continental lateral thermal gradient. (Courtesy of Nikolai Shapiro.)

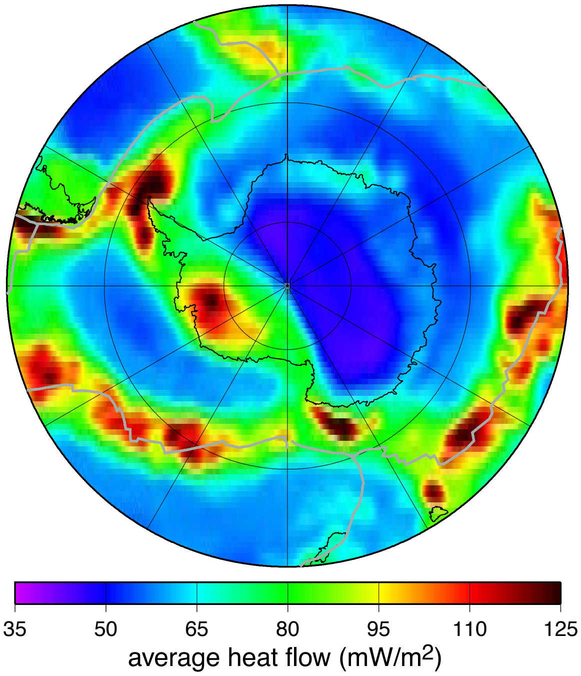

Figure 5: **Map of expected mean heat flux.** The map was produced by extrapolating to Antarctica heat flow measurements observed elsewhere in the world guided by a recent seismic model. (Courtesy of Michael Ritzwoller.)

ital Seismic Networks (FDSN) and deliver data to IRIS's Data Management Center (DMC). With two exceptions (South Pole station (QSPA) and the French Dome C Station (DCC)), current stations are near the coast. SPRESSO is seen as the site of particularly high quality observations, and as the center of US seismic activities in the deep continental interior. As the interior encompasses multi-national domains of interest, international collaboration will be of paramount importance in developing a continent-wide Backbone Network.

Broad-band array installations are needed to improve resolution to length scales of tectonic relevance in regions of interest and signal-to-noise to detect weak signals for particular applications. Two general array types are envisioned. The first is the *Evolving Regional Arrays*, arrays of 10 - 30 broad-band instruments that may be moved around the continent to complement the Backbone Network by improving regional resolution and coverage. These will be large arrays with apertures of hundreds of kilometers. The second array type

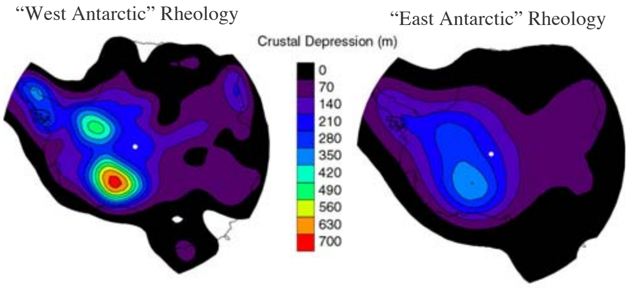

Figure 6: **Visco-elastic response to a plausible loading/unloading history.** The left panel shows the expected crustal depression 10 ky before present using a rheology consistent with warm mantle temperatures and a thin elastic lithosphere expected for West Antarctica. The right panel displays the depression for cool mantle temperatures and thick lithosphere expected for East Antarctica. Differences in the temperature profiles beneath East and West Antarctica are expected to have a dramatic effect on the response of the solid earth to episodes of glacial loading and unloading. (Courtesy of John Wahr.)

will be smaller aperture arrays explicitly deployed for signal enhancement, rather than improved resolution. Both 2-D and 3-D versions of this array type have been discussed, with deployment near the SPRESSO facility optimal for a 3-D array (CRYSTAL, Cryo-Seismic Three-Dimensional Array Lattice), in particular. Integrating over time such deployments on both length scales will produce a continental scale array, which is a seismic earthward looking "telescope" that is referred to here as TELLUSCOPE (from "tellus", related to "terra", Latin for "earth"). TELLUSCOPE is envisioned as a community effort and, as with the Backbone Network, encompasses areas of multinational interest. International cooperation and collaboration is seen as even more important for TELLUSCOPE than for the Backbone Network.

Process-Oriented Experiments are seen as PI-driven installations to address specific scientific objectives similar in nature and scope to PASSCAL experiments that have already occurred within Antarctica and elsewhere in the world. Together with TELLUSCOPE and the Backbone Network, these experiments define the broad-band "passive source" part of AntarcticArray. In addition, an active source system is needed specifically to ad-

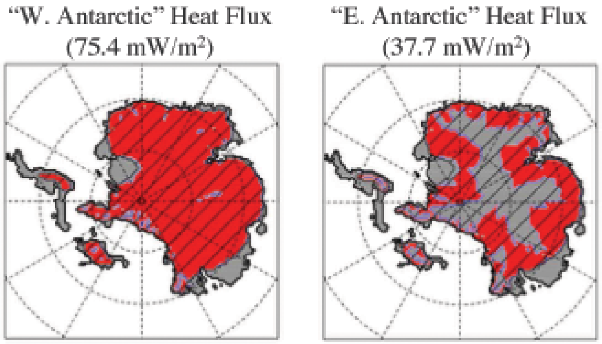

Figure 7: **Basal liquid water from a coupled climate-icesheet simulation.** Estimated average West Antarctic and East Antarctic heat flux were imposed across the entire continent leading to great differences in the expected distribution and extent of basal water (red regions) across Antarctica. (Courtesy of Andrew Nyblade.)

dress ice-bed conditions to improve understanding of icestream dynamics.

Each component of AntarcticArray is described further in this section, contrasting existing capabilities and some recent results with the capabilities needed to address the scientific opportunities and challenges presented by Antarctica.

3.1 Backbone Network

The current state of the Antarctic Backbone Network is shown in black letters in Figure 9. These 11 stations include US GSN stations together with international FDSN stations including SNAA (German), MAT (Japanese), SYO (Japanese), MAW (Australia), DRV (France), DCC (France), and TNV (Italy). An estimate of the resolving power of the current Backbone Network for intermediate period surface waves is shown in Figure 10.

As with every component of AntarcticArray (with the possible exception of SPRESSO), international collaboration and partnership has been and will continue to be crucially needed to effect the Backbone Network. Proposed sites for upgrades to the Backbone Network are identified in Figure 9 with blue and red letters. Shown are 13 station locations. The design goal is to bring the Backbone Network to approximately 24 stations on the Antarctic continent.

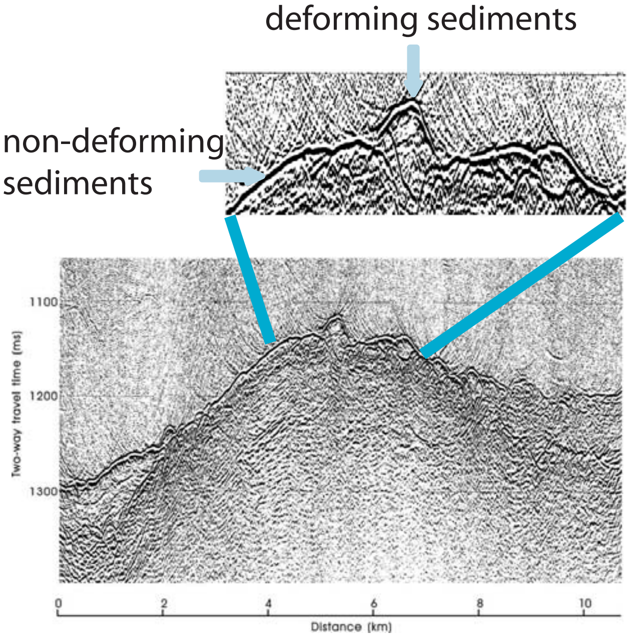

Figure 8: **High resolution seismic mapping of ice-bed characteristics.** Active-source image of regions of the ice-bed that shows signs of deformation, contrasted with areas that appear not to be deforming. (Courtesy of Andy Smith.)

Upgrades to the Backbone Network will be designed to serve two principal functions. The first function will be to directly supplement the broadband stations of the FDSN network. Such stations will need to meet the IRIS GSN instrument specifications and should possess excellent long-period response and operate year-round whenever possible. It is agreed, however, that 6-8 months of operation will be acceptable when year-round operation is not feasible. The 6-8 month operational window is currently achieved with remote temporary installations and defines the minimum operational objective. With present and foreseeable instrumentation, the requirement of year-round operation will be most easily met for stations near Antarctic bases with over-winter capability (current or potential). The proposed sites near (at least) seasonal bases are shown with the blue lettering in Figure 9. These sites correspond closely to those recommended by the ANTEC (Antarctic Neotectonics) initiative, based on similar considerations.

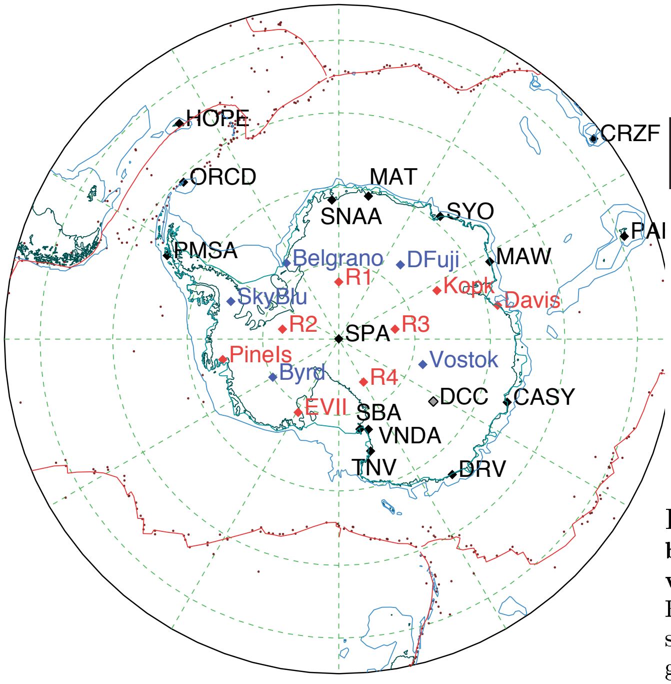

Figure 9: **Antarctic Backbone Network: current and planned.** Current locations of Federation of Digital Seismic Network (FDSN) stations are identified with black lettering. The approximate sites of proposed upgrades to the Backbone Network are shown with red and blue lettering. (Courtesy of Brian Kennett.)

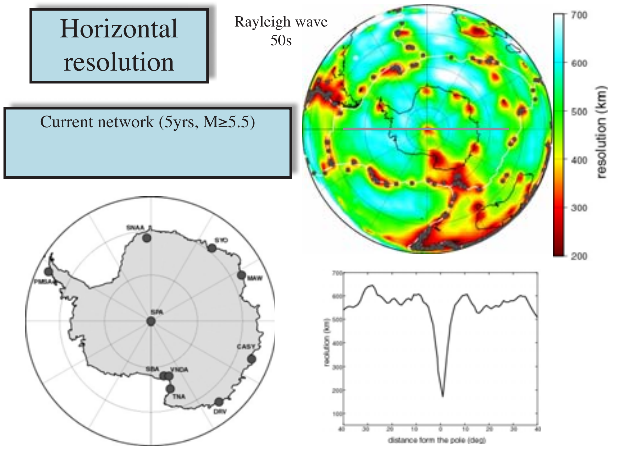

Figure 10: **Resolving power of the current Backbone Network using intermediate period surface waves.** The resolution of five years of simulated 50 sec Rayleigh wave data for the network shown at lower left is shown at upper right. The resolution along the horizontal grey line across the map is shown at lower right. Average resolution is about 600 km diminishing to about 200 km near stations. (Courtesy of Michael Ritzwoller.)

The second function of the Backbone Network will be to augment the existing broad-band network with a stronger focus on regional issues, so that less emphasis may be placed on extended long-period response and year-round operation. The distribution of such stations is designed to improve the uniformity of coverage of the Antarctic continent at the 500 - 1000 km length scale. The proposed sites are shown in red letters in Figure 9. Most of these proposed sites are at locations without existing logistics and will require autonomous power systems. Extension into the dark winter months may be possible at some sites by exploiting wind-power (at a cost of some seismic noise). However, summer-only operation would certainly be of major benefit to structural and seismicity studies. A number of the stations lie at about 750 km from the Pole and may, therefore, be able to be supported with existing US logistical capabilities. Stations in East Antarctica will require support from international collaborators.

The ideal scenario for the Backbone Network would be real-time data transmission, but this is be difficult to achieve at high latitudes. For the most remote sites, it may be necessary to resort to visits at the beginning and end of summer to retrieve data and secure station operation. Uploading data by burst transmission from circling aircraft could also be an attractive strategy. Continuous state of health information may be more important that real-time data delivery in many cases, as it could reduce the number of station visits.

The full set of stations in the Backbone Network would, by itself, make a major contribution to both global seismology and crustal and lithospheric studies of Antarctica. Figure 11 demonstrates that the proposed augmentation of the Backbone Network will improve resolution from intermediate period surface waves by at least a factor of 2 over existing capabilities. This focuses the resolving power of the network from global scales to scales of tectonic relevance. In addition, the presence of these stations with long-term operation provides a framework for effective exploitation of

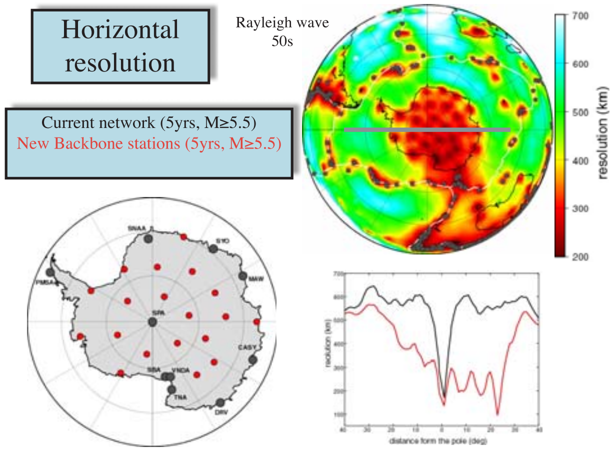

Figure 11: **Resolving power of the planned Backbone Network using intermediate period surface waves.** Similar to Figure 10, but with an augmented Backbone Network (red circles). Average resolution reduces by a factor of two to about 300 km diminishing to about 150 km near stations as the red line in the panel at lower right shows. (Courtesy of Michael Ritzwoller.)

the shorter term deployment of other components of AntarcticArray.

The planned permanency of the Backbone Network presents several challenges, including continuity of funding and operation and maintenance. From a US perspective, the long term stability of Backbone stations needs to be addressed by partnerships with the Incorporated Research Institutions for Seismology (IRIS) as well as the US Geological Survey (USGS). It is expected that international collaborators will need to develop similar relationships with institutions in their own counties that can help to ensure longevity of the Network.

Although the Backbone Network design presented here contains only continental stations, stations that could be deployed on the ocean bottom off the continent would be very attractive. High seas in Southern Oceans may make this alternative unlikely in the near term, but this is seen as a very attractive extension of the Backbone Network in the future.

3.2 SPRESSO

The seismological community has maintained a succession of South Pole instrumentation since the International Geophysical Year (IGY) in 1957. South Polar observations have played important roles historically in global normal mode and core studies. Until recently, because of logistical limitations, seismic instrumentation at the Pole had not taken full advantage of the low noise level potential of the site, being susceptible to noise emanating from the Station. However, IRIS and the USGS have in the past several years developed a new site for seismological science at the Pole. The South Pole Remote Earth Science and Seismological Observatory (SPRESSO), located in the South Pole Quiet Sector, 8 km from the pole has demonstrated a new range of seismology possibilities. (See Figure 12.) In December of 2002, a new South Pole seismic station (QSPA) was installed, consisting of KS45000 and CMG3TB sensors in sub-firn 300 m boreholes. The QSPA site also includes a shal-

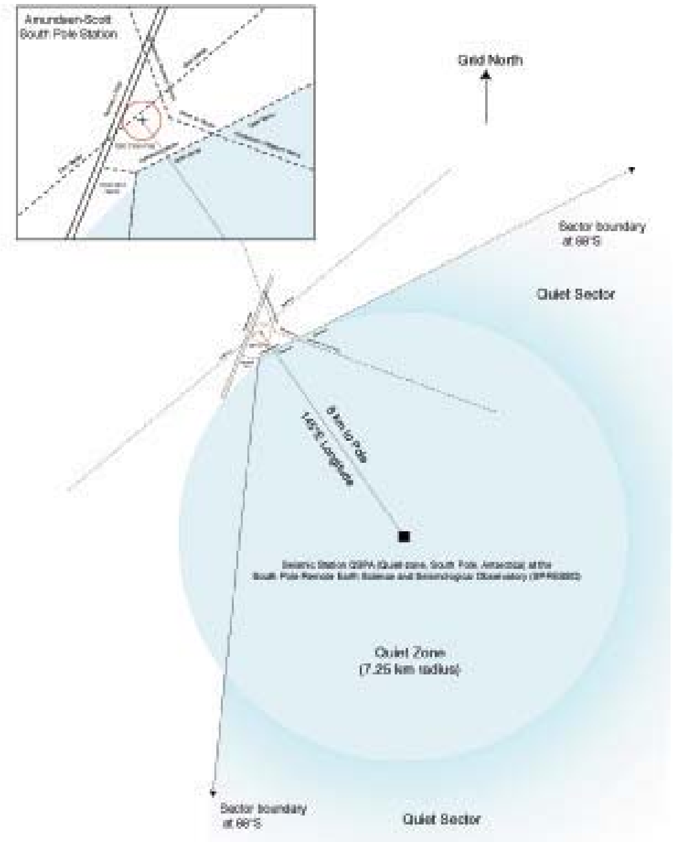

Figure 12: **SPRESSO in the Antarctic Quiet Sector near the Amundsen-Scott South Pole station.** (Courtesy of Rhett Butler.)

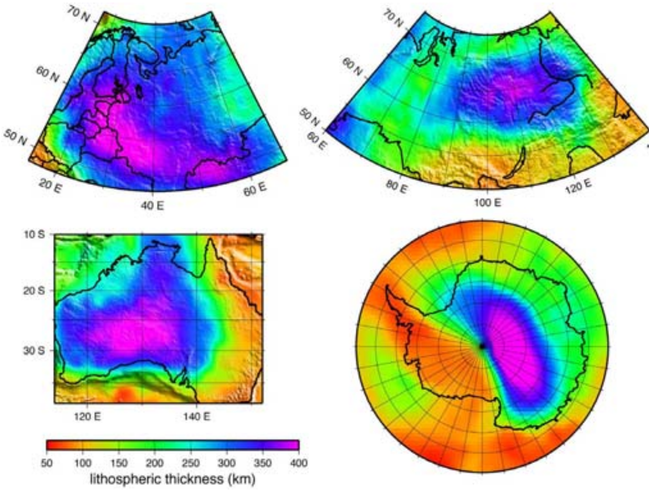

Figure 13: **Comparison of lithospheric thickness across Antarctica with cratonic regions elsewhere.** (Courtesy of Nikolai Shapiro.)

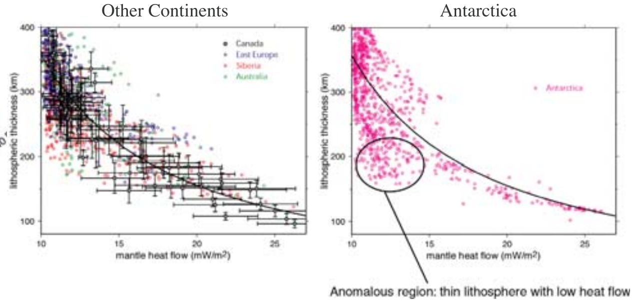

Figure 14: **Lithospheric thickness versus mantle heat flux.** The left panel shows that lithospheric thickness scales approximately with mantle heat flux across most cratonic regions. The right panel shows that the same is true for the Antarctic craton, but there are anomalous regions in East Antarctica with relatively thin thermal lithosphere and very low mantle heat flux. The source of this anomalous behavior remains unclear, but it may be related to Mesozoic rifting around the entire rim of East Antarctica. More highly resolved images of the East Antarctic lithosphere are needed to understand this phenomenon. (Courtesy of Nikolai Shapiro.)

low vault housing both STS-1 vertical and STS-2 sensors for site comparison purposes. SPRESSO is linked to Amundsen-Scott Station via electro-optical cable for power and communications. Data collected so far at QSPA indicate that it is the quietest global seismic station on the planet, particularly in the important several second period range crucial for body wave studies. These recent developments at SPRESSO indicate that the South Pole and other regions of the Antarctic interior provide a world-class resource for pushing the threshold of seismic detectability, both within the seismologically anomalous Antarctic plate and globally.

The exceptionally high signal-to-noise environment of SPESSO and the infrastructure provided by the Amundsen-Scott Station make SPRESSO not only an ideal site for a single broad-band station, but also a good central focus for 2-D and perhaps 3-D array development.

3.3 Regional and Local Array Seismology on Antarctica (TELLUSCOPE)

The current resolution of seismic structure beneath Antarctica by tomographic methods achievable with existing stations is between 500 and 1000 km horizontally across most of Antarctica (Figure 10). It is possible, therefore, to delineate differences between West and East Antarctica, but not to provide information needed to address major issues of continental structure nor to provide an adequate framework for the design of many process-oriented experiments. The ability to focus images of crustal and mantle structures to scales of tectonic relevance will require deployments of large-scale arrays of seismometers. At present, the Southern Hemisphere has only three arrays. The Warramunga and Alice Springs arrays are relatively small aperture arrays about 300 km apart in Australia. The SKIPPY array was deployed in broad segments regionally across nearly all of Australia, and together with USARRAY is a model for the evolving regional array component of TELLUSCOPE. All other seismic arrays lie in the Northern Hemisphere.

Arrays on two different spatial scales have been discussed: *Evolving Regional Arrays* on a regional scale, and both 2D and 3D arrays on a local scale. Both array types are envisioned to be broad-band, buth the purposes of the arrays are complementary. The Evolving Regional Arrays are proposed explicitly to improve resolution whereas the local arrays are designed more to enhance signal-to-noise.

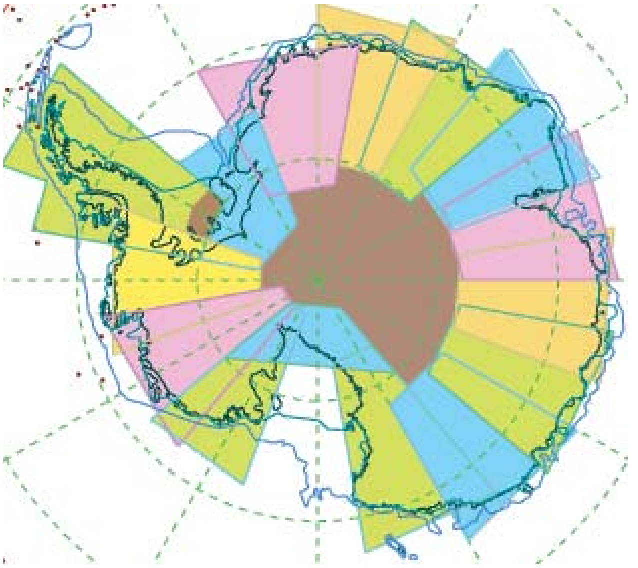

Figure 15: **"Pinwheel" design for the installation of TELLUSCOPE Evolving Regional Arrays.** The intent of this design is for flexibility of installation and to optimize international contributions to the overall product. (Courtesy of Brian Kennett.)

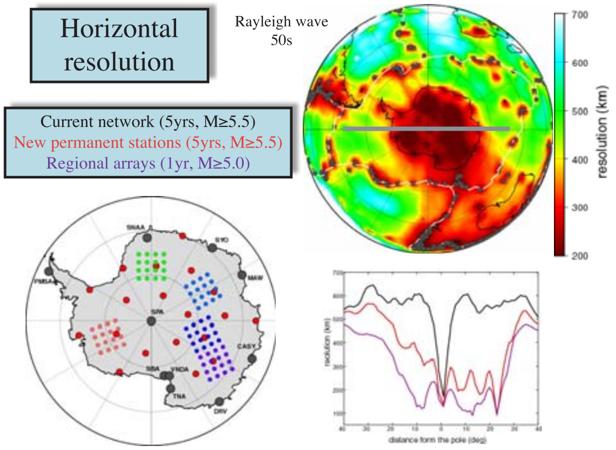

Figure 16: **Resolving power of the planned Backbone Network augmented with several regional arrays (TELLUSCOPE).** Similar to Figure 10, but with an augmented Backbone Network further enhanced to include five 16-station regional arrays. Average resolution reduces by another factor of two to about 150 km diminishing to about 100 km near stations as the blue line in the panel at lower right shows. (Courtesy of Michael Ritzwoller.)

3.3.1 Evolving Regional Arrays

Regional deployments of portable broad-band seismic stations in arrays with horizontal spacing of 100-300 km can provide sufficient coverage to allow the delineation of major boundaries of tectonic provinces even in regions with complete ice cover. For example, it would be possible to determine the inner cratonic contact for the Palaeozoic Transantarctic Mountains. The apparently anomalous relationship between lithospheric thickness and mantle heat flux that may exist beneath parts of East Antarctica (Figs. 13, 14) would also be clarified. Further, the records at individual stations can be exploited to gain information on crustal structure and thickness. Except for a few patches, mostly near the coast, there is currently almost no control on the nature of the crust beneath the ice.

To achieve the necessary station density it will only be possible to cover parts of the continent at any one time. However, progressive deployments with overlapping coverage can evolve to cover the whole continent in time. One to two years of field data at each site would be sufficient to meet most needs, particularly with longer duration recordings available from the Backbone Network sites.

Logistical capabilities exists through the network of international bases on the coastline (particularly in East Antarctica and the Antarctica Peninsula) and the major US capability at McMurdo and the South Pole which has also supported summer camps in West Antarctica. It is, therefore, sensible to consider a sectoral approach with the deployment of 15-30 instruments in a sector using fixed-wing aircraft (supplemented where appropriate with helicopters). Most sectors would extend inland from the coast to match up with deployments from the South Pole. In the Antarctic Peninsula, it should be possible to exploit the concentration of international bases to achieve part of the coverage. Ideally, multiple sectors would be occupied simultaneously through international cooperation.

A possible 4-stage configuration of sectors is shown in Figure 15 based on a model of three sectors occupied simultaneously. This sectoral deployment is referred to as the "Pinwheel". With local recording over summer, sites would need to

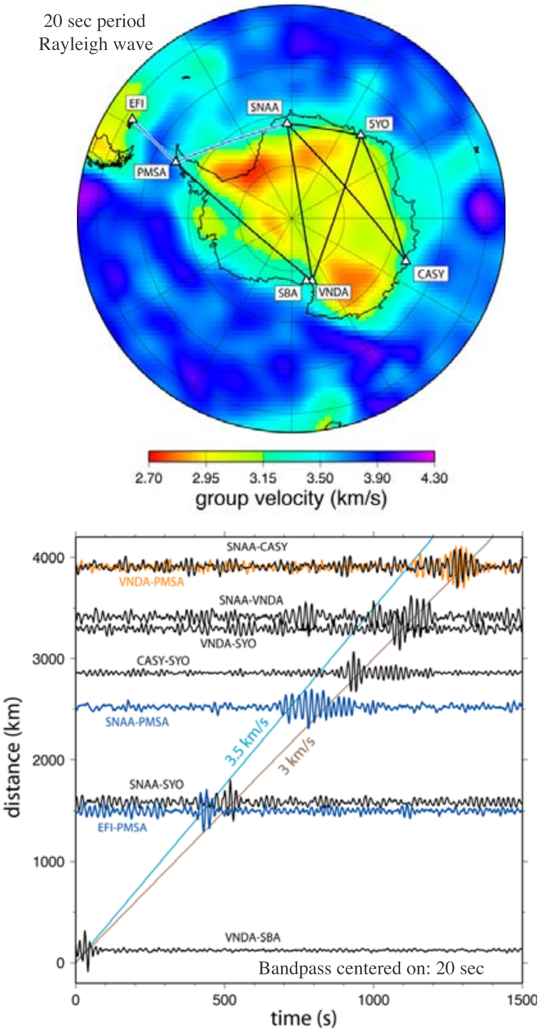

Figure 17: **Inter-station Green functions estimated from ambient seismic noise.** (Courtesy of Nikolai Shapiro.)

be occupied for at least two seasons to achieve ~ 12 months recording. At the end of a stage, the instruments would be moved to the next sector retaining some overlap with the previous sector. As the stages progress the effect is that the "Pinwheel" stations appear to rotate around the pole over time. Exploitation of available seismic events is much more effective if stations are deployed at the same time in different parts of Antarctica, and this is reflected in the sectoral coloring of the Pinwheel design.

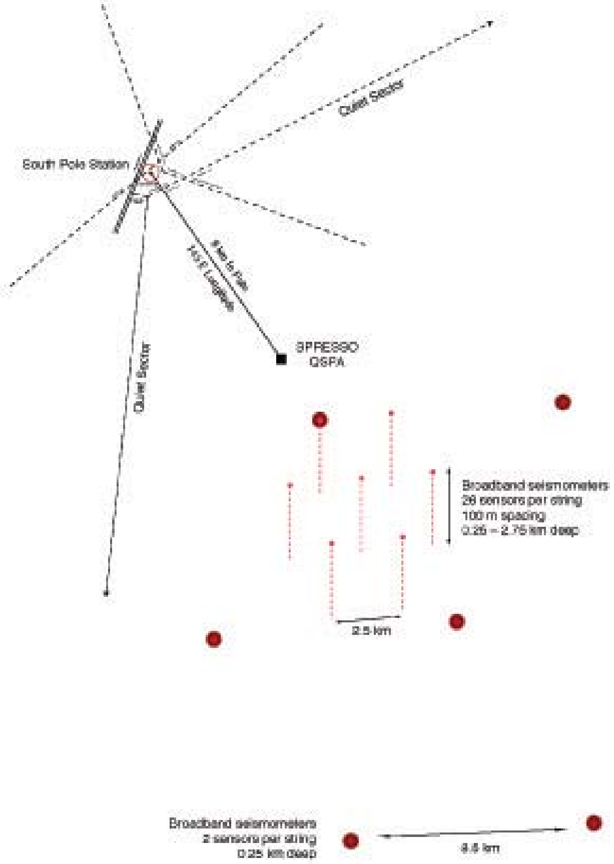

Figure 18: **CRYSTAL – Cryo-Seismic Three-Dimensional Array Lattice.** Small aperture 2-D and 3-D arrays are possible uses for the SPRESSO facility near the South Pole. (Courtesy of Rhett Butler.)

The primary instrument at each site would be a broad-band seismometer with a high fidelity recording system with solar power. However, provided that the payloads do not become too large, it would be beneficial to have auxiliary instrumentation such as a geodetic quality GPS station and a magnetometer. The strong polar ionospheric fields provide good sources for induced magnetic fields which can be employed to examine conductivity structure and thus identify sites for specific and more detailed magnetotelluric studies. The study of the induced magnetic field provides a useful complement to the seismic work because province boundaries are frequently accompanied by conductivity anomalies.

US participation in the Evolving Regional Array (Pinwheel) component of TELLUSCOPE may very well initiate near the South Pole in order to exploit the SPRESSO facility.

New methods of data processing that are now just emerging promise to provide better results from TELLUSCOPE than previously envisioned. Resolution studies such as those shown in Figure 16 are based on earthquake sources near plate boundaries removed from Antarctica by thousands of km. The use of atmospheric and oceanic noise as the source of surface waves, however, collapses surface wave sensitivity kernels to inter-station regions and frees surface wave studies from reliance on earthquakes. This is particularly important for relatively short installations where a good azimuthal distribution of earthquakes may not exist in a 12 month observing window. Figure 17 shows an example of estimates of Green functions recovered from several pairs of Antarctic stations near 20 sec period. The application of this method to much larger numbers of interstation paths across TELLUSCOPE would provide unprecedented constraints on the structure of the Antarctic crust and lithosphere.

3.3.2 Local 2D and 3D arrays

Improved resolution is not the only benefit of the TELLUSCOPE array. Microseismic noise is a fundamental limitation in body-wave seismology as are katabatic winds in some parts of Antarctica. Higher signal-to-noise observations of body-waves can only be accomplished with an array. Smaller aperture 2-D arrays would be envisioned under a US contribution to TELLUSCOPE, perhaps with a focus on deployment at SPRESSO as an inner ring component of a regional array.

A small aperture 3-D array would be a unique concept for development at SPRESSO, and would be based on significant ice drilling and instrumentation capabilities demonstrated by the neutrino physics community in such efforts as the Antarctic Muon and Neutrino Detector Array (AMANDA) and IceCube. The preliminary concept of the 3-D array is referred to as CRYSTAL (Cryo-Seismic Three-Dimensional Array Lattice), and includes a 3-D hexagonal prism of seven sensor strings (at each vertex and the center), each with 26, 3-component broad-band seismometers at 100 m spacing from 250 to 2750 m depth as depicted in Figure 18. The horizontal aperture of this prism would be twice the 2.5 km vertical extent. All sensors would initially be emplaced in water at depth, and are comparable to Ocean Bottom Seismometers, except that they must work in the extreme cold of the ambient ice (-50C). Such an array could be a powerful global resource for studying seismic source processes in earthquake, icequake, and global nuclear test monitoring, for example.

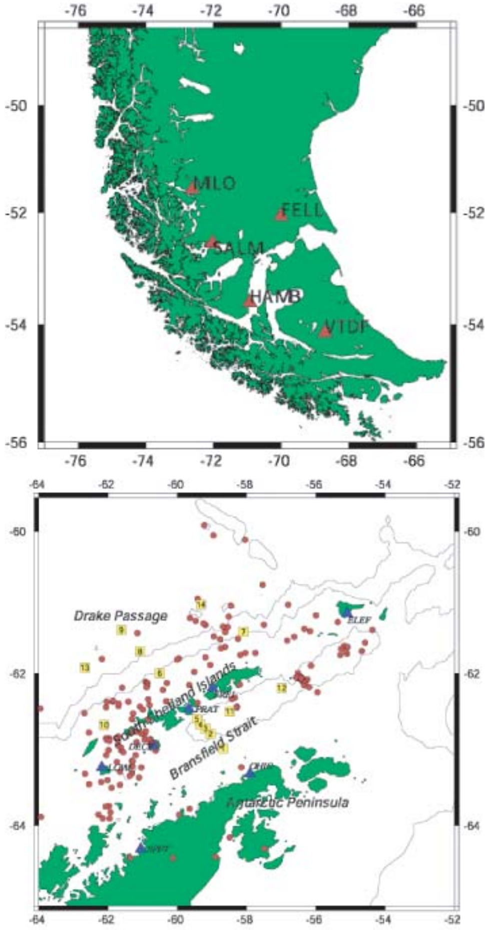

Figure 19: **SEPA network configuration.** Joint US-Chile experiment with 13 broad-band stations in the Antarctic Peninsula, S. Shetland Islands, and Chilean Patagonia operated between 1997 and 1999 together with 14 OBSs in the Bransfield straight. This was the first project to operate an autonomous broad-band station in Antarctica year-around. (Courtesy of Douglas Wiens.)

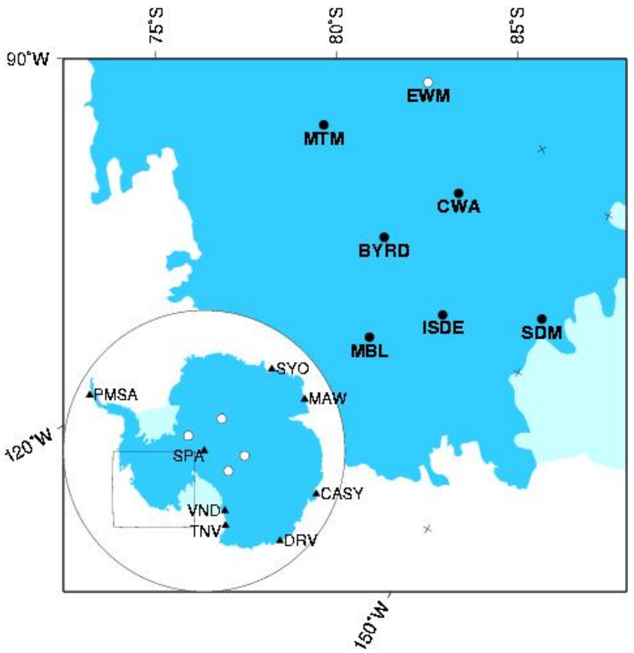

Figure 20: **ANUBIS network configuration.** (Courtesy of Sridhar Anandakrishnan.)

3.4 Process-Oriented Experiments

Many geological and geophysical problems require focused seismographic deployments with higher density than will be possible with the permanent or moving array components of AntarcticArray. These experiments will provide the capability to obtain much higher density deployments in smaller regions for specific goals, such as obtaining higher resolution crustal and mantle structure beneath specific tectonic features, obtaining high resolution earthquake locations, imaging glacial bed conditions with receiver functions, or imaging specific regions of the deep mantle, the core-mantle boundary, or the inner core.

Temporary, focused passive seismographic deployments in Antarctica are currently feasible. Such experiments, including SEPA (Sesmic Experiment in Patagonia and Antarctica, Fig. 19), ANUBIS in W. Antarctica (Fig. 20), TAMSEIS (Fig. 21) across the Transantarctic Mountains, the Erebus Seismic Network (Fig. 22), and the Australian SSCUA (Fig. 23) deployment in E. Antarctica have proven to be highly successful. The scientific objectives for AntarcticArray require expanded capabilities for carrying out temporary passive deployments in Antarctica including access to larger numbers of receivers, concurrency of experiments, and faster turn around. Typical temporary passive experiments will utilize a station spacing that is smaller than the spacing envisioned for the Evolving Regional Array component of TELLUSCOPE (150-200 km) to achieve higher resolution within regions of particular interest. These experiments will typically consist of 20-60 broad-band seismographs deployed for periods of 1-3 years. In some cases these experiments may be designed as “densifications” of scheduled Regional Array deployments to take advantage of this sparser grid and the logistical support available in that part of Antarctica as a result of the Regional Array deployment.

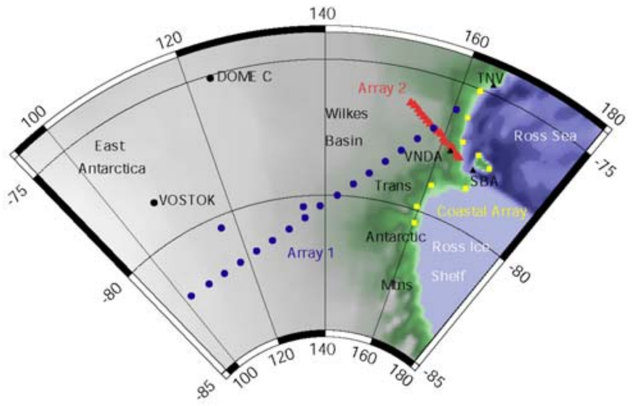

Figure 21: **TAMSEIS network configuration.** (Courtesy of Douglas Wiens.)

To contrast the Evolving Regional Array component of TELLUSCOPE with the Process-Oriented Experiments, recall that the Regional Array is seen as an international, community effort whose purpose is dominantly to improve resolution of crustal and upper mantle structures. The Process-Oriented Experiments will be smaller scale, science driven, and PI led. They will probably also involve less explicit international collaboration, although non-US experiments have and will continue to play an important role in elucidating the history and structure of the Antarctic crust and mantle.

Models of continental evolution suggest that West Antarctica has been assembled in the

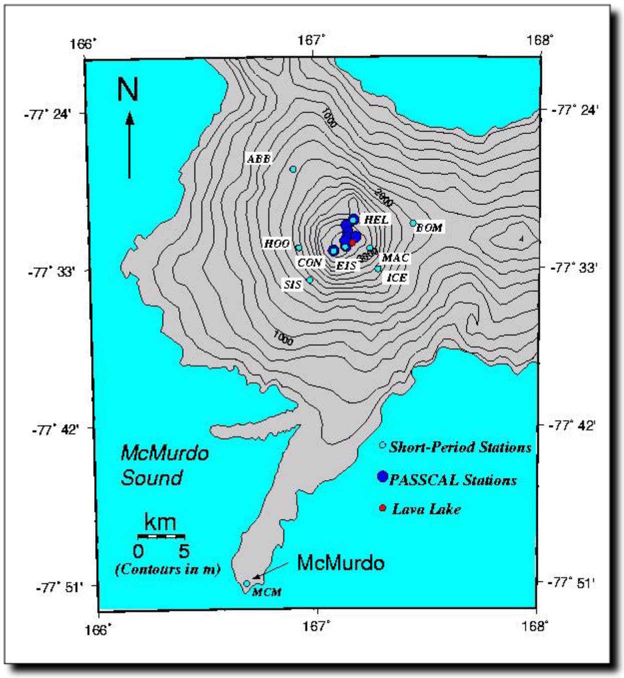

Figure 22: **Erebus Seismic Network configuration.** (Courtesy of Richard Aster.)

Phanerozoic from a number of continental fragments intersecting a possibly dormant major continent rift with currently active volcanism. In contrast, the core of East Antarctica has been in place since the Precambrian. Comparisons with Australia that abutted East Antarctica in Gondwana until rifting began at about 85 Ma, suggest an assemblage of cratonic elements by the Neoproterozoic (as favored in recent geologic models) rather than a monolithic craton. The different components of Antarctica would be expected to have varying responses to long-term deformation and such rheological differences will modulate short-term response to glaciation and deglaciation.

The structure of the crust and lithosphere beneath Antarctica can be divided into three principal distinct units based on formation and tectonic evolution: The East Antarctic Craton, the Transantarctic Mountains (TAM), and the West Antarctic Rift System. The TAM span the length the continent, forming a natural boundary between East and West Antarctica. Structural and tectonic elements exist within each large-scale unit, and it is these smaller elements that will be the focus of many of the Process-Oriented Experiments. In addition, these experiments provide important information about the much deeper Earth. Figure 24 shows recordings of core phases from the TAMSEIS experiment. Large deployments of broadband receivers can greatly increase the number of measurements about the inner core, for example.

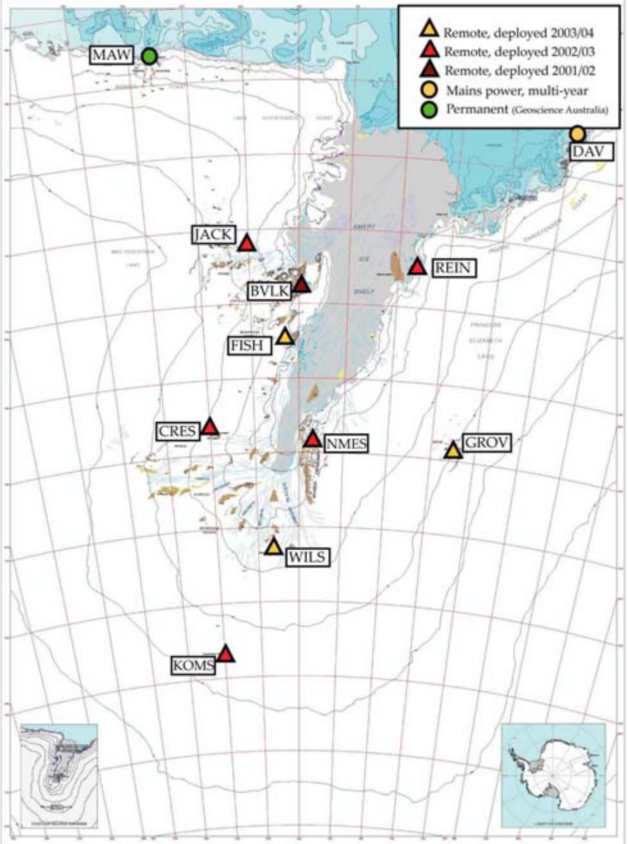

Figure 23: **SSCUA network configuration.** Stations installed from 2001 through 2004, centered on the Lambert Glacier. (Courtesy of Anya Reading.)

Transantarctic Mountains (TAM). The TAM form a major transcontinental range that varies in width from 100 to 200 km and has elevations as high as 4500 m. Unlike many other Cenozoic mountain ranges, which have formed by thrusting, folding and volcanism, uplift of the TAM has been exclusively by vertical crustal movement with gentle tilting of fault blocks. The mountains have a simple stratigraphy consisting of a Precambrian and early Paleozoic basement meta-

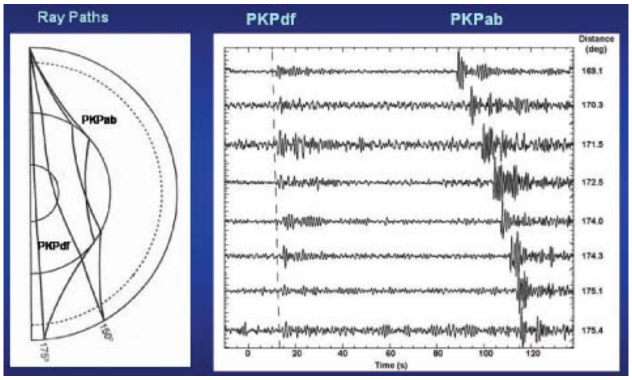

Figure 24: **Core phases observed at TAMSEIS.** Body waves that propagate through the core (PKP_{df}, PKP_{ab}) from an earthquake on the Arctic Ridge (12/8/2001, 81°N, 1°E, $M_w = 5.1$) are clearly observed at several stations of the TAMSEIS network. Nearly antipodal measurements such as these are needed to contrain the anisotropy of Earth's inner core. (Courtesy of Douglas Wiens.)

morphosed and deformed during the Ross Orogeny (∼500-530 Ma), overlain by subhorizontal sediments of the Devonian to Triassic Beacon Supergroup. Both the basement and its cover are intruded by the Jurassic Ferrar Dolerite. Late Cenozoic alkaline volcanism has occurred along the riftside of the mountain range. Apatite fission track dating indicates as much as 7-8 km of uplift in some places since the early Cenozoic, although the rate of uplift remains somewhat controversial. Additional constraints on uplift come from the Kukri peneplain that lies between the basement rock and sedimentary cover and is extensively exposed along the TAM. Near the mountain front, the peneplain had to be at a depth of ∼3 km at the end of the Beacon Supergroup deposition and is now found at elevations of 500-4000 m above sea level. From a number of seismic studies, it is known that the crust under the TAM thickens from about 25-30 km near the Ross Sea to 40-43 km some 100-150 km inland.

Four types of models have been proposed to explain the uplift of the TAM: (1) delayed phase changes (eclogite to basalt or quartz-eclogite to granulite); (2) simple shear extension; (3) various kinds of flexure models; and (4) transform-flank uplift. A principle assumption made in most, if not all, of these models is that thermally perturbed mantle lithosphere extends several tens of kms laterally underneath the TAM.

The thermal gradient between East and West Antarctica across the TAM seen, for example, in Figure 4 is amongst the strongest beneath continents world-wide. At 100 km depth, the contrast between the West Antarctic Rift and the East Antarctic craton across the TAM is more than 1000°C. Along the TAM, the lateral temperature gradient is about 1°C/km at 100 km depth. This temperature contrast extends deeper than 300 km, where the temperature difference is still more than 400°C. The TAM separate lithosphere that is about 70 km thick beneath much of West Antarctica and lithosphere that is deeper than 300 km in parts of East Antarctica (Fig. 14).

The TAMSEIS experiment has already increased knowledge of the structure of the crust and uppermost mantle beneath the Transantarctic Mountains. To improve the knowledge of the structure of the Transantarctic Mountains, their origin and evolution, as well as structural variability will require more focused experiments such as the TAMSEIS experiment in the future.

East Antarctic Craton. East Antarctica is a craton consisting of Archean terranes separated by Proterozoic and younger mobile belts. Bedrock exposure is limited to coastal areas and thus little is known about the interior structure of the craton. Much of what is assumed about its structure relies on correlations with Archean and Proterozoic terranes in India, Africa, and Australia, which were contiguous before the breakup of the Gondwanan supercontinent. The center of the East Antarctic Craton consists largely of a broad, high plateau, which also contains the Gamburtsev Subglacial Mountains. The high elevation of the East Antarctic Craton, which exceeds 1000 m after glacial unloading, is anomalous relative to other cratons. Most models of East Antractic assume that it has existed as a craton with an Archean nucleus since before the assembly of the Rodinia supercontinent. This view is based on the widespread occurrence of Archean and Proterozoic outcrops along the East Antarctic coast and the presence of similar Proterozoic rocks in the TAM. Other studies suggest a more complicated tectonic history for East Antarctica, including multiple Proterozoic to early Paleozoic orogenic events. The Cambrian rocks that crop out near the Lambert Graben in the Southern Prince Charles Mountains. may be related to the 550-500 Ma Australian Pinjarra Orogen and possibly form a suture zone extending into the interior of East Antarctica.

From global seismic images, it is clear that East Antarctica has high seismic wave speeds (Fig. 4) in a thick thermal lithosphere extending to depths greater than 300 km, as compared to lower wave speeds and lithospheric thicknesses less than 100 km in West Antarctica (Fig. 13). The situation is comparable to knowledge of structure beneath Australia prior to 1993, where there is a similar style of structural contrast, and also few permanent high-quality stations. The progressive deployment of regional arrays in Australia since 1993, however, has dramatically improved the picture with 300 km or better horizontal resolution now achieved clearly defining mantle boundaries and sub-structure in the Australian craton.

At present, may first-order structural and tectonic questions cannot be addressed. For example, we cannot address such issues as the support of the sub-ice Gamburtsev Mountains: is this recent and dynamic, or just the eroded residuum of ancient structures? Since the high elevations of the Gamburtsev Mountains form the nucleus for ice sheet accumulation in East Antarctica, the nature of this structure is important for climatic issues. Similarly, what are the structural controls on the accumulation of the ice sheet? Such questions can only be answered by systematic elucidation of the 3-D structure in the crust and mantle of Antarctica at length-scales that are currently impossible to image over broad areas. The anomalous nature of the relationship between lithospheric thickness and mantle heat flux (Fig. 14) also requires much better resolution in particular areas to elucidate.

West Antarctic Rift System. West Antarctica is believed to comprise an amalgamation of several blocks (Marie Byrd Land, Thurston Island, Ellsworth-Whitmore Mountains, Antarctic Peninsula). Rifting of West Antarctica from New Zealand commenced about 100 Ma, with final separation occurring about 72 Ma. Lithospheric stretching between the various West Antarctic blocks and the Ross Embayment during this period led to the initial formation of the West Antarctic rift system. Seismic stratigraphic evidence from the Ross Sea, the most accessible part of the West Antarctic rift system, indicates that there was another phase of rifting in the Cenozoic, which is consistent with recent thermal models of West Antarctica from global seismology (e.g., 4). Crustal structure beneath the rift system has been investigated in a number of places using seismic data. Estimates of crustal thickness range from about 20 km in parts of the Ross Embayment to about 30 km beneath the Byrd Subglacial Basin . Uppermost mantle P wave velocities appear to be normal (~8.0-8.3 km/s), but there is little information on P-wave velocities deeper in the upper mantle. Information from surface waves about S-wave velocities in the upper mantle is more homogeneous, but resolution remains low (Fig. 10).

Thus, it is clear that West Antarctica contains one of Earth's major continental rift systems which is the present day remnant of the rifting of Gondwana that have occurred over more than the past 200 Ma. The thermal structure of the rift and its geological history, however, remain very unclear. Improved understanding will result only with focused experiments designed to image the seismic structure of the crust and mantle with much better lateral and vertical resolution. Interconversion between seismic velocities and temperatures has developed appreciably over the last decade. Better seismic models promise significant improvements in knowledge of the thermal state of the upper mantle.

Volcanism and Seismicity. The origin of the <50 Ma alkaline igneous rocks in West Antarctica and in parts of the TAM is poorly understood and has been associated with similar magmatic activity in eastern Australia, parts of New Zealand and the Pacific plate extending east of the Australia-Antarctic discordance and west of the Antarctic Peninsula. The origin of the magmatism has been conjecturally explained by a number of models, including rifting, mantle plumes, and the detachment and sinking of subducted slabs. Significant amounts of crustal extension are clearly associated with the larger volumes of magmas that form the major eruptive centers in the Terror Rift and Adare Trough. Improved understanding will require much higher resolution studies of volcanic centers. The current Erebus Seismic Network, an integrated seismic and GPS deployment, is an example. Helicorder images about the seismic activity on Erebus are available on the web and are updated regularly:

http://www.ees.nmt.edu/Geop/
Eworm_erebus/welcome.html

Movies of eruptions are also available:

http://www.ees.nmt.edu/Geop/
mevo/mevomm/mivies.html

Seismicity across Antarctica is low, and may be depressed due to the weight of the overlying ice. The threshold of detection and location for Antarctic earthquakes using the current global network of seismometers is $m_b \sim 4.9$. The lack of permanent seismic stations outside of the stable crust of East Antarctica may artificially magnify the reported quiescence of the continent. Preliminary results from portable seismometer deployments in West Antarctica, at Terra Nova Bay, and in the TAM suggest that Antarctic seismicity may be higher than previously thought. Icequakes can also be identified and located with local arrays (Fig. 25), which help provide new information about icestream deformation.

3.5 Active-Source System

An active-source seismic system provides the most direct link between seismic observations and glacial processes. Improvements in large-scale ice sheet models require much better information about the subglacial environment and processes. Information about basal conditions needs to be high resolution and must penetrate the bed to provide constraints on the shallow sub-glacial environment. Active source seismology can provide much of this information. It can, for example, provide constraints on the deforming sedimentary layer beneath fast-flowing ice, the change in bed characteristics at fast-flow onset, subglacial erosion or deposition, water-pressure and sediment deformation along the full length of an ice stream, and can identify deforming versus non-deforming sediment. It can also provide information on geological controls by mapping subglacial landforms, delineating sedimentary basins and the ice-flow margin, and mapping the distribution of bed characteristics such as the existence of water and sediment dynamics. In addition, active-source seismology provides constraints on ice rheology.

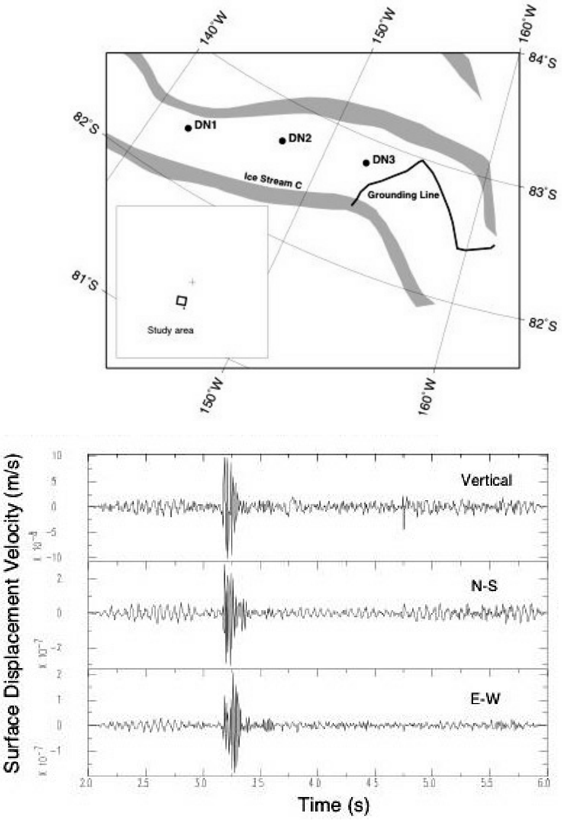

Figure 25: **Icequakes observed at ANUBIS.** Icequakes can be used to infer basal processes. Anandakrishnan and collaborators found an inverse relationship between ice velocity and frequency of icequakes. (Courtesy of Sridhar Anandakrishnan.)

An active-source system complements and combines well with other means of characterizing the ice and the subglacial environment such as drilling and aero-geophysics (notably radar). Drilling provides direct samples, but is very localized. Radar yields information about internal structure, interface characteristics, and water, but does not penetrate the bed to subglacial conditions. A robust research program in active-source seismology is an essential requirement for glaciology in Antarctica.

4. International Collaboration

4.1 International interest

Antarctica has historically attracted scientific interest from many different nations. This remains true today, particularly in the earth sciences, where it is often necessary to investigate wide geographical areas in order to place observations made at individual localities in the proper scientific context. The international extent of the interest in a major program of seismological and related deployments across the continent, as proposed at the SEAP2003 workshop, has grown continuously for more than the past decade. An example of international interest, in addition to the SEAP2003 workshop is the workshop that took place in July 2001, in Siena, Italy, convened by the ANTEC (Antarctic Neotectonics) Group of Specialists. ANTEC is now designated as a Scientific Research Programme Planning Group of the Scientific Committee for Antarctic Research (SCAR). The workshop delegates spanned a wide range of Antarctic geological, geophysical and glaciological disciplines and attended from many different nations. Research interests were discussed from many perspectives and tectonic targets were formally identified and prioritized. The intent was for national programs on modest annual budgets to proceed by addressing the key targets in a loosely coordinated series of smaller experiments, with the ANTEC/SCAR endorsement of the experiment reinforcing its case for approval by the appropriate national program.

Building a seismological network and database from the contributions of many different nations would be useful and the Siena ANTEC workshop, therefore, highlighted the need for a coordinated, international, pan-Antarctic seismic network. AntarcticArray, although emerging from largely US leadership, is congruent with the interest of the international community and further extends the aspirations of the ANTEC group by proposing more stations with closer inter-station spacings. At the SEAP2003 workshop, many contributions were presented by invited members of the international and interdisciplinary communities. Developing these international links, both in terms of addressing Antarctic scientific goals and optimizing the efficiency of pan-continental logistics, is a key component of the follow-on to the workshop.

4.2 Geographical extent of AntarcticArray

Any major Antarctic science program spanning large areas of the continent can be operated with optimal efficiency by employing the logistical resources of more than one national program. Although the US program has by far the largest resource base, the geographic distribution of wintering Antarctic stations implies that the UK and Germany would be well placed to support the deployment and servicing of stations in the Weddell Sea and Antarctic Peninsula regions, while Australia, New Zealand, Italy, France, China and Japan would be well placed to support stations over the vast region covered by East Antarctica. The installation of the Backbone Network of broad-band seismic observatories would be aided through collaboration or cooperation between scientists and the operational staff from the US and those of other nations. The greatest potential for collaboration is in the operation of the Evolving Regional Array. The sectors suggesting the deployment areas in the Pinwheel plan (Fig. 15) have been designed according to the configuration of existing or potential wintering bases (and hence the geographic distribution of potential support from various nations).

4.3 Mechanisms of collaboration

Involvement with other partner nations that operate scientific programs within Antarctica may be achieved through a variety of mechanisms, including scientific collaboration and logistical involvement from the partner nation, scientific collaboration with financial contributions from the partner nation, and logistical support alone, discussed directly with the appropriate Antarctic program. The exact mechanisms by which partner nations would collaborate with the development of AntarcticArray and provide support to station deployments will vary. Scientific collaboration will be dependent on the existence of an energetic international collaborator working in the appropriate country with either pre-existing or developing interests in Antarctica. Where such collaborative opportunities exist, support for AntarcticArray could take the form of a joint application to that Antarctic program and the appropriate logistical support would be forthcoming if the application was well-reviewed and supported. Where no collaborative partners are immediately available, it may be possible to find collaborators through the SCAR national representatives and proceed to a full collaborative relationship. In the case where no collaboration is appropriate, logistical input could be arranged between the US polar research program and the operations staff of the appropriate Antarctic program.

In summary, there is extensive international scientific interest in the broad-band seismic components of AntarcticArray. Both the Backbone Network and the successive deployments of sectors of the Evolving Regional Arrays are likely to attract international collaboration and logistical input from several of other nations with formal interests in Antarctica. It is important that the nature of this international collaboration and support be allowed to be flexible, in order to accommodate the range of operations and procedures of the various international Antarctic national programs.

5. Technical and Logistical Requirements

Each of the components of AntarcticArray faces significant technical challenges. The principal challenges can be reduced principally to power (particularly over-wintering power at remote sites), communications, and continued refinements in seismic instrumentation for increased autonomy and optimal performance at very cold temperatures. The needed improvements, however, should be understood as refinements built on the many years of seismic experience in Antarctica. A solid backbone network is already in existence, although instruments are located at permanent bases. There have also been several regional experiments (e.g., SEPA, ANUBIS, TAMSEIS, SSCUA, and other) that installed IRIS PASSCAL or similar broad-band instrumentation that operated remotely and autonomously year-round. These experiments established the baseline for over-wintering performance at remote sites. Six to eight months of continuous data can be returned using existing capabilities. The duration can be extended, as it has been at the Erebus network, where wind speeds are sufficient for wind power during the winter months. This may not be the case, however, in much of the continental interior. Experience gained from these regional experiments will be the basis for most of the components of AntarcticArray, as autonomous operation at remote sites far from over-wintering bases will be the operational mode for a significant number of proposed Backbone Network sites, the Evolving Regional Arrays, and the Process-Oriented Experiments.

In terms of power requirements, 5-10 W of continuous power are desired. Solar power is not available during the winter months and lack of wind on the Antarctic Plateau makes wind turbines unreliable. New, emerging battery technologies (such as NiCad) may offer significant performance enhancements in the cold. This combined with summer solar and winter wind (when available) will probably define the remote systems in the early operation of AntarcticArray. Eight months per year of recoverable data is sufficient to justify installation of remote stations. Stations need to power up and down smoothly as power comes and goes. New generation Autonomous Geophysical Observatories (AGOs), sites with propane and wind power and $\sim$70 W continuous power, may provide some remote locations with over-wintering capabilities if the AGOs are developed in the future. Further PI experimentation and experience with solar, wind, and batteries are needed.

In terms of communications, there is still no global Antarctic telecommunication capability. Remote stations may often need to operate in a record and store mode, with data becoming available only in summer months. The wait time for data is a problem for source characterization studies that often require real-time or near real-time data, but is not a severe limitation for structural studies. Some continuous communication capability would be useful to provide state-of-health information about the station. Operation and maintenance of remote stations is expensive, and this information would help schedule maintenance visits to utilize logistical resources efficiently.

Continued improvements in seismic sensors and robustness to extreme cold conditions is needed. Further testing of available broad-band sensors is required to identify potential problems and solutions. In particular, some sensors fail intermittently at temperatures of −30°C to −60°C, and this problem must be overcome so the sensor vault does not require additional power for heating. A data-logger that records to these temperatures is also necessary. There has been the general trend of decreasing power consumption in all components and the trend will probably need to continue in the future for over-wintering functioning to be made a reality.

The long-term operation and maintenance of the Backbone Network and the extended-term operation of the Evolving Regional Arrays and Process-Oriented Experiments will require flights into the field during the summer months with aircraft capable of near station landings. Deep field flights may require fuel caches at intermediate sites. Maximizing the autonomy of remote stations will reduce air time. The ability to recover data in burst-mode from deep field overflights of operating stations may also be a way to make optimal use of air time.

Data management, archival, and distribution will be coordinated through the IRIS DMC.

6. Synergism with Existing Facilities and Other Initiatives

Future seismic instrumentation in Antarctica should be developed in full association with the established and effective partnerships and facilities that have resulted in significant advancements in the field during the past several decades. The most relevant examples within the US are IRIS, USGS, and UNAVCO. Facility support that could be provided by these organizations would be extremely valuable in the success of AntarcticArray. The main benefits provided by a facility include centralized support to ensure that projects remain coordinated and on schedule, dedicated technical resources to meet operational challenges, data handling for safe storage and public dissemination, and a full time professional staff to meet the overall program objectives. For large scale initiatives in Antarctica, full time logistical and technical attention is imperative for success. A facility could handle much of the hardware installation directly, and provide hardware and installation specifications when other groups do installations. A facility would incorporate new and proven technology, as well as community experience to meet the program objectives. Collaborations with organizations such as IRIS, USGS, and UNAVCO also provide opportunities to share education and outreach efforts.

6.1 IRIS and USGS

The IRIS Consortium of over 100 research institutions has been an ubiquitous contributor to instrumentation and data archival developments during the past nearly 20 years. The IRIS Program for Array Seismic Studies of the ContinentAL Lithosphere (PASSCAL) and its Instrument Center at New Mexico Tech have significant experience with the deployment of portable instrumentation throughout the world, and in Antarctica, two notable recent examples being on Mount Erebus and across the Transantarctic Mountains (TAMSEIS). The IRIS Global Seismic Network (GSN), in association with the USGS and UC San Diego, is a leader in the deployment of permanent stations throughout the world, including South Pole instrumentation as discussed above. IRIS also operates the world's premier data management system (DMS) for seismology through its DMS program and Data Management Center in Seattle, associated with the University of Washington. Many of the required engineering tasks for AntarcticArray have, thus, already been addressed by IRIS and USGS supported experiments.

6.2 GPS

Co-location of GPS and seismic stations is desired across much of Antarctica. At solid rock installation sites, GPS observations provide complementary information on crustal deformation. At ice sites, they provide dynamical information about the motion of the ice sheet. In either case, the combined power of GPS and seismic observations is substantially greater than either observational modality alone. Examples of current U.S. based GPS projects with direct relevance to AntarcticArray include the West-Antarctica GPS Network (WAGN), Transantarctic Deformation Network (TAMDEF), Mt. Erebus deformation network, JPL continuous stations in the Transantarctic Mountains and Marie Byrd Land, and many ice sheet, ice stream, and ice shelf glaciology projects. There are also numerous foreign GPS efforts across the continent that should contribute to the planning or implementation of AntarcticArray.

UNAVCO is currently providing facility level GPS support for the EarthScope Plate Boundary Observatory. The GPS infrastructure is divided into permanent stations (875 stations from Southern California through Alaska) and campaigns (100 systems in a shared pool). The management plan is summarized here as an example of a facility centralized role in AntarcticArray GPS support.

Permanent stations. The operation of GPS stations, once installed, will be largely automated. Facility engineers will develop communications strategies whereby data are retrieved from stations and delivered to a GPS Seamless Archive Center (GSAC) facility for archiving and processing. All station metadata will be stored in a central database and kept up-to-date by facility staff. A single point of origin for GPS metadata is critical so that solution centers, project principal investigators, and others interested in processing GPS data have concurrent and reliable metadata. The process of updating station metadata will also be simplified by having consistent data entry and update forms and a single point of entry for updating station information. The single point of entry concept means that whenever a critical piece of equipment, such as an antenna or receiver, changes at a station the change propagates to all users of the data. Numerous organizations in the UNAVCO community, for example the Scripps Orbit and Permanent Array Center (SOPAC), the Southern California Integrated GPS Network (SCIGN), and the UNAVCO Facility, have implemented schemes for storing station site information and keeping it current. Once a station is declared operational, it is the job of the facility to oversee the quality and quantity of data flow from the network to the data archives. GPS stations will be monitored, and text and graphic-based reports that describe the status of network stations will be available over the web. The level of site monitoring would be based on the particular data flow methods used to meet the technical and logistical constraints on remote data collection in Antarctica. For stations with daily data telemetry, automatic software will check for both volume and quality. If any of these values exceed a critical threshold, an automated alert will go out to the appropriate distribution, identifying the station and what triggered the alert. Facility engineers and data technicians will try to troubleshoot the station remotely. Depending on season and location, site visits can be deferred until logistics permit. Once the site visit is made and the condition corrected, a maintenance report will be logged for all remote and field troubleshooting and repairs. Maintenance/data retrieval visits will be scheduled for all GPS stations as dictated by the specific data retrieval mechanism used and the need to service individual components, such as batteries. Replacement equipment will be tested by the facility prior to shipment to the field. The facility will provide board level repair for all GPS equipment. All seismic and GPS sites will use similar ancillary equipment (e.g. solar panels and communications equipment) so that maintenance crews can service equipment at both types of sites in the event that they are not all co-located.

Campaign GPS pool. The campaign receiver pool will facilitate PI-based research, rapid response to events such as changes in ice dynamics, earthquakes, and volcanic eruptions, regional scientific investigations, and operational requirements such as reference mark surveys for permanent stations. The facility provides equipment maintenance, plus training and engineering support. Campaign deployment plans would come from PI-based research proposals and/or AntarcticArray wide campaign initiatives. The campaign pool will be centrally managed and maintained by the facility. The facility will schedule the receivers to meet AntarcticArray science objectives and ensure the receivers and ancillary equipment are routinely maintained. The facility will also inventory, maintain, and quality check all campaign equipment prior to deployment, and provide services including training and engineers on request to support large campaigns and new investigators. Standardized campaign measurement and documentation procedures will be enforced to ensure unified and consistent data sets are collected. The facility will work with the community to determine prescribed monumentation for new sites, robust antenna set-up methods, and standardized field documentation - all critical for the integrity of campaign data. Electronic and hardcopy log sheets and site descriptions will be tailored to AntarcticArray, and data submittal procedures will be developed to specifically rapid data archival requirements.

6.3 IPY

Nations around the world are making plans for the International Polar Year (IPY) from 2007 to 2009: www.ipy.org. The IPY will address many questions from the solid earth, oceanic and atmospheric sciences that arise in polar areas. Previous IPYs (1882-1883, 1932-1933) and the International Geophysical Year (IGY, 1957-1958) opened new scientific opportunities and provided unprecedented exploration and discoveries in polar areas. The upcoming IPY will explore new scientific frontiers, particularly in the interplay between polar regions and global systems.

IPY provides an ideal setting for the early development of AntarcticArray, and AntarcticArray should be designed to initiate during the IPY. Conversely, AntarcticArray can help to optimize the scientific achievements produced as a result of the IPY. The goals of AntarcticArray, however, are larger in duration if not in scope than the IPY, and AntarcticArray is probably more like a decadal vision than something that can be completed in the two field seasons of IPY.

7. Education and Outreach

Antarctica, as the most remote place on the planet and because of its many unearthly physical attributes, holds a unique fascination and potential for advancing science education and outreach. Additionally, science E&O for Antarctica potentially benefits from its “extreme science” character. Because of this, first-hand experiences can be especially effective in conveying the excitement of Antarctic science exploration to a wide audience as, for example, in the NSF Teachers Experiencing the Arctic/Antarctic (TEA) program managed by Rice University (tea.rice.edu). Because of its continent-scale focus, AntarcticArray will provide an exceptional opportunity for such educator/scientist partnerships. Further association can be envisioned with the IRIS Education and Outreach program, the USGS, participating institutions, and other efforts. The recent initiation of the EarthScope facility and science program in the U.S. is also catalyzing new associations and a new level of ambitious planning in advancing the solid earth sciences from the public through to the educational establishments. This bodes well for the continued advancement and increasing critical mass of partnership efforts for AntarcticArray.

Appendix A

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Appendix B

March 03 **Monday AM (Mike Ritzwoller, Doug Wiens)**

7:30	-	…	Continental Breakfast in the Foyer outside the Columbine/Balsam Room		
Introduction and Welcome					
8:30	-	8:50	Mike Ritzwoller	University of Colorado at Boulder	Welcome to SEAP 2003
8:50	-	9:05	Terry Wilson	Ohio State University	New Frontiers in Antarctic Geoscience
The Big Picture					
9:05	-	9:35	Ian Dalziel	University of Texas at Austin	Tectonic Framework of Antarctica
9:35	-	9:55	Andrew Nyblade	Penn State University	Constraining Upper Mantle Thermal Anomalies Using Seismic Methods
9:55	-	10:15	Tim Stern	Institute of Geophysics, Victoria University of Wellington	Mountain Uplift and Related Processes in Antarctica
10:15	-	10:35	Sridhar Anandakrishnan	Penn State University	Challenges for Collecting High Quality Geophysical Data in Antarctica
10:35	-	10:55	Break and Poster Viewing		
Earth Structure: Crust to Core					
10:55	-	11:15	Nikolai Shapiro	University of Colorado at Boulder	The Antarctic Upper Mantle: Recent Advances and Future Challenges Using Surface Waves
11:15	-	11:30	J.P. Montagner	Institut de Physique du Globe	Anisotropic Seismology in Antarctica
11:30	-	11:45	Mike Wysession	Washington University	Investigating the Deep Earth with Antarctic Seismometers
11:45	-	12:00	Xiaodong Song	University of Illinois at Urbana-Champaign	The Antarctic Array: Implications for Studies of Earth's Core and Deep Mantle
12:00	-	1:30	Lunch and Poster Viewing		
			Monday PM (Don Blankenship, Sridhar Anandakrishnan)		
Contact with Icesheet Dynamics/Climate Rebound					
1:30	-	2:00	Slawek Tulaczyk	University of California, Santa Cruz	What Lies Beneath an Ocean of Ice? How Lithospheric and Crustal Structure of Antarctica Influence Ice-Sheet Behavior
2:00	-	2:30	Rob Deconto	University of Massachusetts	Coupled Climate – Ice Sheet Modeling of the Ancient Antarctic Environment
2:30	-	2:45	Andy Smith	British Antarctic Survey	Active Sources and Glaciology
2:45	-	3:00	John Wahr	University of Colorado at Boulder	Isostatic Rebound Caused by Antarctic Deglaciation
3:00	-	3:15	Shijie Zhong	University of Colorado at Boulder	Mantle Seismic and Viscosity Structures and Post-Glacial Rebound

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3:15	-	3:30	Break and Poster Viewing
First Working Group Meeting			
3:30	-	5:00	Continental Network/Leap-Frogging Array(s) (Brian Kennett, Arthur Lerner-Lam) - Executive Room (24)
			Interdisciplinary Process-Oriented Experiments (Andrew Nyblade, Ian Dalziel) - Alpine Room (25)
			Technical Challenges (James Fowler, Bjorn Johns) - Porch Room (34)
			Icesheet Dynamics/Climate (Slawek Tulacyzk, Shijie Zhong) - Driftwood Room (25)
First International Collaboration Working Group Meeting			
5:00	-	6:00	Anya Reading, Andrea Moreilli
6:30	-	…	Banquet Dinner at Trios

March 04 **Tuesday AM (Rick Aster, Mike Ritzwoller)**

7:30	-	…	Continental Breakfast in the Foyer outside the Columbine/Balsam Room		
Volcanos and Earthquakes					
8:30	-	8:45	Shamita Das	University of Oxford	Intraplate Stresses Inferred from the Mw 8.1 1998 Antarctic Plate Earthquake
8:45	-	9:00	Steve Bannister	Institute of Geological and Nuclear Sciences, New Zealand	Icequakes or Earthquakes?
9:00	-	9:15	Carol Finn	U.S. Geological Survey	Linking Crust and Mantle: The Origin of Cenozoic Alkali Magmatism in the Southwest Pacific
Marine Geophysics/Margins					
9:15	-	9:30	Rob Larter	British Antarctic Survey	Tectonic Evolution of the Pacific Margin of Antarctica Since 100 Ma
9:30	-	9:45	Lawrence Lawver	Institute for Geophysics, UT Austin	Edge Effects: Tectonic Evolution of the Antarctic Margins
9:45	-	10:00	Joann Stock	California Institute of Technology	Tertiary Seafloor Spreading Between East and West Antarctica and Implications for Antarctic Lithospheric Structure
10:00	-	10:15	Roy Livermore	British Antarctic Survey	Drake Passage and the Scotia Sea
10:15	-	10:30	Break and Poster Viewing		
Previous Seismic Experiments Around Antarctica					
10:30	-	10:45	Jean-Jacques Leveque	IPG Strasbourg	A New Permanent Seismic Observatory in Antarctica: The Concordia Station at Dome C
10:45	-	11:00	Mike Studinger	Lamont-Doherty Earth Observatory	Geological Framework of Lake Vostok, East Antarctica
11:00	-	11:15	Doug Wiens	Washington University	The Trans-Antarctic Mountains Seismic Experiment (TAMSEIS): A Prototype for Large-Scale Broadband Deployment in Antarctica

11:15	-	11:30	Rick Aster	New Mexico Institute of Mining and Technology	Interdisciplinary Year-Round and Real-Time Geophysical Data From Mount Erebus
Synergistic Methods					
11:30	-	11:45	Kazuo Shibuya	National Institute of Polar Research, Japan	Current and Future Plans of the JARE Earth Science Programs and the Seismic Instrumentation Development for Antarctic Research
11:45	-	12:00	Anya Reading	Australian National University	East Antarctica: New Tectonic Models and New Targets
12:00	-	1:30	Lunch and Poster Viewing		
			Tuesday PM (Doug Wiens, Don Blankenship)		
1:30	-	1:45	Andrea Donellan	Jet Propulsion Laboratory	GPS Evidence for a Coherent Antarctic Plate and for Postglacial Rebound in Marie Byrd Land and the Northern Transantarctics
1:45	-	2:00	Don Blankenship	University of Texas at Austin	Investigating the Crustal Elements of the Antarctic Plate with Airborne Radar Sounding
2:00	-	2:15	Garry Karner	Lamont-Doherty Earth Observatory	Paradoxical Gravity Anomalies of the Ross Sea, Antarctica
2:15	-	2:30	John Brozena	Naval Research Lab	Long-Range Aerogeophysical Surveys in Antarctica
2:30	-	2:45	Phil Wannamaker	University of Utah	Thermal Regimes and Architecture of the Crust and Upper Mantle Inferred from Electrical Conductivity Investigations
Model Programs					
2:45	-	3:00	Don Forsyth	Brown University	Proposed NSF Initiative in Oceanic Mantle Dynamics
3:00	-	3:15	Brian Kennett	Australian National University	Determining the Seismic Structure of a Continent – Lessons from Australia
3:15	-	3:30	Break and Poster Viewing		
Second Working Group Meeting					
3:30	-	5:00	Continental Network/Leap-Frogging Array(s) (Brian Kennett, Arthur Lerner-Lam) - Executive Room (24)		
			Interdisciplinary Process-Oriented Experiments (Andrew Nyblade, Ian Dalziel) - Alpine Room (25)		
			Technical Challenges (James Fowler, Bjorn Johns) - Porch Room (34)		
			Icesheet Dynamics/Climate (Slawek Tulacyzk, Shijie Zhong) - Driftwood Room (25)		
Second International Collaboration Working Group Meeting					
5:00	-	6:00	Anya Reading, Andrea Morelli		
6:00	-	7:30	Break - Dinner		
7:30	-	…	Community Forum: Umbrella Initiative for Geosciences? (Terry Wilson)		

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March 05 **Wednesday AM (Sridhar Anandakrishnan, Mike Ritzwoller)**

7:30	-	…	Continental Breakfast in the Foyer outside the Columbine/Balsam Room		
8:30	-	8:45	Opening Remarks		
8:45	-	9:00	Robin Bell	LDEO	International Polar Year
Logistics and Operations					
9:00	-	9:15	Rhett Butler	IRIS	The Global Seismographic Network in Antarctica
9:15	-	9:30	Scott Borg	NSF/OPP	USAP Science Support Capabilities and Possibilities
9:30	-	9:45	Chuck Meertens	UNAVCO	UNAVCO Experiences from Large Instrumentation Initiatives, Operation of a Multi-Agency Technical Support Facility, and Multi-Disciplinary Support to the U.S. Antarctic Program
Reports from Workshop Chairs					
9:45	-	10:05	Technical Challenges (James Fowler, Bjorn Johns)		
10:05	-	10:25	Backbone Network, Leap-Frogging Array (Brian Kennett, Arthur Lerner-Lam		
10:25	-	10:40	Break		
10:40	-	11:00	Glaciology/Climate (Slawek Tulascyk, Shijie Zhong)		
11:00	-	11:20	Process-Oriented Experiments (Andrew Nyblade, Ian Dalziel)		
11:20	-	11:40	International Collaboration (Anya Reading, Andrea Morelli)		
11:40	-	12:00	Closing Remarks		
12:00			Meeting Adjourns		
			Wednesday PM		
1:30	-	3:00	Organizing Committee and Working Group Chairs Meet to Design the Science Plan		
			Organizing Committee: Anandakrishnan, Aster, Blankenship, Ritzwoller, Wiens		
			Working Group Chairs: Dalziel, Fowler, Johns, Kennett, Lerner-Lam, Morelli, Nyblade, Reading, Tulascyk, Zhong		

Antarctic
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