2015 Global Seismographic Network Review

Briefing Book

2015 Global Seismographic Network Review

Briefing Book

PREPARED BY
IRIS GSN Program Management
UCSD Project IDA
USGS Albuquerque Seismological Laboratory

February 2015

Contents

1.0 Introduction

This document summarizes the current state and organization of the Global Seismographic Network (GSN) and plans for the future. It is provided as one element of the comprehensive review of the GSN being carried out as part of the Cooperative Agreement between the Incorporated Research Institutions for Seismology (IRIS) and the National Science Foundation (NSF) under the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) award.

IRIS operates the Global Seismographic Network as part of the SAGE award. The GSN has been one of IRIS' "core programs" since 1986, having been part of all IRIS' previous Cooperative Agreements with NSF. The size, scope, widely recognized quality, and worldwide utilization of the GSN have been a large part of the overall IRIS success story and have driven major scientific advancements in the Earth sciences. IRIS, NSF, and the United States Geological Survey (USGS) cooperate to jointly manage this program. The USGS Albuquerque Seismological Laboratory (ASL), Project IDA (International Deployment of Accelerometers) at the University of California, San Diego (UCSD), and other affiliate organizations operate GSN stations. The teams at ASL and IDA have a long-standing expertise in the deployment, operation, and maintenance of high-quality seismometer installations, and their participation in this project has been a major part of its success.

IRIS has been supported for over 30 years by the NSF, which has provided scientific peer review of the IRIS programs and funding through a series of multiyear awards. Operating as a not-for-profit consortium of 122 universities and research institutions across the United States as well as 126 international affiliate institutions, IRIS has facilitated and embraced a commitment to high-quality instrumentation, data access and sharing, and data services that now underlie much of the research in seismology and solid Earth sciences in the United States and in many parts of the world. Designed as a community organization, IRIS is governed by its consortium members to manage prominent infrastructure resources to support academic research in seismology.

IRIS activities comprise a wide range of programs and projects managed by its staff for the community. The success of community-governed, professionally managed facilities such as the GSN has been demonstrated by the enormous use of facility instruments and data and the wide-ranging scientific research these facilities have enabled.

External reviews are a key component of IRIS. The GSN was the first program of IRIS to participate in an external review, completed in 2003. Since that time, all other IRIS programs, as well as the management structure, have been reviewed. This is the second review of the GSN. As a result of the first review, many changes, such as standardized next generation data loggers, were implemented based on the recommendations of the review panel, and they have improved the performance of the network and the efficiency of the operations and management structures of the network. The current review (see Appendix A for Charge to the Review Committee), more than a decade following the first, provides an opportunity to ensure that the network continues to deliver the high-quality data required to drive cutting-edge science, to pioneer modern approaches to geohazards study and mitigation and earthquake and explosion monitoring, and to remain a trusted reference for global seismological observations and a standard for data quality.

2.0 Overview

The Global Seismographic Network is a 153 station global network of state-of-the-art seismic observatories (**Figure 2.0**) distributed worldwide and operated by IRIS and the USGS, with funding from the NSF and the USGS. GSN stations attempt to obtain seismic data of the best possible quality, balanced with global geographic coverage. GSN sites are a mix of deep (100 m) boreholes and subsurface vaults. The stations have very broadband instruments that record from a period of many thousands of seconds up to at least 20 Hz, and use a combination of very high gain (weak motion) and low gain (strong motion) sensors to record on scale over a wide range of shaking.

The GSN is designed to provide robust, uniform, high-quality, very broadband, high-dynamic-range recording. It has long been a gold standard for the operation of other global, national, and regional seismographic networks whose stations help to fill in regions not covered by the GSN. It delivers continuous data in real time, the data are archived with their metadata, and these data are freely and openly accessible to all. The GSN has operated since 1988 and provides valuable long-term observations of Earth processes as well as observations of infrequent but exceptional events such as great earthquakes. It also provides valuable long-term observations of Earth processes.

The GSN is managed and operated using a unique model. IRIS, with funding from the NSF manages the IRIS component of the GSN and organizes the GSN Standing Committee; the USGS manages the USGS component of the GSN. IRIS and the USGS coordinate activities, and the GSN Standing Committee acts as a joint external advisory committee to both organizations. GSN operations consists of three components. IRIS contracts to Project IDA at the University of California, San Diego, to operate 41 stations. The USGS operates another ~100 stations through its Albuquerque Seismological Laboratory, with funding through a separate line item in the Department of Interior/USGS budget structure. The remaining 12 stations make up the "affiliated station" component of the network. These stations meet GSN's design standards, but funding for operations is provided from other sources.

This dual operator model of network operation allows the GSN to pursue a variety of international partnerships, both with government and private organizations. These organizations can, based on their situation and requirements,

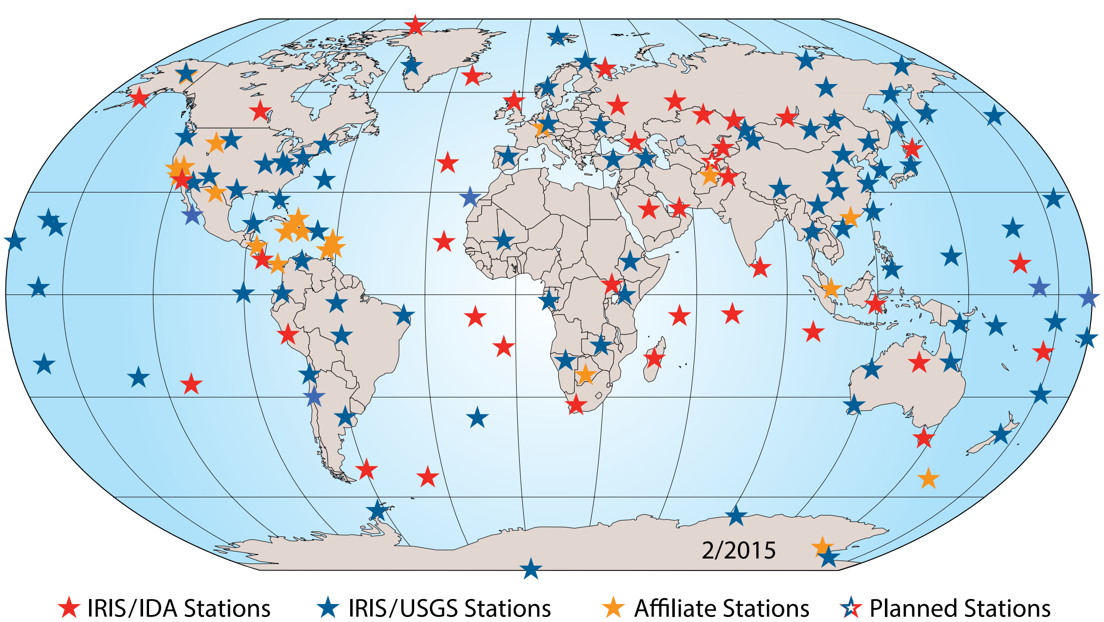


Figure 2.0. The Global Seismographic Network as of February 2015. Coverage provided by the IRIS/IDA and IRIS/USGS portions of the network are shown, as are the affiliate stations.

either work directly with the US government via the IRIS/USGS network operator, or work with an academic-based partner, via the IRIS/IDA network operator. The current station distribution has been optimized to take full advantage of the dual network operator model, while ensuring that many of the decades-long relationships between operators and hosts are maintained, and stable operations are sustained. Further, the operating model encourages a robust evolution of technology and network operations best practices, with both groups working toward the most efficient technical developments and then sharing ideas to achieve standardized operations (a major recommendation from the previous GSN review).

This document provides an overview of the current state and organization of the GSN and plans for the future. Section 3 details GSN design goals in the context of the network's current structure and objectives. Section 4 reviews the current GSN structure and its operational aspects. Section 5 highlights several research and operational applications of GSN data. Section 6 reviews GSN efforts to ensure and maximize data quality. Section 7 describes operational strategies to ensure the resilience of the GSN. Section 8 describes activities and objectives related to GSN renewal. Section 9 describes the management and governance structure of the GSN.

3.0 Design Goals

GSN design goals were originally articulated in the GSN Science Plan (IRIS, 1984) and updated in 2002 (see Appendix B, GSN ad hoc Design Goals Subcommittee, 2002). They were motivated by the science objectives defined for the GSN by the user community. In most respects, the design goals have been met; quantitative assessment of data quality and efforts to meet remaining design goals currently motivates several aspects of GSN operations and maintenance.

In the GSN Science Plan, the technical characteristics of the future GSN were stated as:

- ~100 three-component stations
- Broadband observing, from periods of hours to a frequency of ~10 Hz
- High dynamic range sufficient to resolve ground noise and to record large teleseismic signals (> 120 dB)
- Low-noise instrumentation and environment
- Real-time telemetry

The design goals for the GSN were revisited in 2002. The central design goal for the GSN instrumentation is summarized in the 2002 design goals document:

> *The driving motivation for the GSN has been to record with full fidelity and bandwidth all seismic signals above the Earth noise, accompanied by some efforts to reduce Earth noise by deployment strategies.*

The specific technical design goals have been met. All GSN stations have three-component sensors and provide observations (see **Figure 3.0**) across a wide frequency spectrum and dynamic range (a suite of sensors is used to achieve these goals). All but two stations now have real-time telemetry.

The broad coverage goal of the GSN is ~20 degree station spacing across the entire globe. This goal has largely been met on land. To uniformly cover the entire planet requires stations in the ocean basins, but this coverage has not yet been fully realized (see further discussion in Sections 4.1 and 4.5). Some sites in ocean regions have had to compromise on site noise characteristics to bring the GSN closer to global coverage (e.g., oceanic island stations; see Section 4.1).

Over the years many of the GSN's design goals have been adopted as de facto global standards and have significantly influenced manufacturer and supplier developments.

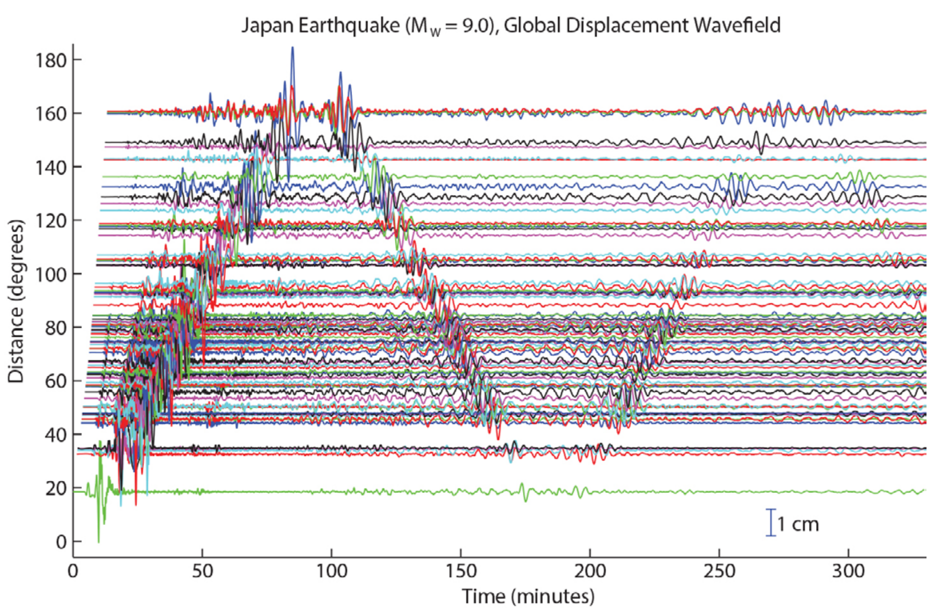


Figure 3.0. Record section from the GSN for the 2011 Tohoku-Oki earthquake. Note the on-scale traces at GSN stations, from the first arrivals to beyond R4, with nearly uniform distance coverage from 20–160 degrees. Stations closer than 20 degrees are not included because their broadband records are saturated (though the strong motion records are on scale). *Courtesy of Rick Aster*

4.0 The GSN Today

4.1 Network Configuration, Coverage, and Capabilities

COVERAGE

Figure 4.1-1 shows the current density of GSN coverage. The location of several other major international networks was factored into the siting of GSN stations. All of these networks together comprise the international Federation of Digital Seismograph Networks (FDSN). GSN contributes its entire 153 station network to the 206 station FDSN backbone (**Figure 4.1-2**). FDSN Working Group I is charged with coordinating the siting and instrumentation for this global backbone of high-quality seismic stations. The GSN has largely met its initial coverage goal of station spacing at ~20 degrees on land. The ocean basins still lack sufficient coverage (see Section 4.5).

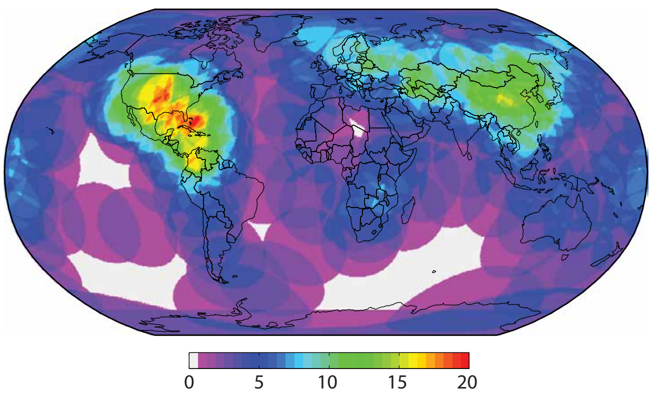


Figure 4.1-1. GSN station coverage as represented through geographical density of stations. Contoured values show the number of stations within 20 degrees of each point on the map. Only GSN stations are used, which includes the IRIS/IDA and IRIS/USGS networks and affiliate stations.

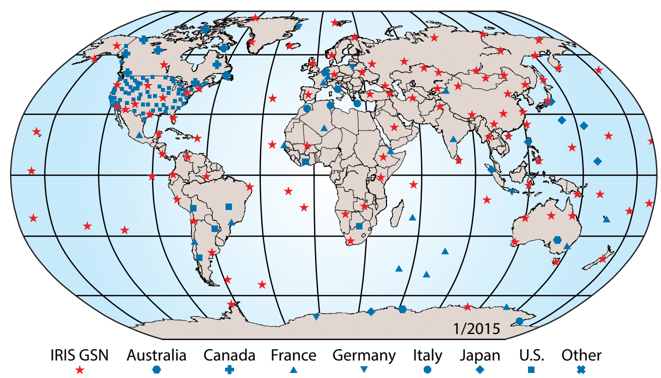


Figure 4.1-2. Map showing the GSN and other stations of the international Federation of Digital Seismograph Networks (FDSN) backbone network.

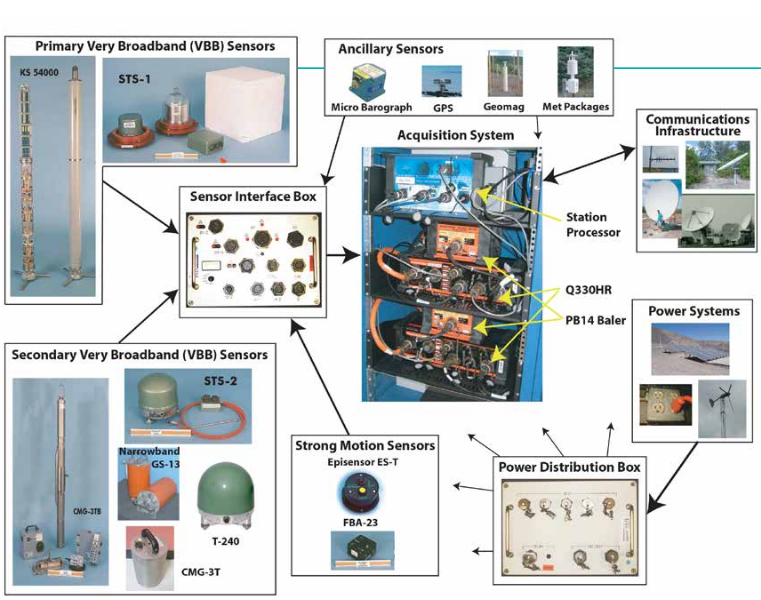


Figure 4.1-3. Instrumentation used at GSN stations. The upgrade of data loggers at GSN sites to the Quanterra Q330HR is nearly complete, marking the conversion of the GSN to "next generation" systems.

INSTRUMENTATION

The GSN uses multiple sensors to meet the broadband and high dynamic range design goals. **Figure 4.1-3** shows the entire suite of current GSN instrumentation. A major development in the evolution of GSN instrumentation has been the concept of primary and secondary sensors. The primary sensor, as the name implies, is the central sensor at a GSN site—it has the greatest bandwidth and is installed in a manner that provides the greatest reduction in noise, particularly in the ultra-long period band. The secondary sensors were initially deployed to extend the short period performance of the GSN stations to better aid in discrimination studies for nuclear test verification (funded by an augmentation from the DoD). As the technology of broadband sensors advanced, the secondary sensor provided

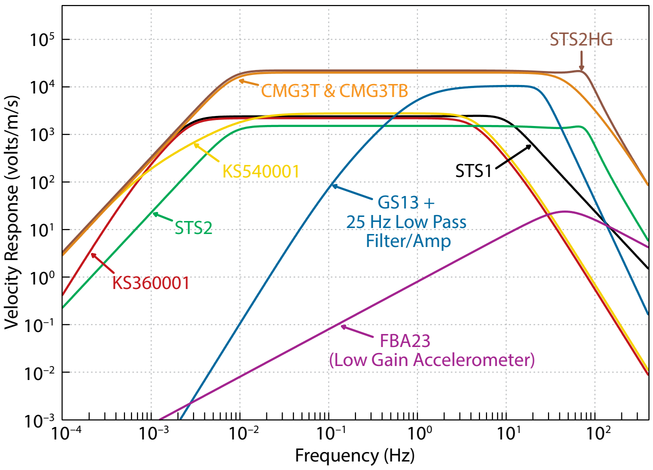


Figure 4.1-4. Amplitude response to ground velocity for sensors used in GSN stations. Note that these are responses only for sensors and do not show the effect of the anti-aliasing filters used in the data loggers.

some redundancy in bandwidth relative to the primary sensor, though with less sensitivity at the longest periods relative to the primary sensor. The secondary sensor may be installed in a lower-cost manner (e.g., if the primary sensor is in a 100 m borehole, the secondary sensor may be in a simple surface vault or shallow hole). The secondary sensor itself typically costs less than the primary sensor. However, as the response curves in **Figure 4.1-4** make clear, the secondary sensors provide some level of broadband performance for GSN stations. Thus, the secondary sensors provide some degree of backup when primary sensors have failed and funding has not allowed for repair or replacement. Although such situations are not ideal, it does allow operation at a reduced level of capability while the primary sensor issues are solved.

The GSN seismic sensor suite also includes strong motion sensors to extend the dynamic range of GSN stations. When large events are relatively close, records from the primary and secondary sensors may be clipped. The strong motion instruments have provided full dynamic range measurements on several great earthquakes. **Figure 4.1-5** illustrates this GSN station capability. All GSN sites can record to below local background noise over the frequency band of 20 Hz to hundreds of seconds.

The GSN also includes non-seismic sensors that may enhance station operation or may simply use the GSN as an observatory platform to extend global observations of other geophysical sensors. State-of-Health (SOH) transducers include internal temperature, humidity, and barometric pressure, as well as other measurements of seismometer- and acquisition-specific metrics (e.g., voltages, mass positions). Other geophysical sensors include microbarographs (now at most GSN stations), co-located GPS observatories, and geomagnetic transducers, and with current funding, the GSN is looking to add infrasound sensors to several GSN stations.

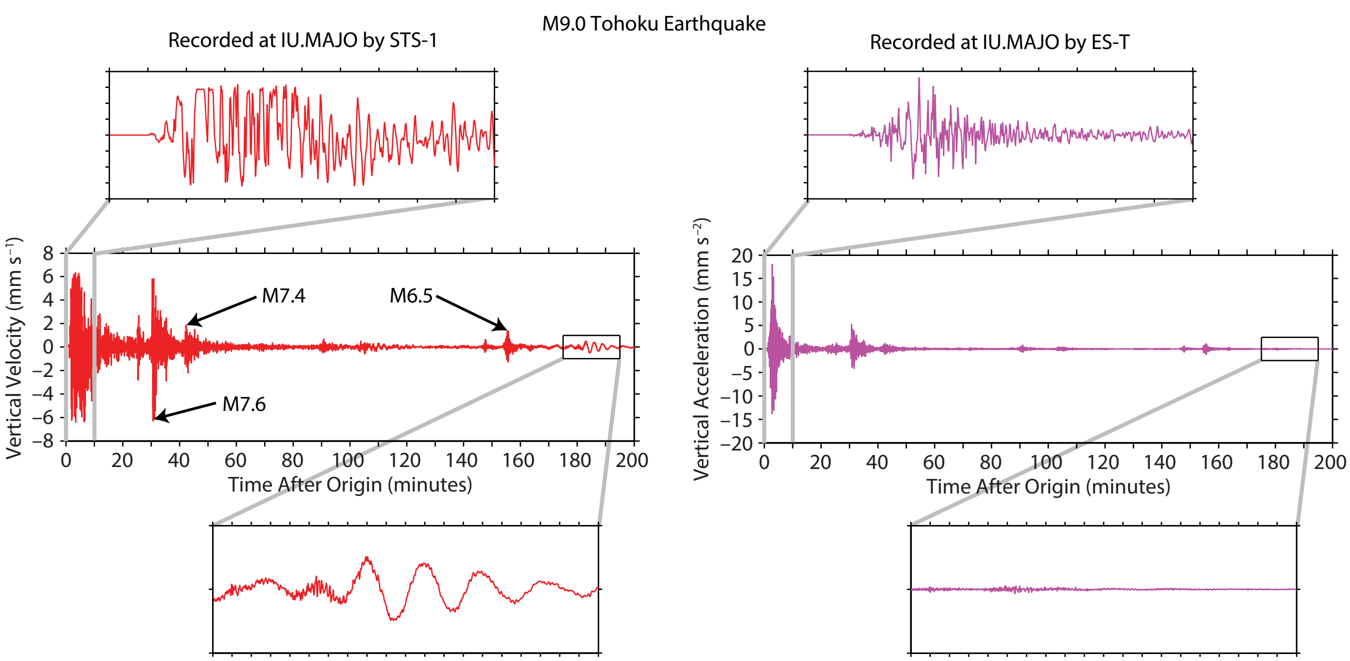


Figure 4.1-5. GSN station MAJO (Matsushiro, Japan) is located less than 4 degrees from the rupture zone of the M9.0, March 11, 2011 Tohoku-Oki earthquake. It contains a STS-1 primary seismometer, STS-2 secondary seismometer, and ES-T accelerometer. These waveforms demonstrate the extremely wide dynamic range of recording provided by GSN stations. Enlarged sections show that the initial arrivals were clipped on the seismometers, but well recorded by the strong motion sensor. Additionally, the R2-arrival of the surface waves can be clearly seen on scale at ~180 minutes on the STS-1, illustrating the capability of GSN stations to record both strong and weak motion. Numerous large aftershocks are also visible.

Over that past seven years, the GSN has been upgrading to standardized systems based on the Quanterra Q300HR high-resolution data acquisition system (DAS). This new system specification was developed by the IRIS community with input from the network operators and the GSN Standing Committee to ensure the GSN design goals could be met or surpassed with the new system. The new DAS records to 26 bits and allows for remote calibrations and lower power operations, improving operational efficiency and dynamic range. Funding for the upgrade was greatly enhanced by the American Recovery and Reinvestment Act of 2009 (ARRA) and NSF augmentations, and the rollout is virtually complete. More information on the GSN upgrade is presented in Section 4.4.

All GSN stations use GPS timing, with disciplined local clocks that can maintain a reasonable level of timing accuracy in the event of the loss of GPS signal. Acceptance testing of the current generation of data loggers found timing errors (registration between the external time signal and the internal time tagging of samples) of less than 3 microseconds for the 20 samples per second channel.

INSTALLATION

The GSN uses a wide range of site installations (**Figure 4.1-6**), but in each case, the site is designed to achieve the lowest noise possible under the circumstances. However, as noted in the 2002 *Design Goals Update* (Appendix B), "The primary limitations at many GSN stations at this time are site noise related. Despite extensive effort, political and logistical situations have resulted in some GSN stations being located in noisy environments." Most sites are either 100 m steel-cased boreholes or are in vaults that have been tunneled underground (either purpose-built for seismic sensors or for other objectives, such as mining). Some vaults are "surface style vaults," with a building at the surface and a vault on bedrock at the foundation of the building. In virtually all cases, the vault installations have a large concrete pier, typically isolated from the floor, upon which the primary sensors are placed. Some site locations date from the WWSSN era or before. However, most sites were purpose-built for the GSN, with the majority of sites installed in the 1980s, including 21 of 41 IRIS/IDA (II) stations. Many sites are now nearly 30 years old and require investment in civil works at the site to keep the stations in good condition (see further discussion in Section 8).

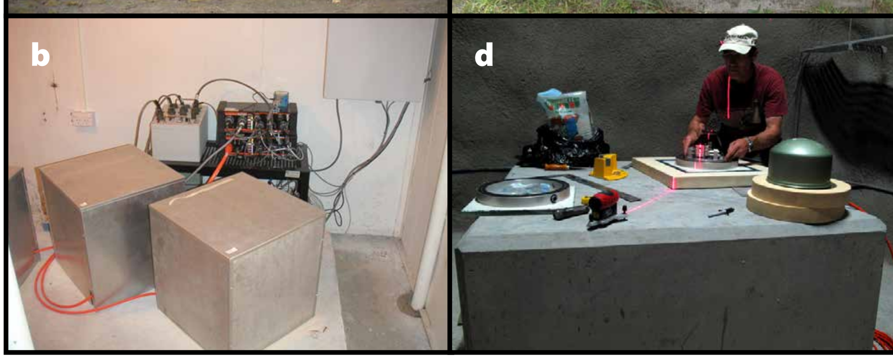


Figure 4.1-6. Typical GSN station installations. (a) Entrance to an underground vault (TAU, Tasmania); (b) instruments on pier (under square insulating covers) (also TAU); (c) equipment hut on top of well head at a borehole station (MSEY, Seychelles); (d) instrument pier in a tunnel vault (UOSS, United Arab Emirates); and (e) equipment building and solar panel array at a borehole site (EFI, Falkland Islands).

COMMUNICATIONS AND DATA FLOW

Although GSN telemetry was initially developed on a station-by-station basis as Internet, VSAT, and other global remote telemetry capabilities evolved, the network has maintained a diverse telemetry topology, both to reduce costs and increase reliability. The GSN lowers the overall cost of telemetry by taking advantage of "free" telemetry (i.e., local Internet Service Providers or host-facilitated long-haul telemetry). Over half of the network benefits from no- to minimal-cost telemetry. The GSN's diverse telemetry structure minimizes single-point-of-failure modes that could occur if the telemetry were all handled through a primary telemetry provider. At present, all but two GSN stations (ABKT in Alibek, Turkmenistan, and NRIL in Norilsk, Russia) transmit their data in near-real time. Both sites are considered closed due to political issues, and IRIS GSN management is working to relocate the sites. Station ALE has limited telemetry due to its presence on a Canadian military base, and IRIS is exploring an Iridium solution based on experience gained on other IRIS polar projects. The actual on-site communications typically use either a direct Internet connection, when available, a radio link to an Internet point-of-presence, or satellite telemetry directly from the station.

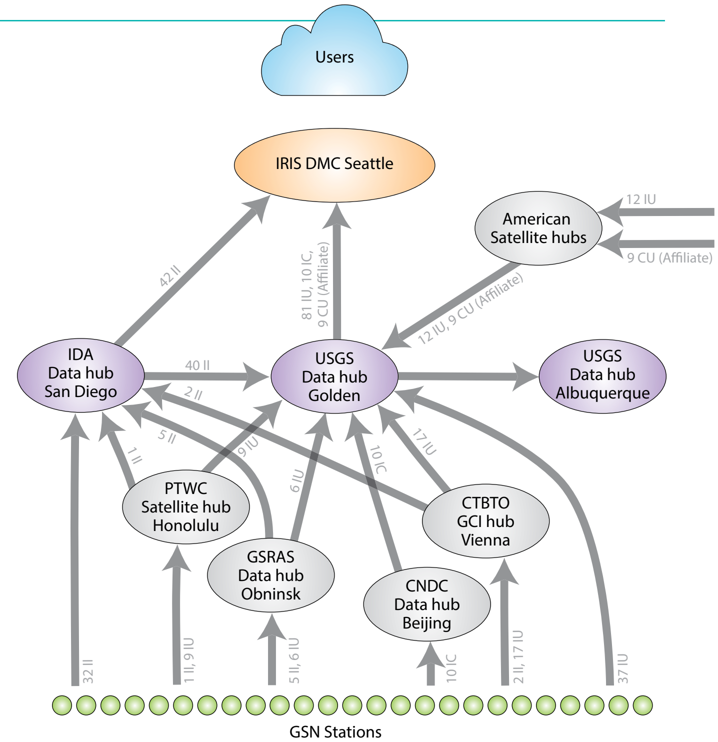


Figure 4.1-7. Data flow from stations to the IRIS Data Management Center and users. Multiple paths and technologies are used, based on availability and cost. In some cases, data flow is to or through key upstream data users who provide communications cost-sharing.

Figure 4.1-7 illustrates the data flow from GSN stations to the IRIS Data Management Center (DMC). Some of the data flow through the Pacific Tsunami Warning Center (PTWC) or Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) data hubs on their way to the DMC. The CTBTO Global Communications Infrastructure (GCI) provides a full communications link (at no cost to the GSN) for 19 GSN stations as well as redundant telemetry to another seven that are all part of the CTBTO's International Monitoring System's Auxiliary Seismic Network. This telemetry topology is a direct result of the multiple uses of the GSN, with data that fulfill both the needs of the research community and mission requirements for earthquake hazard monitoring, nuclear test-ban monitoring, and tsunami warning.

Whether data flow directly from the station or through an intermediate hub, they then flow through one of two Data Collection Centers (DCCs) on their way into the IRIS DMC. While GSN network operations are funded through the IRIS and USGS GSN programs, the DCCs at the ASL and at UCSD are part of IRIS Data Services, and in the case of the UCSD DCC, funded by IRIS. The DCCs focus on data delivery to the DMC, providing and maintaining correct metadata for GSN stations, quality assurance of the data from the stations ASL and IDA operate, and addressing circumstances that require special data handling, such as backfilling following telemetry outages. DCC staff also provide direct feedback on data quality and problems discovered to the network operations staff. The segregation of duties between DCCs and field operations has proven important to the success of the GSN, as it provides an equal emphasis to field operations and data collection/delivery.

The DCC operated by UCSD handles data from the IRIS/IDA stations. GSN data from UCSD are transmitted using *ISI* protocol to a system at the DMC. The DMC system draws UCSD data into its real-time system using the *SeedLink* protocol. The USGS operates the ASL DCC and manages the USGS data. Data from the USGS portion of the GSN are transmitted to the IRIS DMC using a USGS communications protocol called *RTP*. These data come directly to the DMC from the National Earthquake Information Center (NEIC) in Golden, Colorado. Both UCSD and ASL DCCs send a quality-controlled version of the data to the DMC about one day behind real time. These quality-controlled data replace the real-time data delivered to users in a seamless manner, as they become available.

PERFORMANCE

GSN performance can be measured in a variety of ways. Historically, the GSN was held to a Government Performance and Results Act (GPRA) goal of having 80% of the expected data available at the IRIS DMC. **Figure 4.1-8** shows the availability of the primary and secondary sensors over the past 10 years. Prior to the upgrade of the GSN to the next generation systems, which has been occurring since 2007, data availability just met the targets, with network averages in the low 80% range. Since the upgrades (including improved data acquisition systems, sensors, infrastructure, and telemetry), the data availability metric has improved to around 90%. Note that prior to the upgrades, the primary sensors tended to outperform the secondary sensors in terms of data availability. However, the secondary sensors are now often outperforming the primaries as a result of the continued aging of the primary sensor fleet and the upgrading of secondary sensors that was part of the recent upgrade efforts. This highlights the need to replenish and reinstall the primary sensors in the network (discussed further in subsequent sections).

With a revamping of the GSN Quality Assurance System (discussed in Section 6), the community has looked to extend performance metrics beyond just data availability. For the SAGE award, a "calibration completions" quality metric has been added to ensure that the GSN stations are regularly calibrated and the metadata are updated accordingly. This metric is also set at 80% of the network to be calibrated annually, and our current performance is nearly 90%; some stations are still not totally accessible for calibration purposes.

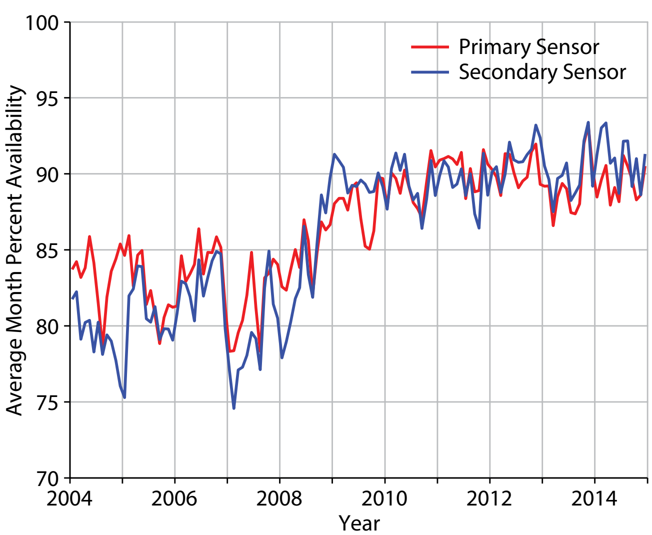


Figure 4.1-8. Plot of monthly GSN data availability for primary (red) and secondary (blue) seismometers. The overall improvement in network performance, beginning in 2008, is driven by the next generation data logger upgrades and other station and instrument refurbishments.

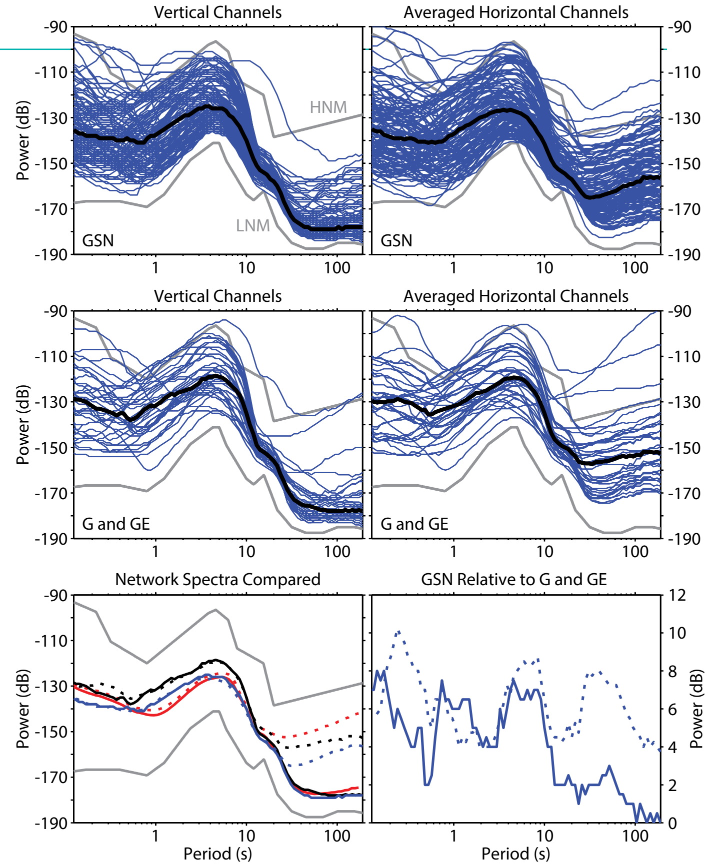


Figure 4.1-9. Median power spectral density measurements (8 Hz to 190 seconds) for 137 GSN stations (first row) and 36 G and GE stations (second row) for 2013-2014 (verticals on left, averaged horizontals on right). For GSN stations with malfunctioning primary sensors during this period, secondary sensor spectra are substituted. The bold black line represents the "median of the medians", characterizing unweighted aggregate performance. The bottom left plot shows medians for the GSN (blue-vertical solid, horizontal dashed), G and GE (black-vertical solid, horizontal dashed), and similar spectral means for the TA (red-vertical solid, horizontal dashed). For the verticals at long periods, most network performance is similar. The spectral medians of short and long period horizontals on the GSN are considerably lower than equivalent G and GE medians. The bottom right plot illustrates this difference; the GSN performs 4-8 dB better for horizontal channels and 2-8 dB better on vertical channels compared to G and GE stations.

Other performance measures can be observed by plotting the median power spectra of the network, which provides insights into station noise levels, potential signal-to-noise levels for predicted events, and relative performance between similar networks. **Figure 4.1-9** compares the spectral performance of the GSN relative to the GEOSCOPE (G) and GEOFON (GE) global networks, as well as the EarthScope Transportable Array (TA). The GSN clearly outperforms these networks on both the vertical and horizontal channel noise levels, especially at long periods. The GSN's superior performance is testament to the investment made in ultra low noise installations (boreholes and deep vaults) and provides a significant improvement in signal detection capabilities across a wide spectrum.

4.2 Data Distribution and Archiving

All GSN data are freely and openly available, and most stations provide continuous data in near-real time. Since its inception, the GSN has archived all of its data in the internationally accepted Standard for the Exchange of Earthquake Data (SEED) format. These data are accompanied by all necessary metadata. All GSN data are archived and distributed by the IRIS DMC, which is part of IRIS Data Services.

The DMC archives approximately 2.7 terabytes of GSN data per year (**Figure 4.2-1**). A total volume of 26.8 terabytes of GSN data are available. All GSN data flow into the DMC via the GSN DCCs. The DMC supports multiple methods for receiving data.

The IRIS DMC supports three primary methods of distributing data to end-users: (1) real-time data through *SeedLink*, (2) traditional requests through email-based methods and a few Web applications, and (3) Web services, a method that seamlessly supports direct data-to-client applications. **Table 4.2-1** summarizes the various tools. All GSN data transmitted from the DMC in near-real time are currently sent using *SeedLink* protocol.

The DMC distributed roughly 200 terabytes of GSN data in 2014 (**Figure 4.2-2**) to a broad user community, with over 52% shipped to international users—a strong indication of the breadth of GSN usage. Of the data held in the DMC archive, the GSN data set is by far the most requested and the "out to in" data volume ratio is nearly a factor of seven (**Figure 4.2-3**).

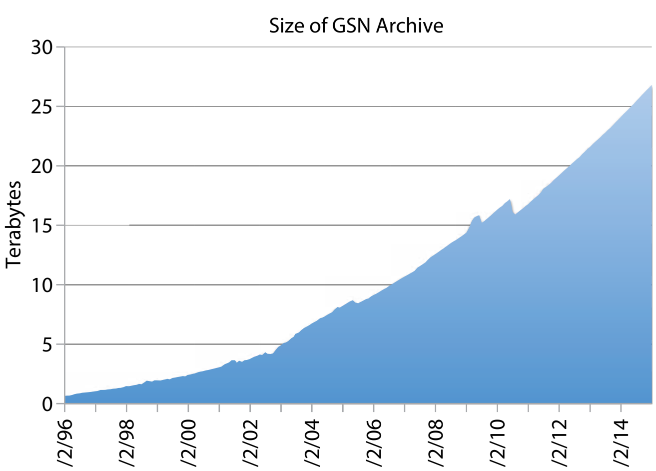


Figure 4.2-1. Cumulative volume of GSN data archived for distribution annually at the IRIS DMC. Data from the GSN are currently increasing at 2.7 terabytes per year. Decreases in data volume are a result of DMC operations that remove replicated data from the archive periodically. The inflection in the archive growth in 2002 represents when the DMC started receiving data from many GSN stations in real time, resulting in multiple versions of data in the archive.

IRIS has worked to establish and promulgate international standards for seismological data to facilitate access by all users. Both the GSN and IRIS Data Services played crucial roles in the development and propagation of the SEED format endorsed by the FDSN. SEED is now the dominant format through which networks exchange data and seismologists receive data. Currently, IRIS Data Services is engaged in an effort to improve and modernize formats and approaches for distribution of data and metadata.

Table 4.2-1. Summary of data access methods supported by the IRIS DMC for GSN data.

WEB SERVICES: REST-like computer-to-computer data requests over the Web

- **Web Service Interfaces**
- **Java API**: Java Client Access Toolkit for FDSN and IRIS Web Services
- **MATLAB Library**: Java Client Access Toolkit for FDSN and IRIS Web Services
- **JWEED**: Java UI client allows users to interactively access data via Web Services
- **Fetch Scripts**: Scripts for allowing convenient downloads of data via Web Services

REAL-TIME STREAMING SERVICE:

- **SeedLink**

EMAIL-BASED REQUESTS: Send a specially formatted email.
The most popular tools for this are:

- **BREQ_FAST**: Batch REQuests, FAST – request gigabytes of SEED data by sending formatted email queries
- **miniSEED**: Email to get miniSEED returned
- **Dataless**: Request dataless SEED volumes

WEB-BASED REQUESTS: Online form submission

- **Buffer of Uniform Data (BUD)**: Tools for examining the current real-time data archive
- **Web Request**: A Web form for submitting BREQ_FAST requests for data
- **Wilber3**: Web-based event explorer allowing you to view earthquake waveforms and access data in various formats
- **Metadata Aggregator**: An online interface for exploring station metadata
- **gmap**: A Google Map interface to IRIS station data
- **SeismiQuery**: A set of pre-formatted database queries that allow users to access data and information stored in the DMC database
- **FetchEvent**: A Perl script to fetch event metadata via Web Services
- **FetchMetadata**: Get station metadata using a Perl script to Web Services
- **IRIS Earthquake Browser (IEB)**: IEB makes it easy to drill down for earthquakes on a zoomable map

Working closely with the FDSN, IRIS is leading an effort to implement an FDSN standard called Station XML. Station XML contains station metadata and miniSEED-formatted time-series data. Presently, five data centers in Europe and two data centers in the United States support these mechanisms.

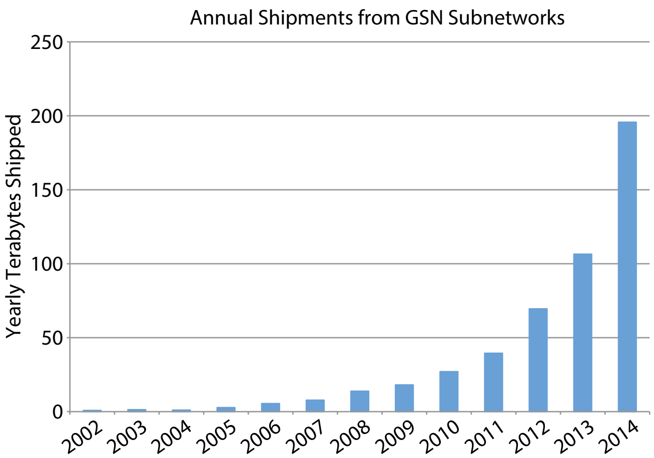


Figure 4.2-2. Volume of GSN data distributed annually by the IRIS DMC from 11 subnetworks (AU, BK, CI, CU, GT, HK, IC, II, IM, IU, MS). About one-third of all the data leaving the DMC in 2014 came from the GSN networks and totaled just under 200 terabytes.

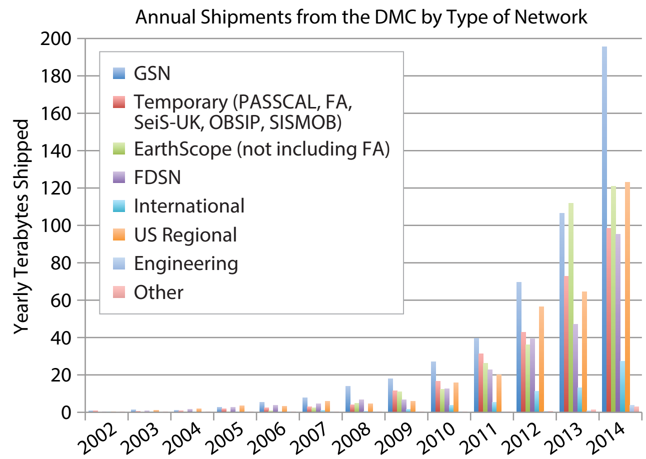


Figure 4.2-3. The GSN normally has more data sent to users by the DMC than any other type of network data, likely a result of the broad geographic distribution of stations and high GSN data quality. In 2014, an unusually large percentage of data distribution was attributed to the GSN. Note that the FDSN column represents data from 65 networks that do not belong to the GSN.

4.3 Cooperative NSF/IRIS–USGS Relationship

The GSN is operated as a partnership between IRIS (funded by NSF) and the USGS. This partnership is crucial to allowing the GSN to serve both its research and operational missions, optimize operations by the distribution of stations between university and government agencies, and take a two-pronged approach to technical challenges.

Details of the cooperative relationship between NSF/IRIS and the USGS are documented in a GSN-specific Annex to the NSF-USGS Memorandum of Understanding (MoU) (Appendix C). The NSF/IRIS–USGS partnership was part of the original plan for the GSN: NSF would fund the construction of the GSN (both civil works and the initial hardware procurements) and then the USGS would take on a portion of operations and maintenance (O&M). IRIS played an important role in establishing a GSN line item in the USGS budget that was specifically for operation of the USGS portion of the network. The funding history chart in Section 9 (**Figure 9.2-1**) shows the increment to the USGS budget that began in 1998. IRIS operates the non-USGS portion of the network via a subaward to Project IDA at UCSD. The inter-agency NSF-USGS collaboration helps to advance the different needs within the relevant agencies and with different sectors of Congress—an important point in sustaining long-term support for the GSN.

A key element of the NSF-USGS collaboration is the coordinated management of the GSN. Responsibility for operation of the GSN rests within the respective management structures of IRIS and the USGS, with each employing its own management policies, procedures, regulations, and points of interface. However, both organizations utilize the IRIS GSN Standing Committee as a joint external advisory committee, both agree to follow the GSN Standing Committee advice to the extent possible within the practical considerations of available funding, and both mutually coordinate their activities. This system enables the GSN to leverage the best of both academic and government operations, taking scientific input from the seismological research community that drives the GSN forward as a state-of-the-art network and avoids a narrow focus on any single operational mission. The balance of research and operational objectives and perspectives ensures the network evolves to meet research community needs while maintaining the operational stability to meet monitoring requirements. For instance, W-phase analyses now routinely utilized by the USGS hinge on the coverage and broadband capacity of the GSN; they were initially developed by community researchers using these data, and would otherwise not be possible with a short-period monitoring network.

The IRIS GSN Program Manager has been instrumental in coordinating the two separate network operations groups, with the goal of improved, efficient GSN operations. This has been particularly important in the standardization of the instrumentation deployed over the past several years. IRIS coordination enabled a simplified procurement process with oversight from the overall community and the development of new components (interface devices) to make best use of the new acquisition systems and sensors. The IRIS GSN Program Manager also coordinates the important process of raising external funds for the program. As discussed in Sections 8 and 9 below, the NSF and USGS have provided minimal direct funding for instrumentation recapitalization since ~2006, so external fundraising has been imperative to the health of the network.

Bringing together government- and academic-based network operators, via the USGS ASL and Project IDA, respectively, provides different perspectives, capabilities, and expertise. The USGS presence helps to ensure that other government agency needs (e.g., the tsunami monitoring mission of the PTWC) are addressed, as well as the government's international obligations (e.g., participation in the CTBTO International Monitoring System). Further, the dual-operations model leverages international engagement. For example, there are situations where an academic-based network operator can operate more readily than a government organization. Conversely, there are other situations where a government-to-government operational model serves best.

4.4 Current Efforts and Short-Term Plans

An important recent effort in the GSN has been the upgrade of station data loggers to next generation systems. This new hardware represents a major modernization and recapitalization effort within the GSN, which stemmed from recommendations following the 2003 review and has resulted in standardizing a major network component. The work is essentially complete (**Figure 4.4-1**), with only three stations left to be upgraded at the most challenging sites. This process demonstrates that reaching 100% completeness in any upgrade of a large, distributed network is approached asymptotically, and for some period of time, multiple generations of equipment may be present. The next generation equipment has had a measurable impact on reliability, and thus the uptime/data availability of GSN stations (**Figure 4.4-2**).

Efforts are underway to further augment the GSN with other geophysical sensors—to complement and/or to enhance the seismic signals. Already the GSN has a variety of other geophysical sensors co-located at GSN sites, including microbarographs, GPS receivers, magnetometers, and weather sensors (e.g., wind speed, direction, humidity, temperature). Currently, the GSN is deploying a suite of state-of-the-art barometric pressure, infrasound, and meteorological instruments at nine stations. The design of these specific sensor packages was developed and field proven by deployment at over 1,000 EarthScope Transportable Array sites. These nine stations are a prototype effort for the GSN, and if it works well and the data prove useful, there may be further deployments of this particular sensor suite. Co-located low-frequency pressure recordings are particularly relevant to GSN observations. These channels record low-frequency pressure fluctuations; the tilt introduced by

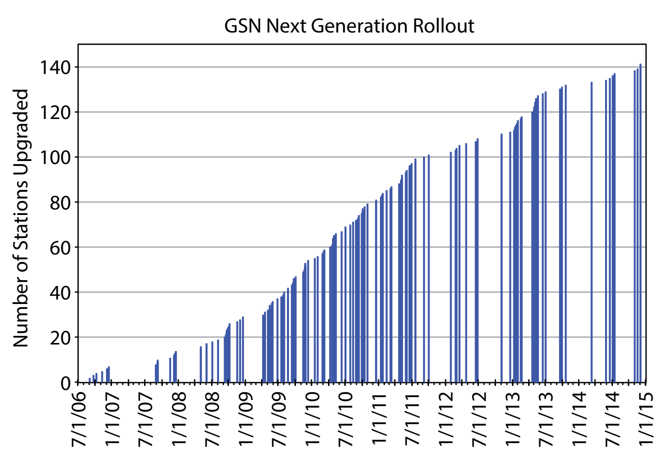


Figure 4.4-1. Cumulative number of GSN stations (currently 141) upgraded to the next generation hardware configuration, which constitutes 98% of the planned upgrades.

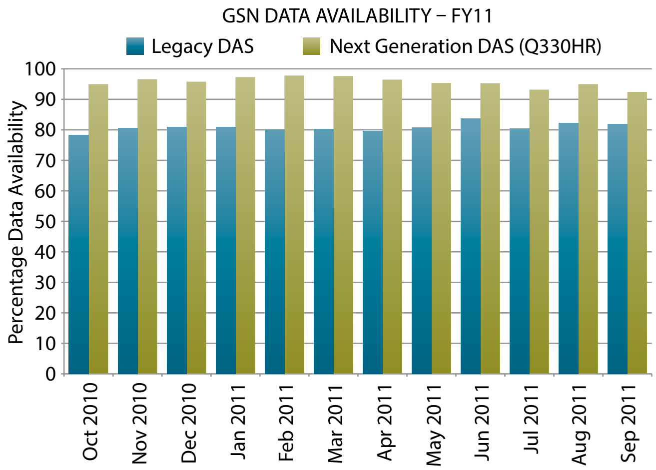


Figure 4.4-2. Impact of next generation data loggers on data availability. In FY11 there was a significant population of both legacy and next generation data acquisition systems deployed, allowing a direct comparison of data availability between the two generations of hardware, with the newer hardware clearly outperforming the old.

these pressure fluctuations is one of the largest sources of noise on low-frequency horizontal seismometer channels. The deployment of these instruments to the GSN provides the opportunity to remove pressure-related noise from seismic time series during data processing, potentially enhancing the already high quality and utility of GSN data.

Revamped calibration procedures have been put into effect across the GSN network to improve the overall calibration and to incorporate capabilities available with the new generation of equipment (see Section 6.2 for further discussion).

The GSN is also taking advantage of station relocations necessitated by external situations (e.g., a station becoming inaccessible due to changing political conditions; a station experiencing cultural encroachment) or the opportunity to add affiliate stations. For example, from time to time, GSN stations have been closed due to civil unrest (e.g., II.GAR in Garm, Tajikistan, in 1992) or for political reasons (II.NVS in Novosibirsk, Russia, in 1994). The hardware at these sites is typically repurposed as part of new GSN deployments. Following recent political developments in Turkmenistan, IDA was forced to terminate operations at station II.ABKT, opening a critical gap in coverage across central Asia. In response, IRIS and IDA were able to leverage new and existing contacts in Tajikistan and Uzbekistan, and are working to replace the Turkmenistan site with two new GSN stations. Instruments for the Tajik site were obtained with funding from the Department of Energy. The Uzbek station is funded under the standard IRIS award to UCSD and will utilize, as possible, the equipment from the II.ABKT station. Work is progressing well, and both sites should be operational by the end of 2015.

Presently, the GSN is working to replace borehole sensors. This effort is critical, as the current GSN primary borehole sensor, the Teledyne Geotech KS-54000, is aging and a number of units are experiencing problems for which one-to-one replacement solutions are no longer available. IRIS, through a coordinated effort of the IRIS Director of Planning, GSN Program Manager, and the GSN community, responded to long-term Congressional interests in supporting the GSN through a coordinated effort to fund replacement of primary borehole sensors. In 2012, Congress provided \$5.7M to the Department of Energy's (DOE) National Nuclear Security Administration to replace aging GSN sensors. Although the funds were allocated to support both the IRIS and USGS GSN subnetworks, DOE transferred these funds to USGS for ease of managing the funds transfer. These funds are for the development and purchase of new borehole seismic sensors across the GSN. The sensor specifications used as the basis for this procurement were established by the IRIS Instrumentation Committee, which includes representation from both network operators.

The USGS is working with the selected vendor, Kinemetrics Inc., to obtain an instrument that meets GSN specifications, and will then procure sensors to be installed at both USGS- and IDA-operated GSN stations. If funds remain after the borehole sensor procurement, the USGS is authorized to spend the remaining funds on vault sensors. Once the borehole sensors are procured, the GSN will need to conduct an installation campaign. Enhanced funding will be required to support the installation of borehole sensors, upgrade borehole civil works, and improve test facilities to get the new instruments to suitable field sites more quickly. IRIS has been working with Congress in response to an interest in increasing the Department of Interior budget to fund the focused installation efforts. The President's FY2016 budget request to Congress for the USGS GSN contains a one-time increase of \$4.9 million to support the installation of borehole sensors and to repair vaults. For now, the new sensors will be installed on maintenance trips-of-opportunity, until such time as augmented funding is received.

4.5 Opportunities for Global Seismological Observing

The established GSN framework presents a number of opportunities to enhance global observations to achieve the full scientific objectives of the GSN. Although some of the GSN's design goals remain a challenge, the GSN has fundamentally advanced seismology in many ways. Science gains from initiatives such as the EarthScope Transportable Array suggest additional opportunities for the GSN. Technological improvements to sensor emplacement and telemetry, especially related to the many aspects of operating seismic stations underwater, may fundamentally change how the GSN operates in the future.

OBSERVATIONS IN THE OCEAN

Long-term observations in the ocean basins are fundamental to achieving the GSN's design goal of full global coverage with stations separated by about 20 degrees. To the extent practical, islands have been used to achieve coverage in the ocean basins. But to complete the full global coverage requires a number of long-term ocean bottom stations (**Figure 4.5-1**). To this end, the GSN Standing Committee and the Ocean Bottom Seismograph Instrument Pool (OBSIP) Oversight Committee are developing a joint strategy document that addresses the topic of enhanced long-term observations from the ocean basins. Recently, several technical developments have put long-term ocean bottom seismometer (OBS) observations within reach. These developments include an increase in cabled ocean floor observatories, which can address data access, power, and timing issues. For stand-alone stations, the development of chip-scale atomic clocks can provide a significant improvement in timing accuracy. With long-term timing addressed, it becomes more feasible to add more batteries, using advanced chemistry formulations (being driven by the consumer market), to increase OBS bottom time. Finally, the development of wave gliders equipped with acoustic modems, or autonomous underwater vehicles equipped with acoustic or optical modems, may be able to address real-time, or at least periodic, data telemetry from OBS instruments. If these continuing advancements can be leveraged, then there are many potential impacts. From the perspective of monitoring, this would improve the ability of the GSN to characterize tsunamigenic events. The GSN is already heavily used by various tsunami-ºg systems, and the addition of stations (whether on land or on the ocean bottom) near potential tsunami sources would be a major advancement. From a more basic perspective, additional GSN stations, particularly to fill gaps in coverage across the ocean, would improve whole-Earth tomography and associated mantle dynamics studies as well as better resolve the rupture processes of globally distributed seismicity.

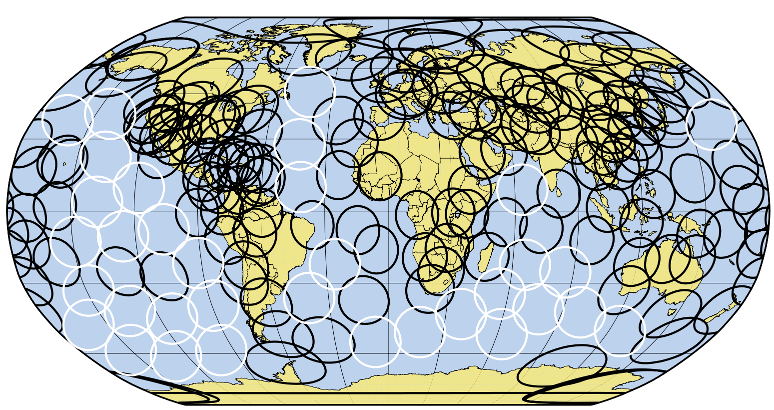


Figure 4.5-1. Map showing existing GSN stations (black circles) and the notional distribution of approximately 34 additional oceanic stations (white circles) required to meet the GSN design goal for global coverage of stations at 20 degree separation. Circles have a radius of 10 degrees.

Broadband arrays have the potential to advance a broad set of seismological topics, including both deep imaging of Earth's interior and the detailed characterization of earthquake rupture processes. A 2013 workshop on this topic [*Koper and Ammon*, 2013] identified numerous potential scientific advancements that would result from increased deployment of broadband arrays.

Tomographic models of Earth's mantle agree at long wavelengths, but there remains significant uncertainty at scales of tens to hundreds of kilometers. To address fundamental questions related to the Earth's composition and dynamics, detailed imaging at this scale requires multi-array analyses. Additionally, arrays are valuable in detecting small seismic events and can be exploited to achieve resolution beyond the classical diffraction limit when estimating relative locations of similar sources. Array-based techniques for studying short-period energy radiation during earthquake rupture propagation allow studies of large earthquake ruptures without requiring specific a priori information, such as source-receiver Green's functions or fault-plane geometry. These techniques have the potential to address some of the outstanding questions in source physics, such as why and how large earthquakes start and stop (**Figure 4.5-2**). Another concept is to place arrays or individual stations at locations selected so as to increase the observations of important seismic phases (**Figure 4.5-3**). Such sites can maximize the potential observing power by placing stations at critical distances from seismically active areas.

Discussions at the 2013 workshop highlighted the special need for broadband arrays in the Southern Hemisphere, especially in Africa, in order to regularize global coverage. Additionally, participants agreed that the greatest scientific potential would come from three-component, broadband arrays, deployed over the long term (at least half a decade), over up to hundreds of kilometers aperture. The GSN provides the natural framework of international sites and collaboration to serve as the foundation for deployment of arrays.

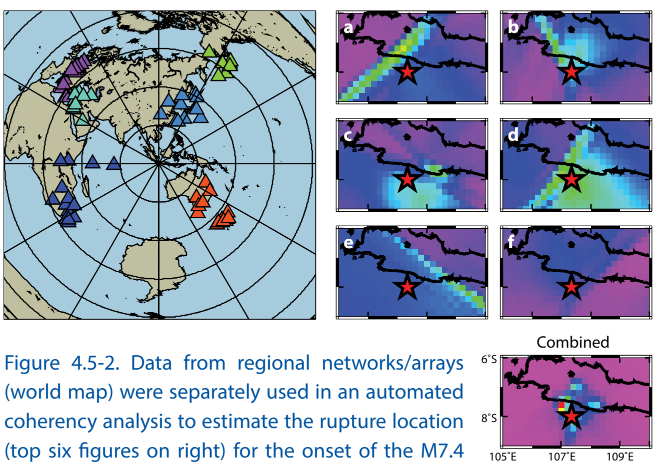


Figure 4.5-2. Data from regional networks/arrays (world map) were separately used in an automated coherency analysis to estimate the rupture location (top six figures on right) for the onset of the M7.4 Java earthquake on September 2, 2009. These source characterizations are then combined to produce a high resolution model of the rupture (bottom right). *Figure and caption modified from Roessler et al. [2010]*

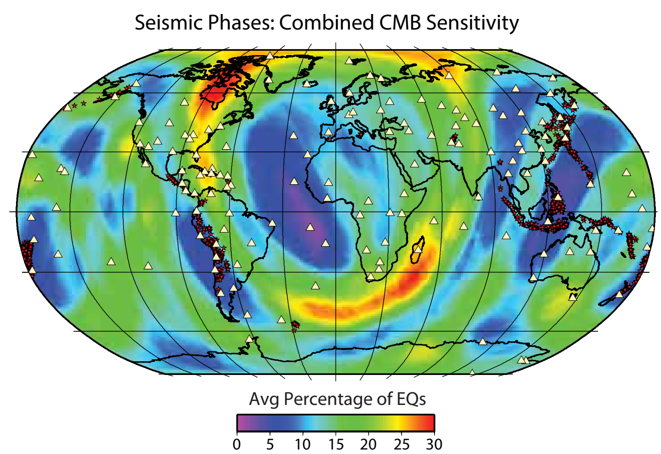


Figure 4.5-3. Example of strategic station deployment. The contour map indicates locations that have a preferential ability to observe phases that sample the core-mantle boundary from deep earthquakes. The map contours the number of events that would be recorded at seismic stations placed on a uniform 1° x 1° grid, based on a catalog of deep events (red stars) occurring between 1990 and 2010 with depths ≥ 100 km and M_w ≥ 5.7. Color shading on the map indicates the percentage of all earthquakes (1,095 total events) that would be recorded at each grid point. For reference, current GSN stations are shown as beige triangles. The analysis considered the following seismic phases (and distance ranges): (1) SPdKS [Δ=105°-115°], (2) ScS [Δ=70°-85°], (3) ScP [Δ=30°-50°], and (4) Sdiff [Δ=100°-130°]. *Courtesy of Gavin Hayes, USGS*

5.0 GSN Data Usage

The GSN provides real-time, continuous, high-quality, very-broadband data obtained over a long time period and reliably archived with required metadata. These characteristics allow the GSN to serve as a multi-use network. GSN data are used for studies of earthquakes and non-earthquake seismic sources and other natural hazards, for studies of Earth structure on multiple time and length scales, and for operational earthquake and explosion monitoring. The results from such studies provide central inputs to investigations in fields across the Earth sciences, including characterization of the inner and outer core, mantle dynamics, evolution of the continents and ocean basins, volcanology, surface deformation and the hydrological loading response, and disciplines which increasingly utilize seismic data, such as glaciology and geomorphology.

5.1 Research Uses

GLOBAL SEISMICITY UNIFORMLY CHARACTERIZED

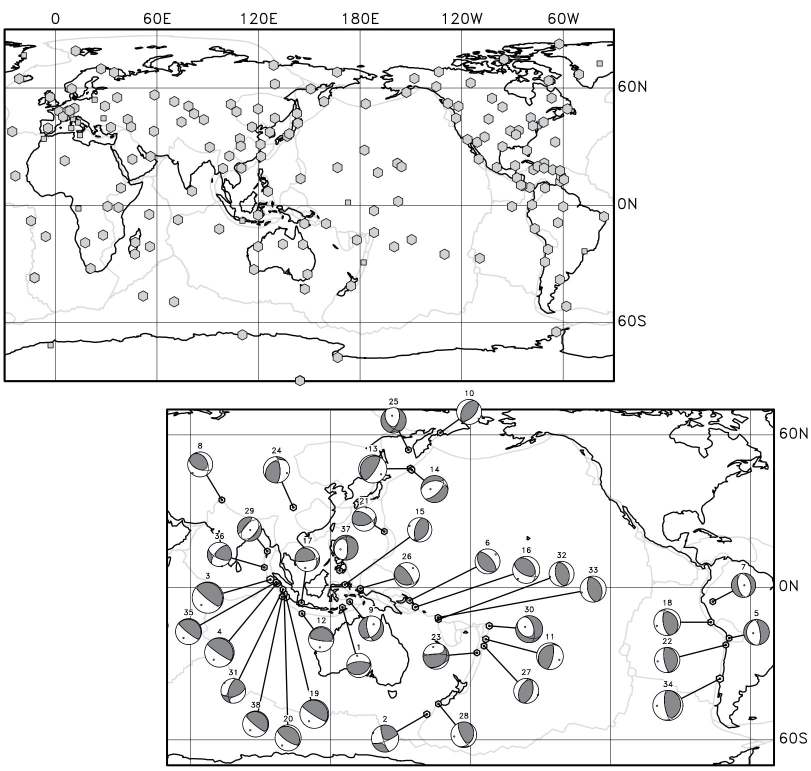


Figure 5.1-1. (top) Map showing the locations of the GSN and other international stations that contributed seismograms to GCMT analyses in 2010. (bottom) Centroid locations and moment tensors for the 38 largest ($M_w \geq 7.5$) earthquakes of 2004–2010. Plate boundaries are shown by gray lines. The full moment tensor is shown by shading; the nodal lines of the best-double-couple focal mechanism are also shown. *Figures from Ekström et al. [2012]*

Ekström et al. [2012] use global seismic activity recorded at IRIS/USGS GSN stations in a systematic effort to determine earthquake moment tensors (**Figure 5.1-1**). These solutions are part of the global centroid-moment-tensor (GCMT) project, which maintains and extends a catalog of global seismic moment tensors beginning with earthquakes in 1976. Starting with earthquakes in 2004, the GCMT analysis leverages advancements in the mapping of propagation characteristics of intermediate-period surface waves and includes these waves in the moment-tensor inversions. This modification of the CMT algorithm enables the globally uniform determination of moment tensors for earthquakes as small as $M_w = 5.0$. For the period spanning 1976 to present, over 42,000 centroid-moment tensors have been added to the catalog.

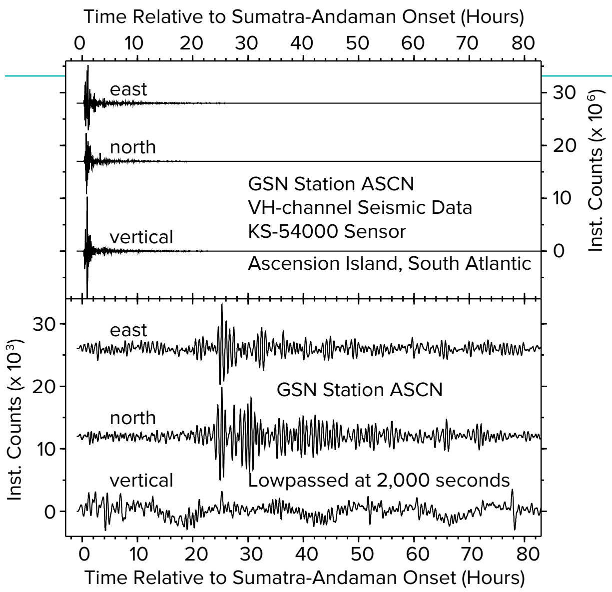


Figure 5.1-2. Seismic data from the 2004 Sumatra-Andaman earthquake recorded at GSN station ASCN in the Atlantic Ocean. (upper panel) Demeaned VH-channel data, sampled every 10 s. (lower panel) A low-passed version of the same data with a corner frequency at 0.5 mHz (2000 s period), obtained with eight passes of a Butterworth filter. Note the arrival of tsunami-related motion roughly 24 hours after the earthquake. This signal is prominent on the horizontal components, but modest on the vertical. *Figure from Park et al. [2008]*

2004 SUMATRA-ANDAMAN EARTHQUAKE

Strainmeter data recorded at the Gran Sasso Observatory, Italy, recorded seismic free oscillations from the December 26, 2004, Sumatra–Andaman earthquake. These measurements resolve toroidal free oscillations with periods > 1000 s. *Park et al.* [2008] reconstructed their time evolution, comparing with synthetic seismograms that include normal mode coupling effects from Coriolis force, attenuation, and ellipticity. Several scenarios explained their observations, including a slow-slip component of the seismic moment release, errors in the composite-CMT source model, unmodeled coupling effects to Earth's secular modes, and feedback from the earthquake's tsunami on Indian Ocean coastlines. To examine these hypotheses, *Park et al.* [2008] reviewed data from several GSN stations, including ASCN (Ascension Island, Central Atlantic Ocean) (**Figure 5.1-2**). The observed oscillatory motion at ASCN was far lower than the predicted amplitude for over 10 hours after the earthquake, but rose to a peak at 25 hours after onset. The time delay showed that the high noise level of the horizontal seismic records at ASCN is far from a stationary stochastic process. The long-period wave train illustrated that Ascension Island experienced a substantial oscillatory displacement or tilt by tsunami-related water motion in the Atlantic Ocean.

2011 TOHOKU-OKI EARTHQUAKE

The GSN has played a critical role in understanding the fifteen great (M > 8) earthquakes that have occurred since 2005, including the M9.1 Tohoku-Oki, Japan earthquake on March 11, 2011 (**Figure 5.1-3**). With recent advances in data processing and improved GSN data availability, rupture modeling and back-projection imaging using seismic array data for great earthquakes can now be done quickly after large events [*Kiser and Ishii*, 2011]. Results show that seismic wave excitation is often strongly depth dependent, with high frequencies generated more efficiently down dip and low frequencies dominating up dip. Several mechanisms have been proposed to explain different rupture behaviors, including pore-fluid pressurization, resistance from subducted seamounts, and combinations of dynamic nonlinear effects. GSN records from a wider range of such earthquakes are required to be confident of such new inferences.

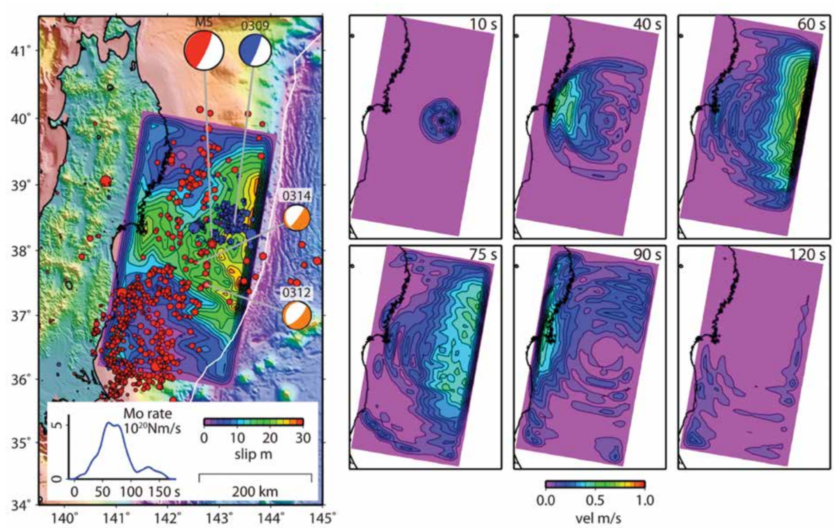


Figure 5.1-3. (left) Total slip contours (in m), shown with focal mechanisms of the foreshock, mainshock, and two normal-faulting aftershocks. Red symbols show the mainshock (star) and aftershocks (circles); blue symbols show the largest foreshock (star) and foreshocks (circles). The inset shows the moment-rate function. (right) Snapshots of slip rate at different times during the earthquake. *Figure from Ide et al. [2011]*

IMAGING EARTHQUAKES AND SLAB STRUCTURE

Zhan et al. [2014a,b] modeled complex waveform patterns for a portion of the Kuril subduction zone. The best fitting slab models have relatively fast cores with smooth edges that are compatible with thermal modeling. They have also discovered a super-shear rupture process for the M_w 6.7 aftershock of the 24 May 2013 M_w 8.3 Sea of Okhotsk deep earthquake (**Figure 5.1-4**). The aftershock ruptured downward along a steeply dipping fault plane at an average speed of 8 km s^{-1}, suggesting efficient seismic energy generation.

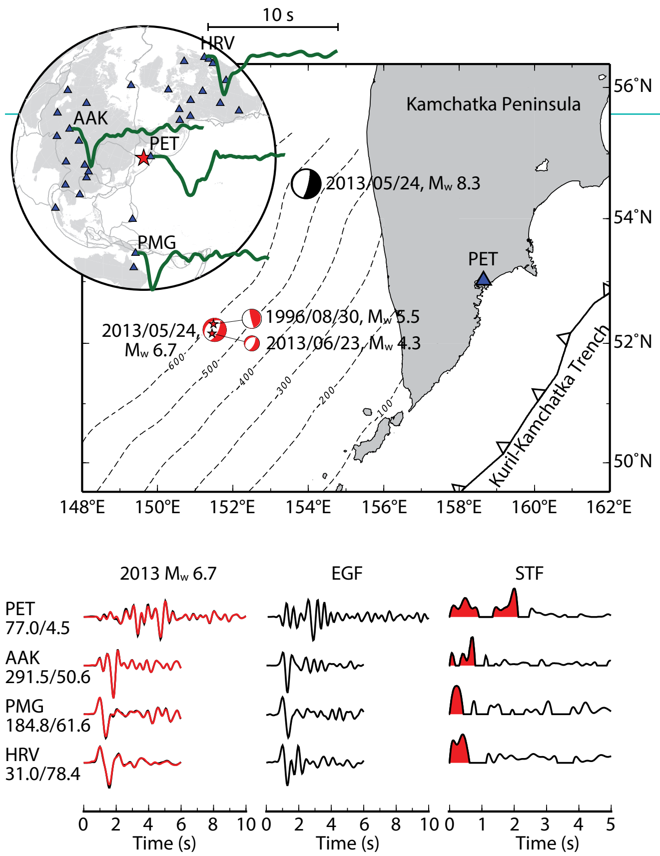


Figure 5.1-4. (top) The 2013 Okhotsk M_w 8.3 mainshock and M_w 6.7 aftershock are displayed as the black and red beach balls, respectively. The two red stars connected with two smaller beach balls represent the empirical Green's functions (EGF) events used in this study. The inset shows the GSN stations used in this study and their P wave vertical displacement seismograms (green lines). (bottom) The three columns display vertical-component seismograms of the M_w 6.7 earthquake, the EGFs and the deconvolved source-time functions (STFs). The black and red traces in the first column are the data and predictions, respectively. The two numbers beneath the station names are distance and azimuth in degrees. In the third column, the STF durations are defined by the red shading, which includes most of the energy. *Figures are from Zhan et al. [2014b]*

THE LITHOSPHERE-ASTHENOSPHERE BOUNDARY

High-fidelity broadband records over long time spans at GSN stations combined with dense spatial arrays have led to the surprising discovery of discontinuous decreases in seismic wave speeds at depths of 50 to 130 km [*Rychert and Shearer*, 2009]. In the ocean and in tectonically active areas, this discontinuity is likely related to the lithosphere-asthenosphere boundary (**Figure 5.1-5**). But, a similar discontinuity is also observed midway through old continental lithosphere, where it is associated with several layers of distinct heterogeneity and anisotropy measured from long-period surface wave and overtone waveforms and SKS splitting data. Understanding this structure, which is difficult to explain through normal thermal mechanisms, will lead to fundamental new understanding of how melting is distributed, how plate motions affect and are influenced by variations in composition and rock fabric, and how continents are formed.

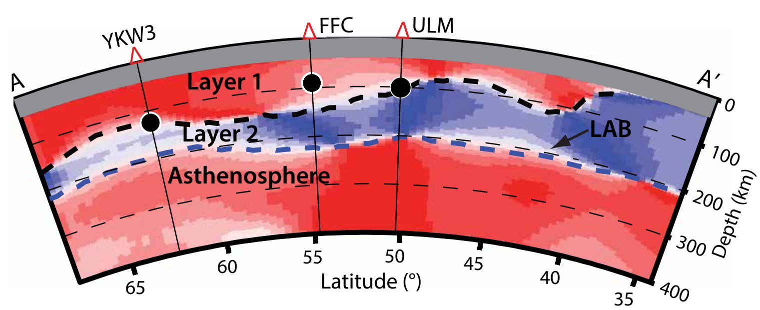


Figure 5.1-5. Cratonic cross section that shows the departure of the fast axis of azimuthal anisotropy from the direction of absolute plate motion of the North America plate in the hotspot reference frame. The mid-lithospheric discontinuity occurs in the depth range where a low-velocity layer is detected from receiver function studies. *Figure from Yuan and Romanowicz [2010]*

SURFACE WAVE ANISOTROPY IN THE UPPER MANTLE

Yuan and Beghein [2014] analyzed azimuthal anisotropy of the upper 800 km of the mantle, determined from horizontally polarized SH wave energy (**Figure 5.1-6**). The results from this study have important implications for mantle transition zone phase changes and possible constraints on mantle flow fields and mantle layering. The contrast of the SV and SH results presents particularly interesting signatures (or lack thereof) associated with ocean age as well as the depth of the lithosphere-asthenosphere boundary beneath Archean cratons. Studies like this depend critically on large compilations of Love and Rayleigh wave phase velocity measurements that are assembled from decades of observations [e.g., *Trampert and van Heist*, 2002; *Visser et al*., 2008; *Yuan and Beghein*, 2013]. Typically, these studies can include hundreds of thousands to millions of observations taken from decades of network operation. The GSN, with its global station distribution, high-quality recordings, and long-term operation provide a critical mass of observations for all of these studies. The investigators obtain the bulk of their waveforms from the IRIS DMC both for the GSN and other networks.

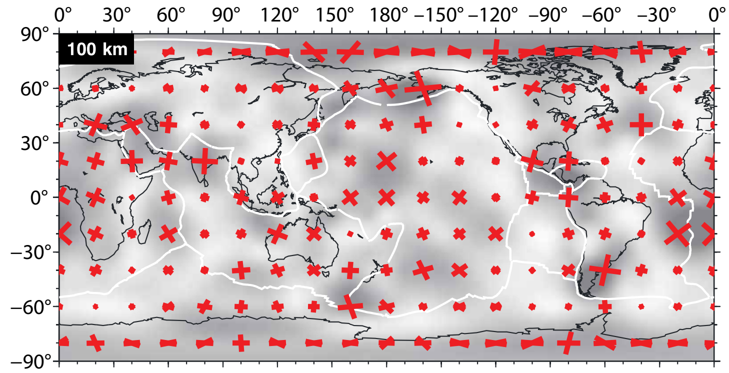


Figure 5.1-6. The lateral variation in azimuthal anisotropy at 100 km depth. Crosses show fast directions, with maximum scale corresponding to 3.9%. The background gray scale also represents the lateral variation in anisotropy. *Figure modified from Yuan and Beghein [2014]*

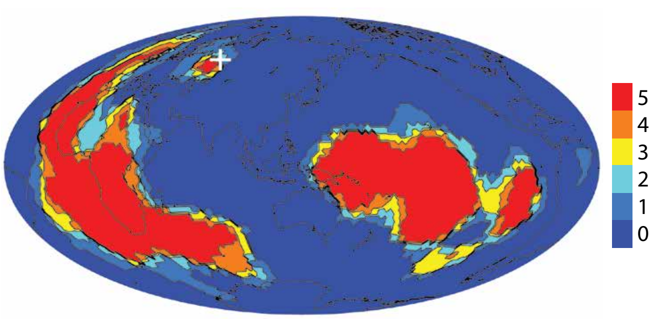


Figure 5.1-7. Map showing that five well-regarded models have a Vs profile that cluster analysis identifies as distinctly slow. The analysis demonstrates consensus on two large low-shear wave speed provinces, the African and the Pacific, within a single, globally contiguous faster-than-average lower mantle. *Figure from Lekic et al. [2012]*

LOWERMOST MANTLE STRUCTURE AND COMPOSITION

Seismologists are collaborating with geodesists, geodynamicists, and material scientists to determine density, temperature, and other mantle properties that cannot be measured based on seismic wavespeeds alone. This progress comes in part from resolving the structure of large, low-shear velocity provinces at the base of the mantle using high-quality broadband data from the GSN and its international counterparts (**Figure 5.1-7**). This work reveals the distinct average velocity profiles within and outside irregularly shaped high- and low-velocity provinces in the lowermost mantle. Modeling of broadband waves that propagate along and across the province borders show that they are sharp, indicating that the distinctive properties cannot be due to temperature differences alone. If large and chemically distinct reservoirs continue to exist in the mantle, then occasional reorganization of mantle circulation could profoundly alter the cycling of volatiles between Earth's interior and the ocean and atmosphere.

WHOLE MANTLE ANISOTROPIC SHEAR VELOCITY STRUCTURE

The radially anisotropic shear velocity structure of Earth's mantle provides a critical window on the interior dynamics of the planet, with isotropic variations that are interpreted in terms of thermal and compositional heterogeneity and anisotropy in terms of flow. Building on the significant progress made in more than 30 years of global seismic tomography, *French and Romanowicz* [2014] expanded the insight on the radially anisotropic shear velocity structure of Earth's mantle (**Figure 5.1-8**). Using waveform data, they develop a whole-mantle model, the first model derived from numerical forward modeling based on a spectral finite element method.

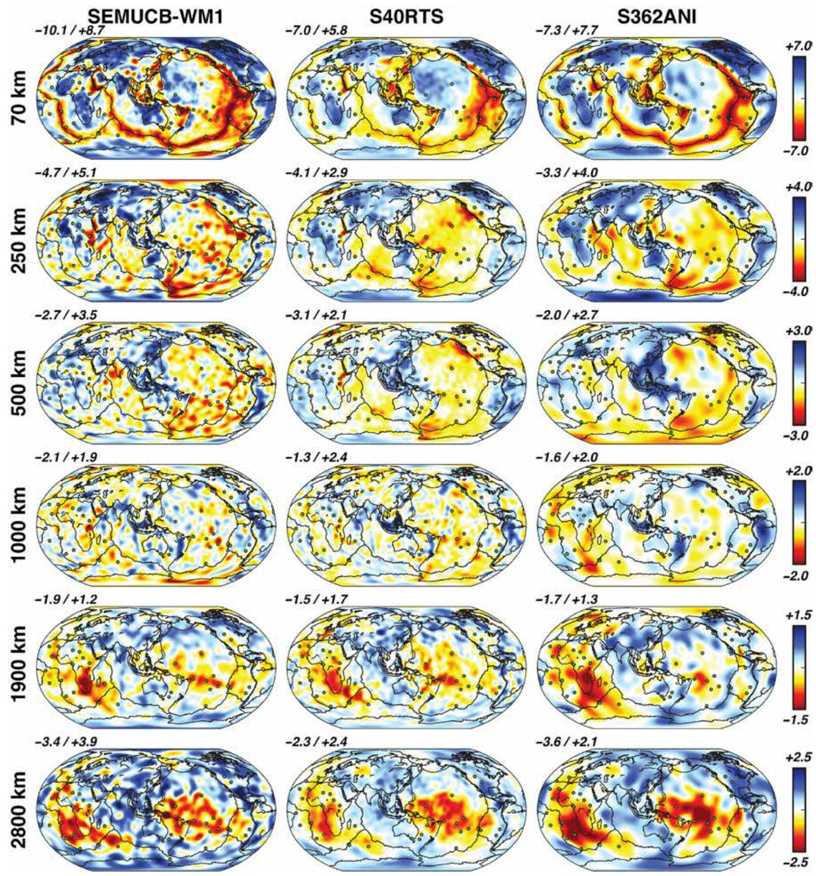


Figure 5.1-8. Map views of global shear-wave velocity variations at a range of depths throughout the mantle for models SEMUCB-WM1 [*French and Romanowicz*, 2014], S40RTS [*Ritsema et al.*, 2011], and S362ANI [*Kustowski et al.*,2008]. Variations are plotted in percent with respect to the global mean at each depth, with the exception of 2800 km, plotted with respect to the 1-D model PREM [*Dziewonski & Anderson*, 1981]. Inset values (upper-left corner of each panel) represent maximum peak-to-peak variation for each model at the corresponding depth. *Figure from French and Romanowicz [2014]*

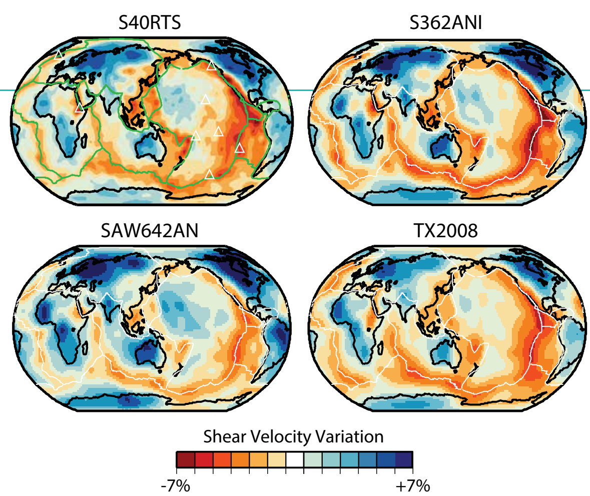


Figure 5.1-9. Maps of the variation in shear-wave velocity at a depth of 100 km for models (upper left) S40RTS [*Ritsema et al.,* 2011], (upper right) S362ANI [*Kustowski et al.,* 2008], (lower left) SAW642AN [*Panning and Romanowicz*, 2006], and (lower right) TX2008 [*Simmons et al.,* 2009].

GLOBAL SHEAR WAVE VELOCITY MODELS

Models of global shear-wave velocity (**Figure 5.1-9**) were obtained through a variety of modeling and regularization algorithms, yet yield highly consistent patterns and amplitudes. These results illustrate the significant impact of the GSN's global data coverage. The models have 10 to 20 times the resolving power of models developed during the early years of the GSN and exhibit consistency even in smaller details, such as the variation in structure beneath West Africa or northern Eurasia. Other models are embedding dense regional data sets, such as those collected by the USArray Transportable Array, within the global data sets to create self-consistent global-regional models.

DEEP MANTLE PLUMES AND CONVECTIVE UPWELLING

Lateral variations in temperature and composition produce topography on the 410 and 660 km seismic discontinuities, which arise from solid-to-solid phase changes in the mineral olivine. *Schmerr et al.* [2010] used underside reflections of shear waves, a technique that requires the stacking of hundreds to thousands of seismograms (**Figure 5.1-10**). This method has flourished from the deployment of the GSN and regional seismic arrays. By analyzing over 130,000 broadband seismograms that sample beneath the Pacific Ocean, they find the discontinuities to be relatively flat beneath most of the Pacific, except under subduction zones and volcanic hotspots. Beneath Hawaii and volcanic hotspots of the South Pacific, they found the phase boundaries to be closer together, consistent with a warm upwelling originating in the lowermost mantle impinging upon the 660 km discontinuity. This feature may be related to large volume volcanic eruptions, such as the Cretaceous Ontong Java Plateau flood basalts.

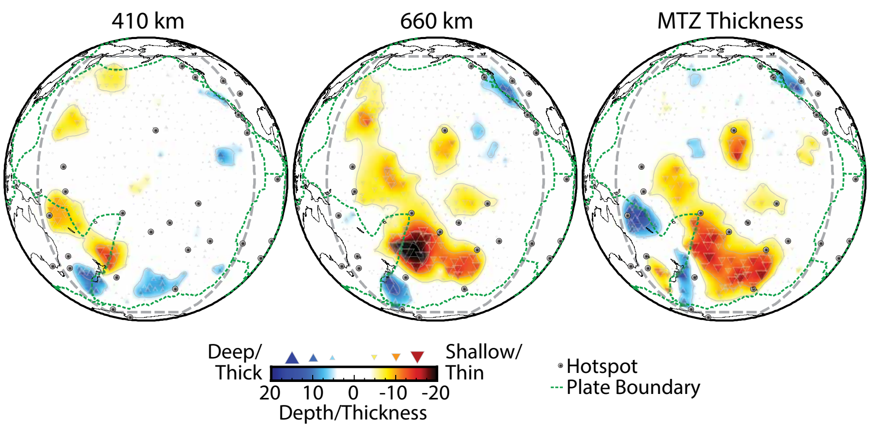


Figure 5.1-10. Topographic maps for discontinuity depths and transition zone thickness in our Pacific study region. The depths are plotted relative to average values of 418 km, 656 km, and an average transition zone thickness of 242 km. *Figure from Schmerr et al. [2010]*

HOTSPOT–RIDGE INTERACTIONS

Gaherty and Dunn [2007] probed variations in mantle temperature, composition, and fabric along hotspot–influenced sections of the Mid-Atlantic Ridge (**Figure 5.1-11**). They inverted for frequency-dependent surface wave phase delays of nearby ridge earthquakes recorded on broadband island-based seismic stations, and used these data to estimate one-dimensional mean shear velocity and radial shear anisotropy profiles in the upper 200 km of the mantle within two seafloor age intervals: 5–10 Ma and 15–20 Ma. The velocity variations observed between Ascension, the Azores, and Kolbeinsey are consistent with approximately ±75° potential-temperature variation among these sites. The fabric near the Azores and the Kolbeinsey Ridge is stronger, suggesting that the hot spot increases mantle deformation beyond that produced by slow seafloor spreading in these regions.

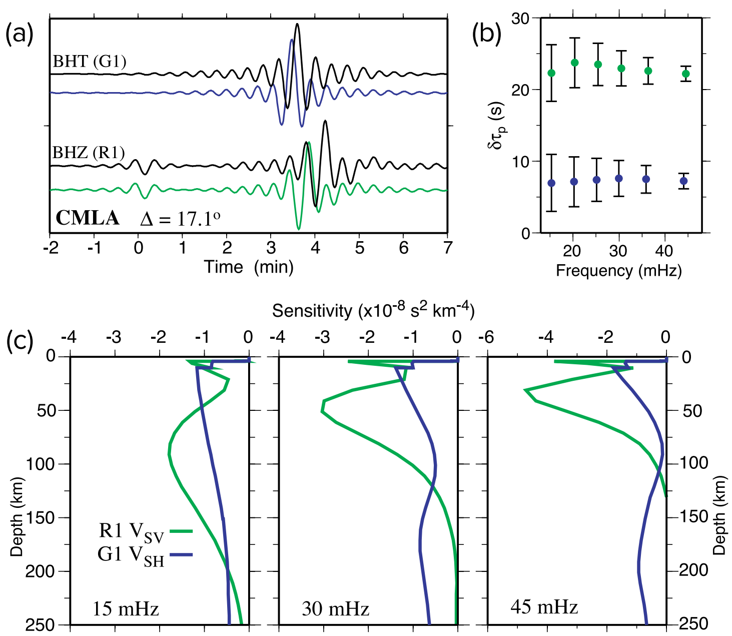


Figure 5.1-11. (a) Observed (black) and synthetic (colored) seismograms for a typical source-receiver pair for a Mid-Atlantic Ridge earthquake recorded at 17° epicentral distance on GSN station CMLA (Azores, Portugal). Top traces are tangential component waveforms, with the Love wave arriving at 3–4 min. Bottom traces are vertical component, dominated by the Rayleigh wave arrival. Time scale is relative to the predicted P wave arrival time. The broadband P wave is clearly visible and provides source static for this event. (b) Frequency-dependent phase delays (travel time residuals) for these two waveforms, measured by cross correlation between the observed and synthetic waveforms. Blue circles depict frequency-dependent Love wave travel times, while green circles show phase delays for the Rayleigh wave. (c) Partial-derivative (sensitivity) kernels for both Love and Rayleigh phase delays in three frequency bands. At 15 mHz, the phase delays are sensitive to average velocity structure in the upper 150–200 km, while at higher frequency, the sensitivity is concentrated at shallower depths. *Figure from Gaherty and Dunn [2007]*

SEISMIC INTERFEROMETRY

Lin and Tsai [2013] examined continuous data from all GSN stations between 2000 and 2009, and demonstrate that several body wave phases (e.g., PP, PcPPKP, SKSP, and PPS) that propagate between nearly antipodal station pairs can be clearly observed without array stacking using the noise/coda cross-correlation method (**Figure 5.1-12**). Based on temporal correlations with global seismicity, they showed that the observed body waves are clearly earthquake related. From single earthquake analyses, they also confirmed that earthquake coda energy observed between ~10,000 and 30,000 s after a large earthquake contributes to the majority of the signal. The PKIKP phase, which does not benefit from the focusing effect near the antipode, can now also clearly be observed for long-distance station pairs.

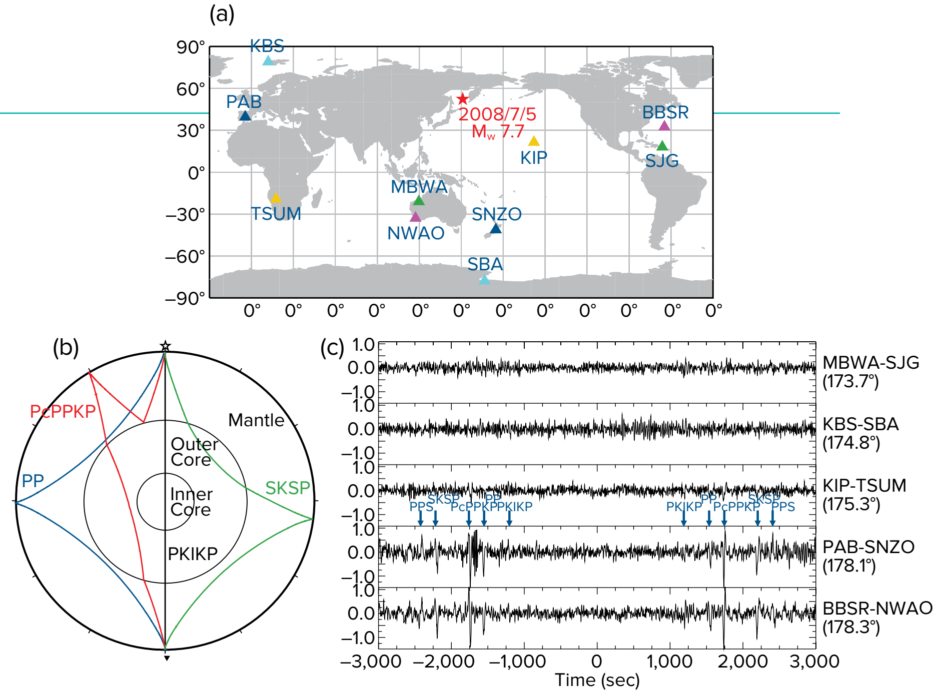
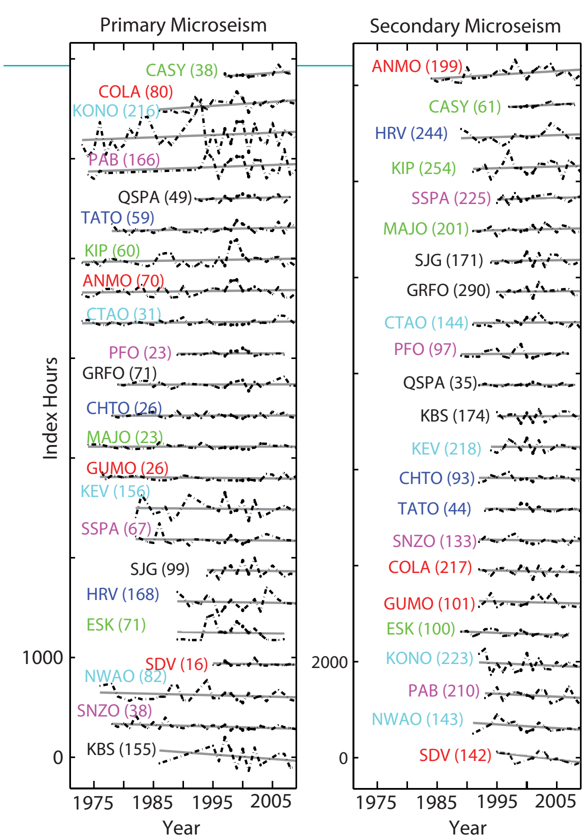


Figure 5.1-12. Ambient noise cross correlations for five nearly antipodal GSN station pairs. (a) The triangles mark the locations of the stations with antipodal pairs colored the same. (b) Schematic plot of the PKIKP (black), PP (blue), PcPPKP (red), and SKSP (green) raypaths. The star and filled triangle denote source and receiver locations, respectively. (c) The observed broadband ambient cross correlations sorted by distance. Several observed body wave phases are indicated. *Figure from Lin and Tsai [2013]*

GLOBAL STORM ANALYSIS

Storm-generated gravity wave energy transfers to the seismic wave field and generates globally ubiquitous seismic background noise peaks near 7 s and 14 s periods, called microseisms. Aster et al. [2010] used continuous digital ground motion data recorded by the GSN and precursor instrumentation to chronicle microseism power extreme events for 1972–2009 (**Figure 5.1-13**). Because most land-observed microseism surface wave energy is generated at or near coasts, microseism metrics are particularly relevant to assessing changes in coastal ocean wave energy. Extreme microseism winter storm season event counts reveal the widespread influence of the El Niño-Southern Oscillation. The double-frequency (7 s) microseism is particularly volatile, suggesting that the weaker single-frequency microseism (14 s) directly generated by ocean swell at coasts is likely a more representative seismic proxy for broad-scale ocean wave energy estimation.



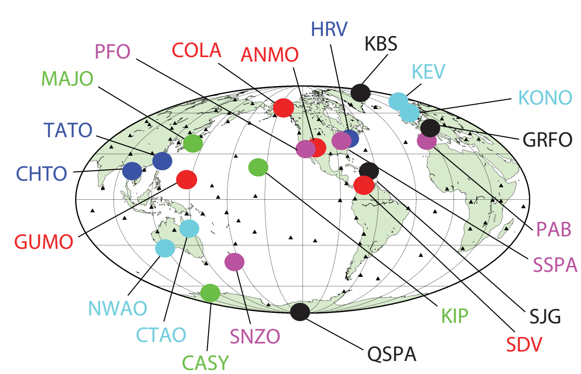


Figure 5.1-13. (right) Map shows the locations of the GSN and predecessor seismic stations. (above) L2 regression analysis of winter-month annual average 95th percentile microseism index trends for the primary and secondary microseisms, respectively. Average microseism index hours per year are indicated. *Figures from Aster et al. [2010]*

5.2 Monitoring/Hazards Uses

NATIONAL EARTHQUAKE INFORMATION CENTER USAGE

The primary mission of the NEIC is to operate 24/7 and determine, as rapidly and as accurately as possible, the location and size of all significant earthquakes that occur worldwide. The NEIC disseminates this information immediately to concerned national and international agencies, scientists, critical facilities, and the general public. Earthquake alerts are e-mailed to over 300,000 recipients. Additionally, the NEIC directly phones and provides situational awareness to 24/7 US operation centers, including Department of Homeland Security, the State Department, and the White House.

The NEIC collects and provides a comprehensive catalog of earthquake source information, which serves as a solid foundation for scientific research. The NEIC pursues an active research program to improve its ability to characterize earthquakes and understand their hazards. These efforts are all aimed at mitigating the risks of earthquakes to humankind.

The GSN, along with the Advanced National Seismic System (ANSS) US backbone, form the core station set that is required to fulfill NEIC's monitoring mission. The NEIC receives data from 1,700 seismic stations but relies heavily on GSN data because of its stations' unparalleled low-noise levels and low-frequency response. Low-noise stations are used to detect smaller signals and provide more accurate timing and amplitude measurements necessary for accurate location and magnitude estimates. The low-frequency response enables the use of advanced techniques to accurately model the magnitude and source characteristics through algorithms such as W-phase moment tensors and finite fault modeling. These detailed source parameters improve USGS real-time products such as ground shaking estimates (ShakeMap) and estimates of fatalities and economic loss (PAGER).

Network improvements over time have facilitated the rapid dissemination of earthquake information to the public. In 2011, accurate information about the great size of the Tohoku-Oki earthquake was available within minutes to hours compared to the 2004 Sumatra-Andaman earthquake, which took hours to days for dissemination. This dramatic improvement is a direct result of investments made in the GSN and the NEIC, and the research and development of rapid characterization of great earthquake sources.

GSN stations are used significantly more often than other real-time global stations in W-phase inversions, which are helpful for rapidly characterizing potential tsunamigenic events, more accurately estimating earthquake magnitude estimates than other methods, and rapidly providing event focal-mechanisms. The fairly uniform station distribution of the GSN relative to events, as well as overall data quality, improves the utility of this process. An examination of 3,261 events shows that the use of GSN stations dominates the calculation of NEIC W-phase moment tensors (**Figure 5.2-1**) and the global coverage improves the response time in critical seismically active areas (**Figure 5.2-2**).

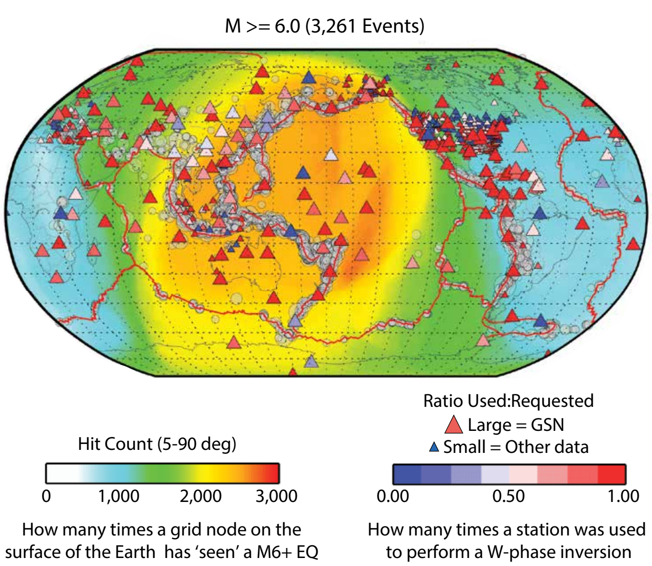


Figure 5.2-1. Hit count for points within 5-90 degrees of a M6 or higher earthquake. Station colors indicate how often they are used in a W-phase inversion. GSN stations in the central and eastern the Pacific Ocean capture many candidate events for W-phase analyses. Overall GSN data are used at a much higher rate for W-phase inversions than other networks. *Courtesy of Gavin Hayes, USGS*

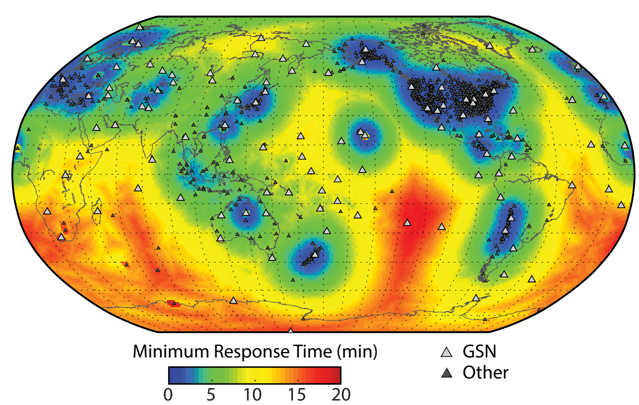


Figure 5.2-2. Idealized minimum response time required for calculating a reliable W-Phase inversion based on global station coverage. GSN stations are marked. Regions colored yellow to red are likely targets for future strategic growth of the GSN and would improve overall W-phase responsiveness. *Courtesy of Gavin Hayes, USGS*

GSN stations also are also heavily used in the production of finite fault models that show the extent and details of a fault's rupture. These models are important for real-time response because the extent of rupture is a critical element in properly estimating the spatial extent and amplitude of ground shaking. These calculations of ground shaking are used in PAGER estimates of fatalities and economic loss (**Figure 5.2-3**). Finite fault models are also useful for assessing future earthquake hazard potential. A recent study following the 2014 M_w 8.2 Iquique earthquake leverages finite fault models and shows the potential for a M≥8 megathrust earthquake still exists in northern Chile (**Figure 5.2-4**).

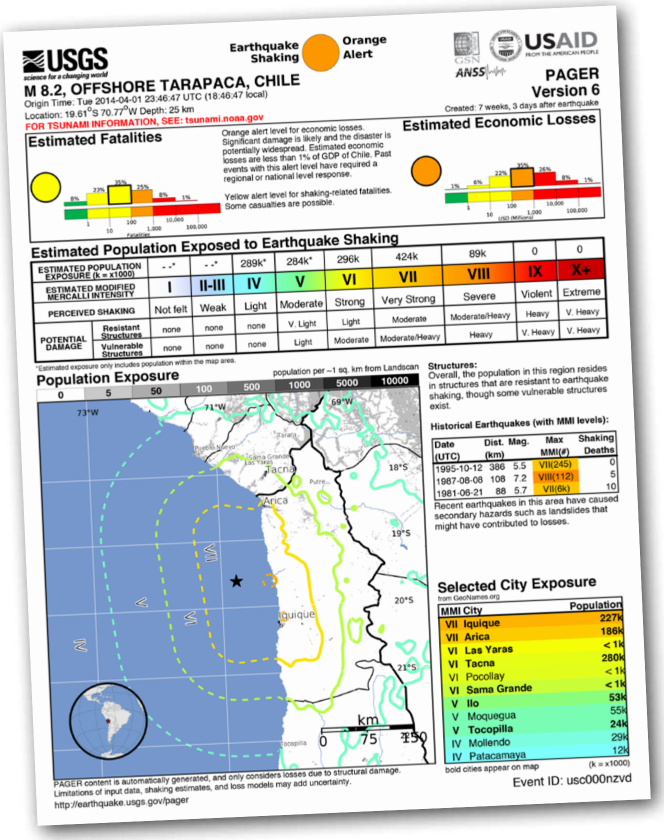


Figure 5.2-3. PAGER results for the 2014-04-01 Iquique earthquake. See http://earthquake.usgs.gov/earthquakes/pager for more information.

The continued operation and maintenance of the GSN is essential for NEIC to successfully produce products used for emergency response and hazard analysis. Reduction in coverage, real-time access, or instrument quality would directly impact the quality and timeliness of NEIC products.

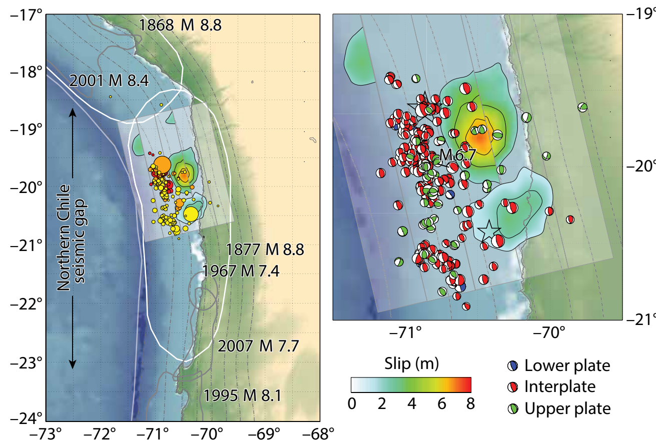
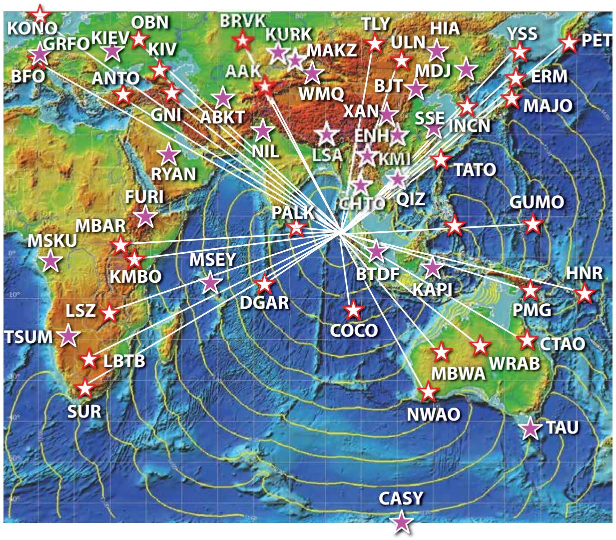


Figure 5.2-4. The modeling of potential for future megathrust earthquakes in Northern Chile relied on GSN data to assess the seismotectonics of the March–April 2014 Iquique sequence, including analyses of earthquake relocations, moment tensors, finite fault models, moment deficit calculations and cumulative Coulomb stress transfer. *Figure from Hayes et al. [2014]*

TSUNAMI WARNING

The GSN plays a vital role in tsunami warning. Seismic signals from earthquakes propagate over 20 times faster than a tsunami travels. Well-recorded earthquakes serve not only to provide early warning and location, but also to characterize the tsunamigenic potential of the event. Large earthquakes are of particular concern because the area of the fault rupture and coincident displacement of the seafloor often relate to tsunami size.

Tsunami warning centers (TWCs) base their initial tsunami warnings strictly on seismic data analysis (e.g., **Figure 5.2-5**). Seismic data are used for the critical first alert because tsunami warnings must be issued prior to the tsunami arriving at the nearest coasts and direct tsunami observations are usually not available until after that point. While there is not a one-to-one relationship between the size of an earthquake and the size of the resulting tsunami, the earthquake parameters provide the information necessary to estimate whether or not a dangerous tsunami may have been generated. The long period and high dynamic range of GSN instrumentation, as well as its real-time telemetry, is ideal for providing the fast, accurate data essential for timely response to a tsunami threat.



The National Tsunami Warning Center uses a large number of GSN stations in its real-time analyses. Out of 652 stations, it uses 65 IRIS/USGS and 36 IRIS/IDA stations. These stations are especially important for international regions where data from other networks are sparse. GSN stations comprise a large proportion of the NTWC's data coverage for the ocean. GSN station distribution across the Atlantic, Pacific, and Indian Ocean basins is vital to this effort.

Figure 5.2-5. GSN stations used in real time for Sumatra-Andaman earthquake and tsunami warning. Due to GSN station proximity, the first alarm at the Pacific Tsunami Warning Center (PTWC) was sounded before the earthquake source rupture was complete (eight minutes from origin time). *Figure modified from the PTWC*

VERIFICATION SEISMOLOGY

Seismology plays an important role in the discrimination of human-caused explosions, especially resulting from the use of nuclear and chemical weapons. Data from the GSN make a critical contribution in the effort to verify worldwide compliance with the Comprehensive Nuclear-Test-Ban Treaty. Countries that have tested weapons recently (India, Pakistan, North Korea) do not report data from local seismographic networks; the closest openly available data are from GSN stations. The completely open nature of the GSN means that events cannot be hidden by censoring data from a single station.

Both the CTBTO and Air Force Technical Applications Center (AFTAC) operate independent detection networks, the International Monitoring System (IMS) and United States Atomic Energy Detection System (USAEDS), respectively. However, over 50 GSN stations are officially designated as Auxiliary IMS Stations, and GSN data are frequently used to supplement analyses for specific events for both the CTBTO and AFTAC. In collaborative fashion, four IMS and two USAEDS stations contribute to the GSN footprint.

GSN data also indirectly support the monitoring and treaty verification activities of these agencies. The long recording periods, geographic distribution, and good quality of GSN stations have resulted in improved models for seismic velocities and attenuation at local to regional scales across the Middle East, Central Asia, North Africa, and Europe. The constraints provided by these products are vital for understanding the wave propagation effects of the lithosphere on source waveforms at regional distances, improving the overall quality of verification studies (e.g., **Figure 5.2-6**).

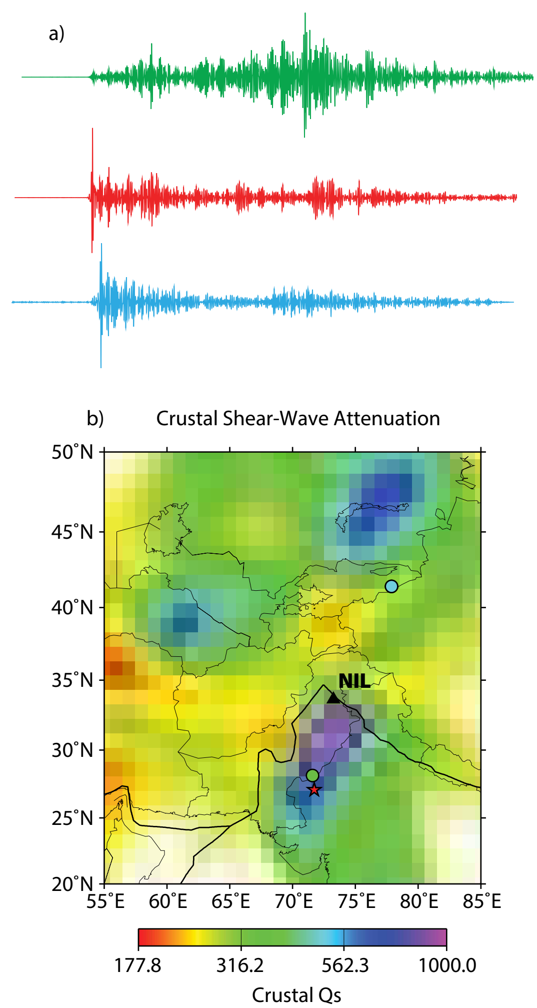


Figure 5.2-6. (a) Waveforms of two earthquakes (shown in green and cyan) and one nuclear explosion (shown in red) recorded at GSN station II.NIL (Nilore, Pakistan) and filtered between 1–2 Hz. (b) Shear-wave attenuation model of the crust from amplitude topography of regional phases. This map is primarily sensitive to the attenuation of the direct crustal shear-wave Lg. Black triangle is GSN station II.NIL, red star is the 1998 Indian nuclear explosion, and circles are the earthquakes near the Indian test (green) and in Kyrgyzstan (cyan). The importance of understanding attenuation in the lithosphere aids source discrimination studies. *Figure and caption modified from Pasyanos and Walter [2009]*

GSN STATIONS – ANCHORING OTHER NETWORKS

Because GSN data are telemetered, they can be directly incorporated into outside networks for analyses. There are numerous examples where GSN station data are used by national networks, particularly in developing countries with earthquake monitoring programs, including Venezuela (IU.SVD), Panama (CU.BCIP), the Dominican Republic (CU.SDDR), Ecuador (IU.OTAV), Peru (II.NNA), and Chile (IU.LVC and IU.LCO). Even countries with well-established seismic networks will often incorporate GSN stations, such as New Zealand (IU.SNZO).

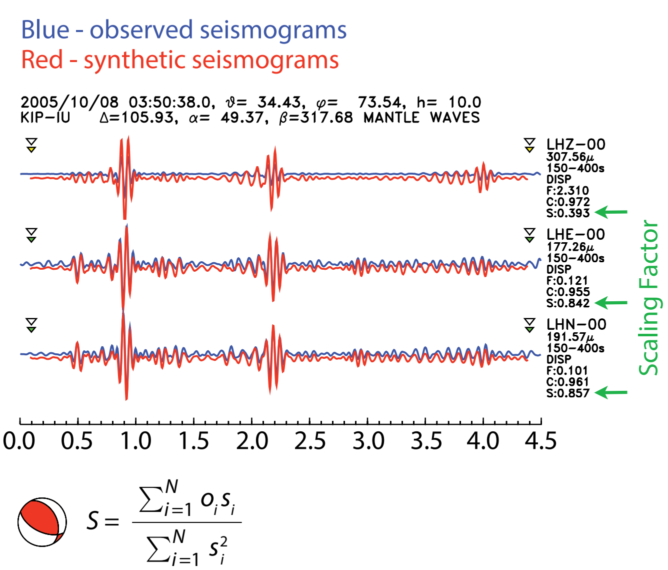
GSN stations have also been used as anchors, reference stations, or additional points for analysis for portable seismic deployments, such as those facilitated by the IRIS PASSCAL program. Recent examples of this use include the Africa Array (II.MBAR, IU.LSZ), the Madagascar and Comores Seismic Experiment (II.ABPO), the North Anatolian Fault and Central Anatolian Tectonics deployments (IU.ANTO), Peru Lithosphere and Slab Experiment (II.NNA), Program to Investigate Convective Alboran Sea System Overturn (IU.PAB), and the Northeast China Extended Seismic Array (IC.MDJ). These examples encompass only US-deployed temporary experiments from over the last decade. The GSN also contributed two IRIS/IDA and 13 IRIS/USGS stations to establishing the permanent Reference Network component of the EarthScope USArray.

6.0 GSN Data Quality

Making high-quality observations has always been a key GSN goal. Over the past 10 years, however, aging of GSN equipment and the discovery of GSN data problems have highlighted the importance of quantifying, validating, and maintaining GSN data quality. This has motivated the creation and implementation of a more holistic approach to ensuring GSN data quality, igniting a discussion across all of IRIS, and spawning several key IRIS activities during 2014–2018. While the GSN's focus on quality may have been re-energized by the discovery of problems, it has had the effect of putting the GSN at the forefront of devising and evaluating quality control efforts that span all aspects of network operation: instrumentation, routine monitoring and analysis of waveform data to detect and/or track problems, action plans that address station quality issues as they are found, and effectively communicating data quality issues to users. This section presents a brief history of the issues that motivated the GSN's renewed focus on quality, and details the GSN's approach to achieving improved and assured data quality.

6.1 Recent History

Indications of problems with the long-period response of the STS-1 sensors used in the GSN began to emerge in the mid-2000s. These issues were identified by the Waveform Quality Center (WQC) at the Lamont-Doherty Earth Observatory (LDEO) and were observed as scaling problems when performing their ongoing global centroid moment tensor analyses (**Figure 6.1-1**) [*Ekström et al*., 2006]. In 2010, the WQC issued a series of 10 reports detailing performance issues that were observed at 10 different GSN stations since installation. In addition to problems associated with the degradation of the STS-1 sensors, maintenance issues such as high noise levels, channel polarity, orientation, and metadata accuracy were also identified. Two studies published by the IDA group in 2005 and 2007 also indicated there were ongoing issues related to metadata inaccuracies. This latter work focused primarily on observations of radial normal modes and tides.



$$S = \frac{\sum_{i=1}^{N} o_i s_i}{\sum_{i=1}^{N} s_i^2}$$

Figure 6.1-1. Example of the GSN sensor performance issue identified by the WQC. The scaling factor between the observed and synthetic waveforms indicates that the vertical component seismometer is not functioning correctly. *Figure from Nettles and Ekström [2009]*

IRIS responded to the quality issues by organizing a Quality Assessment Team (QAT) to review the state of data quality policies, practices, and procedures across all of IRIS' observing activities. IRIS also appointed a GSN Data Quality Panel, with outside membership, to review GSN QC issues and the GSN's response. The QAT assembled a comprehensive set of materials documenting QC practices and procedures, and the Data Quality Panel reviewed these materials and provided feedback. The GSN went on to develop a *Concept of Operations* as well as an *Implementation Plan* for the GSN Quality Assurance System that is currently being executed. The GSN has also developed a *Data Quality Goals* document that guides the current GSN quality objectives and is intended to be updated at regular intervals.

A number of activities related to GSN data quality have been undertaken over the past nine years. These include:

- Deployed new STS-1 feedback electronics boxes (FBEs)
- Implemented a new calibration policy, which will ultimately include guidelines for when metadata are updated based on calibration results
- Deployed next generation equipment to overcome limitations and aging issues of the legacy GSN station hardware
- Developed a guide to sensor orientation best practices and onsite "absolute" calibrations
- Developed and began implementing the Data Quality Assessment (DQA) tool at the ASL Data Collection Center
- Implemented the Modular Utility for Statistical Knowledge Gathering (MUSTANG) tool at the IRIS DMC for computing quality metrics

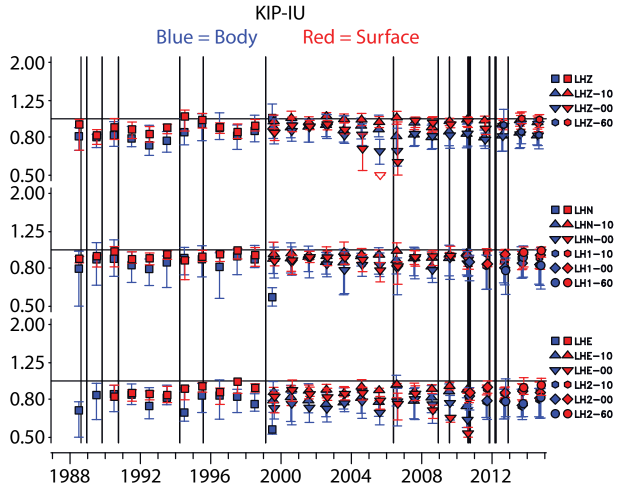


Figure 6.1-2. Station amplitude response as a function of time for IU.KIP in Hawaii. Symbols indicate the scaling factor between data and synthetics for earthquakes with $M_w \geq 6.5$ in the body wave band (blue, ~60 s) and the surface wave band (red, ~175 s). The primary vertical channel (top panel, symbols labeled LHZ-00) shows scaling issues that were rectified with the replacement of the vertical component feedback electronics box in 2006. A complete station upgrade was performed in 2010. *Figure from Gee et al. [2014]*

- Implemented the Latest Assessment of Seismic Station Observations (LASSO) tool for aggregating MUSTANG data metrics into actionable reports
- Implemented a problem-tracking system at ASL to integrate QC and field-engineering efforts

These efforts have had a positive impact on both data and metadata quality and improved disclosure of quality related data metrics to the user community. In a follow-up paper in 2012, the IDA group found, using the same methodology as their earlier studies, a measurable improvement in metadata accuracy for those sensors whose responses were checked using the new quality assessment tools. In a recent study, *Gee et al.* [2014] showed improvements in data quality due to recent upgrades of seismometers, feedback electronics boxes, and data loggers (**Figure 6.1-2**) as well as improved calibration procedures and policies. They also showed that with careful analysis of the data and station records it is possible to correct metadata for some historical station epochs.

6.2 GSN Approach to QA/QC

6.2.1 SHORT- AND INTERMEDIATE-TERM PLANS

GSN data quality goals are discussed in detail in the *Data Quality Goals* document. These goals address:

- Station location accuracy
- Sensor orientation accuracy
- Timing accuracy
- Sensor frequency response
- Data availability
- Complete and accurate ground motion recording
- Minimization of seismic noise

These goals are derived primarily from the original GSN design goals and the 2002 update. The *Data Quality Goals* document has begun to quantify metric targets against which performance can be evaluated.

Implementing the calibration policy, in which all broadband sensors must be calibrated at least once per year, has resulted in a significant number of recent calibrations, as can be seen from the table on the IDA website (http://ida.ucsd.edu/web/WhatsNew/recalibration/html/GSN_recalibration_table.html). Calibration information for USGS-operated GSN stations can be accessed with the calibration tab for specific stations (e.g., http://earthquake.usgs.gov/monitoring/operations/station.php?network=IU&station=TUC#calibration). Analysis of these calibrations

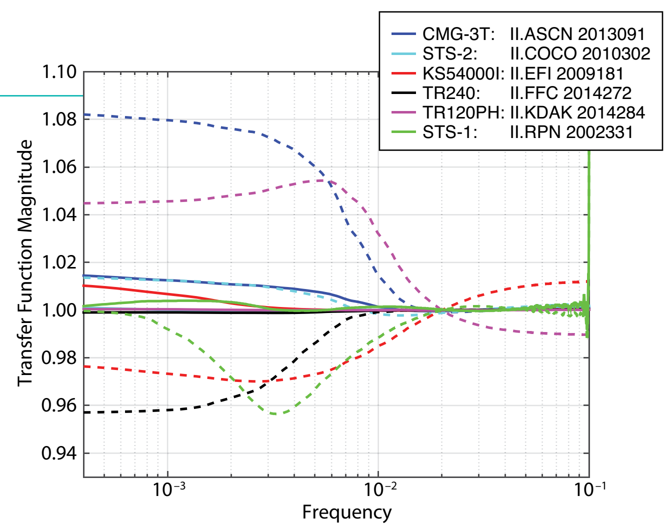


Figure 6.2-1. GSN network operators refine sensor response models by analyzing the output of known signals injected into the sensor's calibration coils. Shown here is the magnitude of the transfer function between pairs of time series: (1) the coil input convolved with the modeled instrument response and (2) the observed sensor output, for examples of broadband sensors used in the GSN. A well-modeled response should yield unity across the passband. Dashed lines denote instrument responses based on the manufacturer's nominal model, which fit poorly in many cases. Solid lines represent models whose parameters were adjusted to fit the observed output. In all cases, these fit to 1% accuracy.

(e.g., **Figure 6.2-1**) has led to many updates to station response metadata and provides an additional tool for identification of problem sensors.

Implementation of MUSTANG and DQA systems has been a significant undertaking. In parallel, LASSO and the MUSTANG Data Browser were developed as publicly available software clients to visualize and analyze the MUSTANG metrics. The DQA was created as an in-house quality assessment tool for the ASL, in collaboration with IRIS. As is often the case with software engineering, these tools took longer to develop than originally anticipated. However, all of these tools are now online and are being used routinely as development continues. The quality metrics computed by MUSTANG are available via Web services functionality. The IDA DCC incorporates MUSTANG metrics into its data quality analyses using Web services.

These tools and software enable both network operators and end users to quickly characterize stations and networks, as illustrated through examples in **Figures 6.2-2–6.2-5**.

EXAMPLES FROM SOFTWARE AND TOOLS

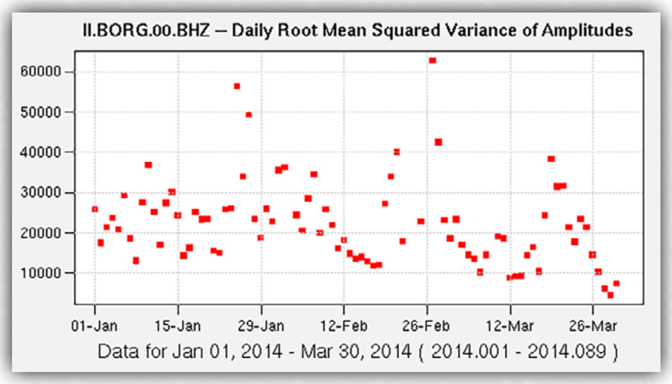


Figure 6.2-2. MUSTANG's data browser enables users to generate quick plots of MUSTANG metrics and can be adjusted to display station or network views, plot one or more metrics, and show either single channels (e.g., BHZ) or sets of channels (BH?). Options allow users to scroll through multiple metrics for a station or set of channels and define different time windows.

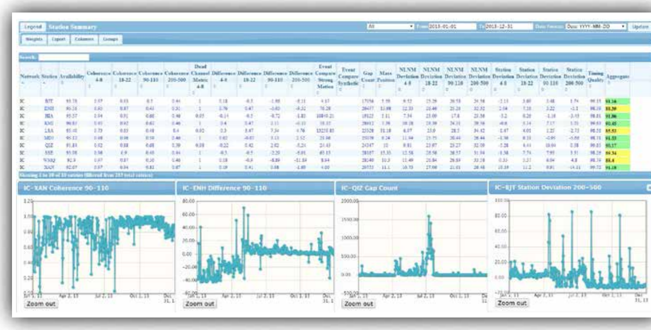


Figure 6.2-4. The DQA summary page for the New China Digital Seismographic Network (network code IC) for 2013 shows the table entries for metric summaries and the data quality aggregate. Four plots of summary metrics are shown, where the daily values have either been averaged or summed over the channels at each station. *Figure and caption modified from Ringler et al. [2014]*

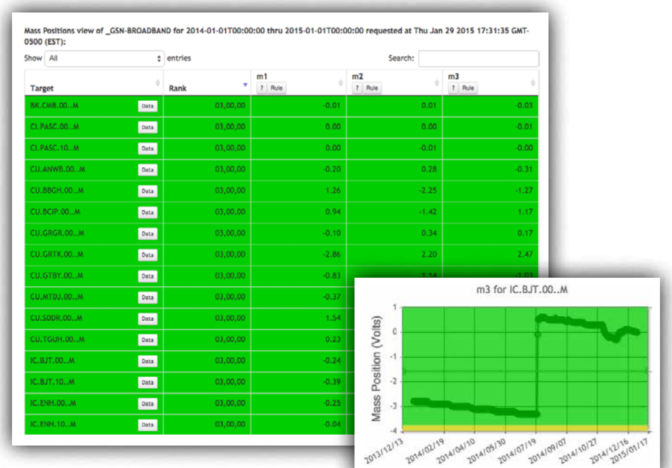


Figure 6.2-3. LASSO displays metrics, either singly or in related groupings, and can also calculate derived metrics such as seismometer mass positions. In this example, mean GSN mass positions for 2014 are displayed, and clicking on "m3" for IC.BJT.00 shows a single mass position channel for that seismometer. The change in voltage from a re-centering pulse can clearly be seen. LASSO also provides default rule sets for ranking selected metrics, which can be modified by users and incorporated with weights to create qualitative or quantitative ranking schema. This provides ways to evaluate network performance using structured criteria.

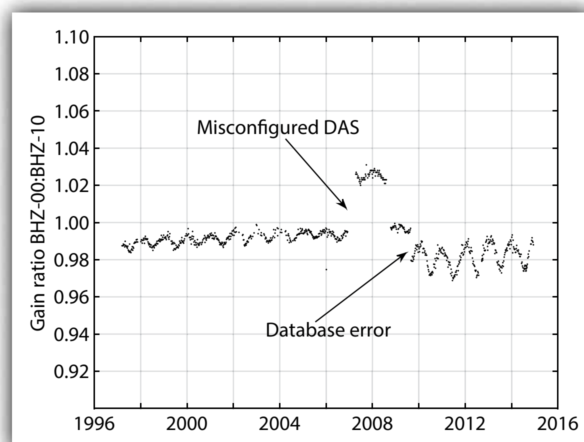


Figure 6.2-5. IDA DCC calibration analysis tools, some reliant on MUSTANG, are used operationally to identify station quality issues across the GSN. The plot shows a computed gain ratio of BHZ-00:BHZ-10 channels at II.WRAB centered on the microseismic peak compiled using MUSTANG. If the relative gains of the KS-54000 and the STS-2 (later TR-240) were perfectly characterized, this quantity would be 1.0. Inspection of this plot and subsequent investigation uncovered two metadata issues: (1) a misconfiguration of the DAS in early 2007 introduced an incorrect DAS sensitivity for BHZ-10 for one year, and (2) a database entry error was introduced in 2013 that created a 1% offset in BHZ-10 gain from 2009–present.

Operationally, the central goal of using MUSTANG, LASSO, DQA, and related software is to identify and incorporate actionable QC results in operations and maintenance planning and decision making. The GSN management is identifying and experimenting with ways that these software tools are best incorporated into management and operations activities. These tools will also be used to assemble and summarize information on longer-term or chronic issues for the GSN Standing Committee, so that prioritization of stations and issues can be performed in an objective and quantitative way that has not been possible until now. Such an approach is needed to enable resources to be strategically allocated to ensure the highest possible data return. The goal of presenting summary QC information to the Standing Committee partially motivated the creation of the LASSO QC tool.

Overall, the current multipronged approach to data quality represents a partnership among the two network operators and the IRIS DMC, combined with external input and oversight from the GSN Standing Committee. The underlying metrics, analytical techniques, and presentations will be used throughout IRIS observational programs, and the MUSTANG metrics are being computed for all data in the IRIS DMC (current and archived). As previously noted, the tools and metrics are openly available and network operators everywhere will be encouraged to use them to assess (and improve) the quality of their network operations.

6.2.2 LONGER-TERM PLANS AND CHALLENGES

The longer-term plan for implementing the quality system is to ensure that all facets of data quality are addressed—upgrades to station equipment and infrastructure, service visits, calibrations, monitoring of waveform quality, management response to identified issues, transparency to data users, and governance oversight for the entire process, including providing guidance on long-term issues and directions. The IRIS Instrumentation Services programs, spearheaded by the Instrumentation Services Standing Committee, has developed a set of "Quality Principles" (Appendix D) that guides the overarching approach to data quality across all IRIS programs. These principles articulate key operating practices for the network and provide a sort of "Bill of Rights" for data users.

One challenge for maintaining the quality of any established network is cost. O&M budgets are tight and have been declining, causing tension between preventative maintenance via regular service visits and condition-based maintenance responding to issues as they arise. Running current generation equipment helps substantially, but the cost of ongoing recapitalization is not built into the GSN O&M budget, and even small parts stretch the budget.

The impact of hardware modernization is clearly demonstrated by the upgrade to next generation data loggers. As **Figure 4.1-8** illustrated, deployment of new data loggers resulted in a measurable and significant increase in station reliability.

For O&M, the primary cost drivers related to maintaining data quality include:

- Labor, travel, and materials and supplies to perform preventative maintenance or effect repairs when issues are detected
- Labor and software to analyze and assess data quality
- Investments in equipment and infrastructure to maintain quality and realize efficiencies

With the possibility of flat funding for GSN O&M in the coming several years, the GSN may need to balance geographical coverage and the cost of optimal maintenance of individual stations.

An unsolved challenge in data quality is communication with data users. GSN users need clear and reliable information about known data problems, about metadata changes, and about the reliability of data during any given time period. Some information is available through the USGS and IDA websites. An increasing amount of information is available via MUSTANG and LASSO, but much work remains to be done.

An additional challenge is obtaining feedback from the GSN user community that can be used in network quality management. IRIS has maintained a Data Problem Report (DPR) tool for some time, and this tool allows problems to be flagged via a simple, standardized report that is parsed into a searchable database. To date, input via this tool has been restricted to a specific list of data quality experts to ensure the integrity, and maximize accuracy, of the reports. The GSN and IRIS Data Services programs have initiated discussions about how to address this challenge.

It is worth noting two nascent IRIS programs that may help address several of the challenges described above:

- ***Research Ready Data Sets (RRDS)***. In this initiative, IRIS Data Services will develop tools, based on metrics computed by MUSTANG, that allow users to subset their data requests based on values (or ranges) of data metrics. For example, a user might request data for only those periods when timing is known to be locked, or when RMS noise levels are below a given threshold. Development of the RRDS tools will rely heavily upon MUSTANG metrics. Development of the RRDS project will begin in year 3 (FY16) of SAGE.

- ***Dirt-to-Desktop (D2D)***. The goal of this initiative is to simplify and streamline the process of moving data from the sensor (the "dirt") through to the DMC and then to the user's "desktop." Wherever possible, sensors should be self-documenting and self-describing, and all efforts should be made to minimize the number of human "touches" of the data and metadata between the sensor and the archive. The benefit will be improved data quality, fewer errors, and lower costs. D2D is still at the conceptual stage, and IRIS is working to articulate the goals and framework as a guide to vendors, software developers, and network managers.

Much longer term, it is likely that the GSN's efforts in enhancing data quality will have a broader impact than on the GSN alone. Over the years, the GSN has been adopted by many as a global standard in areas such as technical design goals, open access data, and long-term data archiving. This has led to a significant increase in the quality and quantity of global data available for research and monitoring. While many networks have adopted these technical and operational goals, many remain significantly below achieving GSN data quality—with a resulting lost opportunity in global data resources. As the GSN works to set specific goals and procedures for quality assessment, it would be a natural progression that this leads, as past experience in technical and operational standards indicate, to a significant increase in data quality and resources throughout global, national, and regional networks.

7.0 GSN Resilience

A key strategy for GSN operation is the concept of "resilience"—making the network robust to failure and identifying and mitigating risks and vulnerabilities. Resilience may be considered in two ways. First is the technical approach to resilience—the specific technologies or operational practices that make the GSN more robust. Second is the management and organizational approach to resilience—providing an operating structure for the GSN that enhances resilience through diverse capabilities and approaches. Of course, both of these elements of resilience are critically dependent on stable and adequate funding for the network, which is discussed in the next section on *GSN Renewal*.

Technical resilience is a fundamental element of GSN station design. The GSN implements primary and secondary broadband sensors (**Figure 7.1**), uses both high-gain and low-gain sensors to ensure signals remain on scale, and uses both on-site data recording and telemetry (and, in some cases, multiple telemetry paths). In order to maintain technical resilience, it is important to ensure that GSN equipment remains up to date and that obsolete equipment is replaced with maintainable systems. For example, some of the current "next generation" systems are already more than 10 years old. Therefore, an important task for the GSN program in the next five years will be to begin the search for the next "next generation" acquisition systems with concomitant recapitalization funding.

Station locations and coverage are periodically reviewed with respect to cultural encroachment, the changing political landscape, property ownership and access, natural disasters, and other variables in order to increase the network's technical resilience.

Figure 7.1. The surface vault at IU.CASY (Casey, Antarctica) houses three STS-1 components as well as a STS-2 secondary sensor. This arrangement demonstrates the redundancy built into GSN station design.

The current dual-operator structure of the GSN enhances resilience by providing a diverse approach to both the operational and technical challenges faced by the GSN. For example, IRIS and USGS testing of sensor emplacement strategies and thermal insulation (**Figure 7.2**), evaluation of prototype sensors (**Figure 7.3**), and development of calibration techniques and other QC measures have benefited from the different but complementary expertise of the two operators and the environments in which each is embedded. As new techniques are developed by one of the operators, they are vetted and often improved through ongoing technical interchange between the operators. Many current best practices used across the network were developed in this way. In addition, as mentioned in Section 4, having diversity in communications and data paths (i.e., separate and distinct data collection "centers" allow for multiple paths and mitigation of points of failure in the data flow from the GSN. There have been instances in the past when one or the other DCC were shutdown temporarily. However, due to having diverse data flow topologies, data from the complete GSN were not lost.

As discussed in the previous section, there has been a great deal of effort applied to data quality assurance. With new tools, metrics, and monitoring procedures applied not only at the DCCs, but also the DMC, data from the GSN are more robust, problematic stations are identified more quickly, and the actual state of data are more transparent to the end users. Tools developed for DMC usage are now applied to the entire IRIS archive, allowing data quality assessments for all the contributed dataset. This raises the bar on all data quality and helps in the resiliency of all data sets.

Global seismology resilience is also protected by international partnerships in global seismic station operations. With the FDSN, several International partners contribute to global seismic observations and the GSN has lead the way in establishing quality standards and practices that have vastly improved the quality and availability of the international partners in global seismology. Although complete loss of the GSN is unlikely, if this were to occur, there still exists a substantial network of high-quality stations that would provide partial global coverage.

Further, the government-academic partnership can be used to navigate and enhance international relationships and partnerships. There are some situations where a non-governmental organization (such as IRIS) or an academic-based organization (such as Project IDA at UCSD) can pursue agreements or partnerships that would be much slower to realize between government organizations. For example, IDA was able to use its endowment to establish a station in Pakistan at a time when the Pressler Amendment legally barred sending government-owned equipment there. In other situations, the US government, as represented by the USGS, can create government-to-government agreements and collaborations that would not otherwise be possible. The USGS' establishment of GSN affiliate stations in Afghanistan and throughout the Caribbean illustrates this capability very well.

Figure 7.2. Thermal isolation tests on M2166 seismometers at ASL utilize water- or sand-filled containers to dampen the effect of temperature on seismometer noise performance. Preliminary results show considerably slower thermal noise perturbation rates when using water-filled bricks in additional to a standard foam covering.

Figure 7.3. Metrozet M2166-VBB triaxial seismometer on the left and M2166-EM electronics module on the right. Metrozet seismometers have been deployed for testing at three GSN stations and ASL to evaluate their potential as a replacement vault instruments. Performance has been documented and subsequent work with Metrozet has resulted in further modifications to improve overall instrument performance.

8.0 GSN Renewal

The science that motivates the operation of the GSN requires continuous, high-level, long-term network performance. However, equipment and infrastructure age, and new technology and installation approaches provide new observing possibilities, leading to the need for ongoing and regular renewal of network components. *Leith* [2008] notes that: "Network completion is a beginning, not an end, and there is a need for continual rejuvenation of such a network, both to improve operational capabilities and to open new avenues for scientific exploration."

Stable funding is critical to ensure basic network operations are provided consistently and reliably. **Figure 8.0-1** illustrates network evolution for the WWSSN, a precursor network to the GSN. A period of intense spending during construction and capitalization rapidly expanded the number of stations, followed by a prolonged period during which the network operating budget was slowly reduced and the network decayed, with the number of stations reduced to save costs. Long-term, high-quality observations require a level of funding that sustains and renews the network. To this end, IRIS has advocated for the GSN with the NSF, the USGS, and the other organizations within the federal government that benefit and/or rely on GSN data as part of their operations. To date, NSF and USGS funding for the GSN has been augmented by funds from DoD, DOE, DoS, NOAA; funds from ARRA; and contributions from host nations in terms of land use and security. IRIS will continue to cultivate funding from those agencies that benefit from GSN data.

Broadly, there are three ranges of serviceable lifetimes of infrastructure fielded by the GSN. Typically, electronics and field computers have the shortest working lifetimes. The GSN has realized significant lifetimes with these systems, with the average age of data loggers (at II and IU stations) reaching 15 years prior to the next generation upgrade campaign (**Figure 8.0-2** illustrates the average ages of the II component of the GSN.) This was a remarkable service life, and it is prudent to assume a shorter life in the future because field computers and electronics have many of the same characteristics that lead to obsolescence (with typically much shorter working lifetimes) in other information technology equipment.

Sensors have a typical working lifetime of at least 10 to 20 years and sometimes more. At numerous GSN locations, the original sensors are still in service (**Figure 8.0-2**). As noted earlier, many of the original GSN borehole sensors

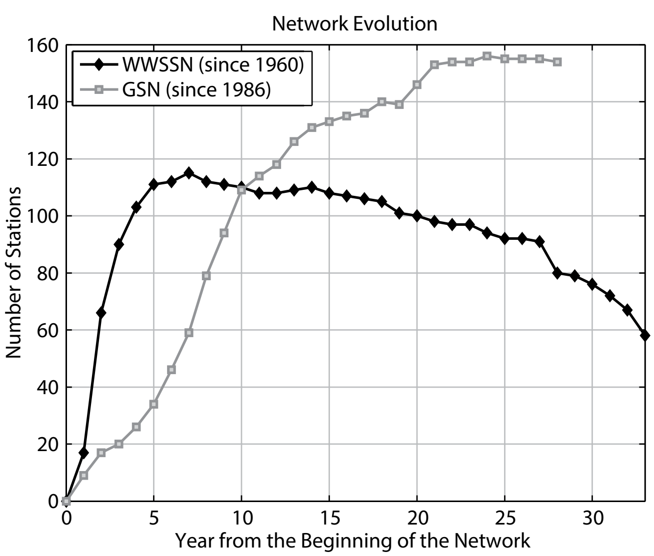


Figure 8.0-1. Comparison of WWSSN and GSN network evolution. The evolution of the number of WWSSN stations illustrates a sort of network decay curve that is often discussed in the context of large observing networks. A challenge for the GSN is to avoid the WWSSN's fate.

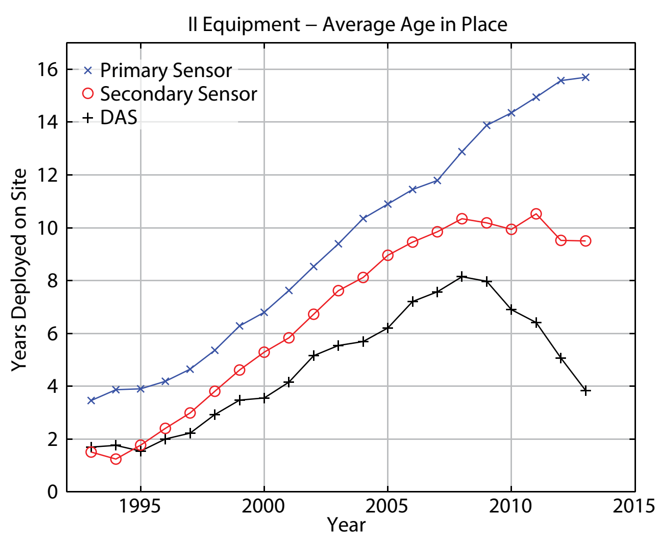


Figure 8.0-2. Age progression of hardware at GSN stations operated by Project IDA. By 2013, primary sensors at II stations were nearly 16 years old. Reduction in the age of secondary sensors and data loggers demonstrates the impact of renewal efforts

are now failing and require replacement. Installation conditions are also a factor in the service life of a station. It is clear that conditions at many GSN stations are not ideal—with (unavoidable) high levels of humidity being a particular culprit that degrades the performance of both mechanical and electrical systems.

Finally, civil works have working lifetimes of decades, but eventually all man-made construction exposed to the elements requires repairs and improvements—for example, roofs leak, concrete erodes, cables corrode, and typhoons happen.

8.1 Process and Plans for Network Renewal

The GSN renewal process involves community, governance, and management working together. GSN management monitors GSN performance, flags issues, identifies immediate service priorities, and projects long-term service cycles and needs. The GSN program manager presents this information to the GSN Standing Committee at least twice per year. Near-term issues are dealt with as a routine management task, with little need for further review or discussion with the Standing Committee. Intermediate- and longer-term issues require greater discussion—because such decisions implicitly involve the relative prioritization of existing work and the budget for such efforts is extremely limited. The Standing Committee, through its diverse membership and background, represents the needs and objectives of the GSN user community in this planning process.

At a high level, the present GSN renewal plans are focused around several major objectives:

- Replacement of the data acquisition equipment
- Replacement of the primary borehole sensors
- Replacements (as needed) of the primary vault sensors
- Repair/replacement of infrastructure
- Strategic relocation or infill of station sites
- Improvement of installation methods

Within the next five years, the current generation of data loggers used in the GSN will no longer be commercially available (even though the several year rollout of these systems was just completed) as this model of hardware will be roughly 15 years old. It will be necessary to project instrumentation needs and define specifications for the next "next generation" systems and begin cultivating funding sources for recapitalization.

As discussed earlier, the USGS is presently engaged in procuring replacement borehole sensors, and these units will be deployed at both USGS and IDA operated sites. Deployment of these sensors will be challenging for multiple reasons, including the need to make special installation trips as an effort above and beyond normal O&M activities, and the need to address infrastructure issues that must be rectified before the new sensors can be installed.

Although it is clear that some of the vault sensors are in need of replacement, there are no specific funds available for this task. If the USGS procurement of borehole sensors comes in under budget, there may be some funds left for procurement of vault sensors.

Civil works at a number of GSN sites are in serious need of remediation. Issues include boreholes that leak water, vaults with decaying piers, and vault buildings or equipment "huts" that leak and need repair. Most of these sites have been identified and roughly prioritized. IRIS has been working hard to obtain funding for these GSN activities, and it has recently been learned that President's FY16 budget includes augmented funding for the USGS to address these needs.

8.2 Challenges

Obtaining funding for new equipment and site repair/improvement is a first-order challenge for the maintenance and renewal of any network. IRIS, NSF, and the USGS have been successful in obtaining external funds required for several aspects of renewal, funds that are above and beyond normal operating budgets—roughly $22M since 2006 (see Section 9 for further discussion). The GSN continues to seek funding for recapitalization and the deployment of new equipment.

A key tension that arises when seeking extra funds is how to achieve balance between (re-)capitalization and O&M. When extra funds are obtained, they are often designated strictly for capital costs. A challenge that must be faced is how to deploy a large quantity of new equipment in a timely fashion, when such deployment "campaigns" are typically above and beyond normal O&M activities. Often such deployment campaigns require other deferred maintenance to be addressed (e.g., trying to avoid the situation of a new data logger being connected to an aging and failing power supply).

Another challenge is identifying how, and at what level, the GSN should take advantage of opportunities to develop enhanced international support for its stations. When the GSN was founded, there were few resources within host countries to adopt or support stations with GSN goals or to maintain stations to GSN standards. That situation has changed. Over the past 30 years, many host countries have developed national and regional networks that, in various ways, are based on GSN standards and procedures (a credit to the GSN). The advent of new techniques, such as the adoption of W-phase analysis, has changed how national networks view the importance of very broadband sensors. A challenge going forward is to identify how best to leverage these international efforts and interests.

The need for standardization is a challenge of running a large network. Standardization is critical to ensure high data return, enable consistent and predictable operations, and to control costs. It typically takes several years to complete upgrades, with the result that the upgraded hardware evolves through one or more models during the course of the upgrade. This challenge can best be addressed by completing upgrades quickly and well—which requires the ability to employ expert staff of sufficient size. The tension between network evolution and tight configuration control also existed throughout the 10 years of the EarthScope Transportable Array in the lower 48 states. Transportable Array results provide IRIS with a good case study that demonstrates the benefit of closely managing the evolution of station configuration.

Creating a routine process for projecting instrumentation needs and requirements, identifying the corresponding specifications, and communicating with vendors is always a challenge. This process tends to be used episodically, as funding is available. However, it is to the GSN's advantage to project desired targets and encourage vendors to spend their own research and development dollars towards reaching these targets. This process only works on an ongoing basis if development directions generally lead towards procurement activities.

A key role for IRIS and the USGS in managing the GSN is to address the challenges identified above. The GSN must serve the scientific community, and this community continuously drives network evolution—to make more, increasingly diverse, and better observations. However, the GSN must also meet steady-state operational objectives. It is important that a focus on bottom line costs does not drive the network toward stasis.

9.0 GSN Management and Governance

This section provides an overview of the GSN management, budget, and governance structures. Coordination between IRIS and USGS operations are discussed, including the benefits and challenges of a multi-operator approach.

9.1 Management

Figures 9.1-1 to 9.1-3 display organization charts and staffing levels for relevant GSN operations at IRIS, IRIS/IDA, and the USGS ASL.

In 2010, IRIS restructured its management to create three directorates, encompassing Instrumentation Services (IS), Data Services (DS), and Education and Public Outreach (EPO). The Instrumentation Services directorate brings together all of IRIS' observing programs under one umbrella, with the goal of taking greater advantage of commonalties across them, and improving the efficiency of interactions with the other IRIS directorates. With this new structure, the IS management team is able to share expertise to the benefit of each program and work together on pan-IRIS projects. The senior managers within IS include the IS Director, the GSN Program Manager, the Portable Program Manager, the Ocean Bottom Seismograph Instrument Pool Project Manager, and the Transportable Array Manager (see red boxes in **Figure 9.1-1**). Some examples of areas where the IS management team have collaborated include major procurements, developing a common approach to data quality, subrecipient monitoring, and instrument testing. Some of these nascent efforts, particularly related to data quality and instrument testing, will continue to develop under the SAGE award.

Over the past 10 years, the IRIS GSN Program Manager position has evolved significantly. Currently, the GSN Program Manager oversees the Project IDA subaward activities, coordinates with USGS staff on procurements and activities, interfaces with GSN stakeholders, coordinates with other IRIS programs, and works with the IRIS Director of Planning to develop external recapitalization funding. In response to the 2003 external review, GSN management was expanded from one position to two, with the creation of a GSN Operations Manager position. Kent Anderson was hired for this new position, and his time was split among the GSN, USArray Permanent Array, and serving as the IRIS Polar Coordinator managing various IRIS Polar activities. Upon the departure of previous GSN Program Manager Rhett Butler, Kent Anderson became the acting GSN Program Manager, then permanent GSN Program Manager, but he still carried the Polar Coordinator duties. This split position did not allocate sufficient time to the GSN Program Manager duties, and in 2013, IRIS decided that the Polar coordination duties should be staffed separately.

In 2014, and in response to opportunities created by staff departures, IRIS settled on a new structure for the management of the GSN and PASSCAL programs as well as Polar activities. A new position, Portable Programs Manager, would oversee both the PASSCAL program and Polar activities, as these two sets of activities are closely interrelated. This person would be assisted by a newly created Project Associate position. The GSN Program Manager position would then be solely dedicated to managing the GSN. These changes had the effect of organizing the work more efficiently and logically, and staffing the work with a cost-effective mix of senior and junior personnel. Kent Anderson agreed to take on the new role of Portable Programs Manager. Following IRIS policy, the IRIS Board of Directors appointed a committee to conduct a search for a new GSN Program Manager. Katrin Hafner was selected, beginning in this role on January 20, 2015, and bringing significant experience in network operations to the GSN from her experience as the Transportable Array Chief of Operations.

Within Project IDA at UCSD, the Director provides overall guidance for the project, and the Executive Director provides day-to-day management (**Figure 9.1-2**). This structure has been in place for over 10 years and has worked very efficiently. Both the Director and Executive Director attend GSN Standing Committee meetings to ensure communication across both program management and governance. The Executive Director provides direct line management for both the GSN network operations and data collection center teams.

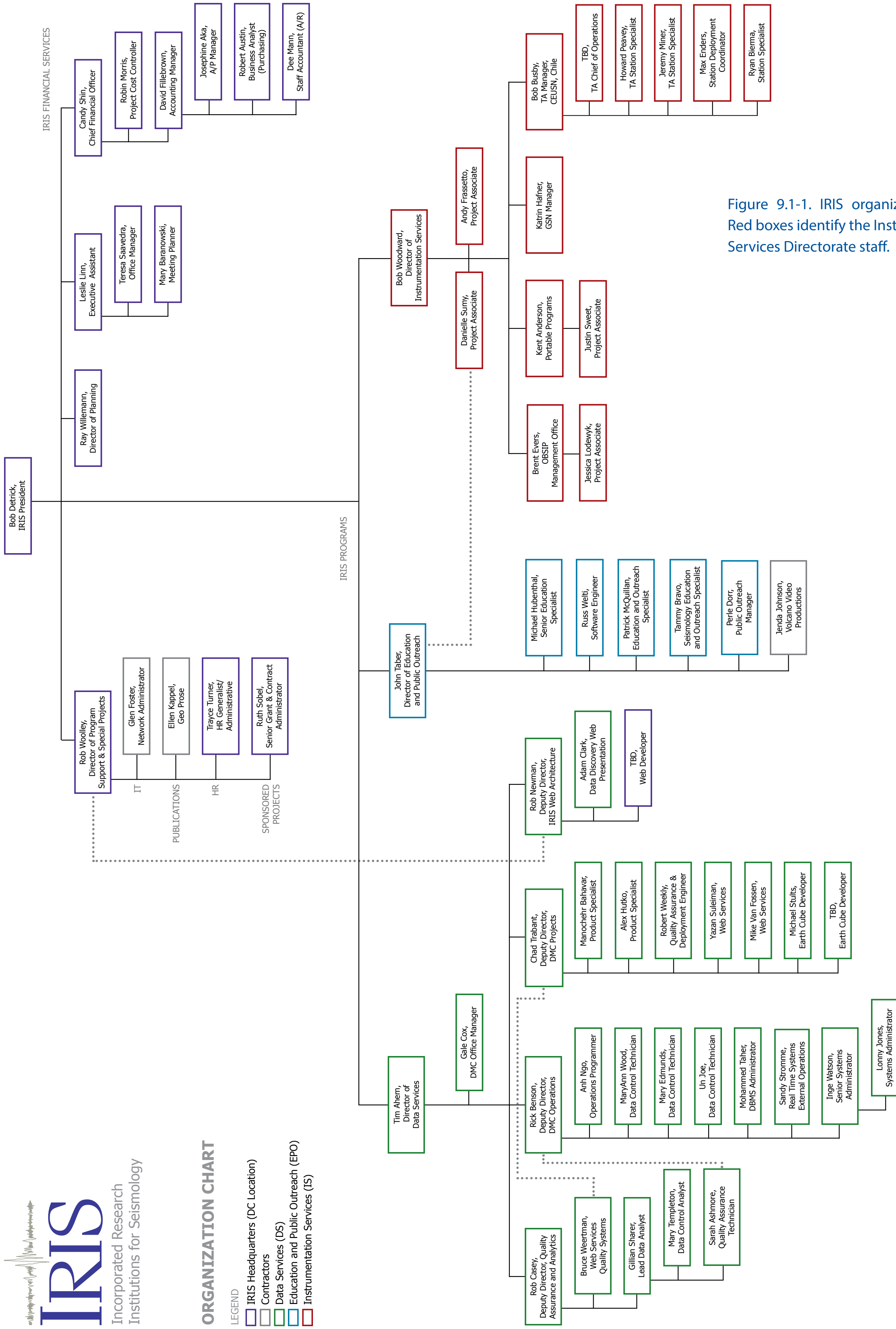


Figure 9.1-1. IRIS organization chart. Red boxes identify the Instrumentation Services Directorate staff.

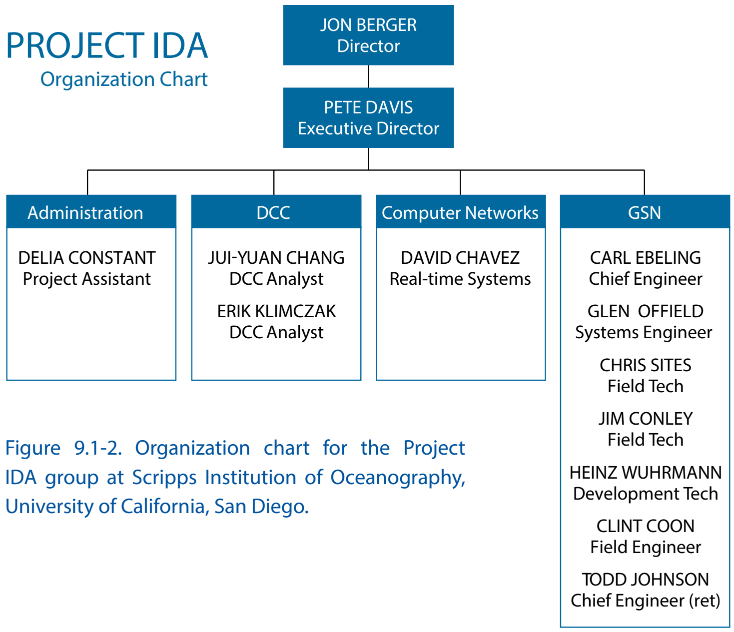


Figure 9.1-2. Organization chart for the Project IDA group at Scripps Institution of Oceanography, University of California, San Diego.

The USGS component of the GSN is one of six science programs within the USGS Natural Hazards Mission Area, and is a line item in the USGS budget. The GSN is operated by the Albuquerque Seismological Laboratory, which is managed by the Geologic Hazards Science Center in Golden, Colorado. Lind Gee served as the scientist in charge of ASL until December 2014 and was succeeded by David Wilson in January 2015. Programmatic responsibility for the GSN is overseen by the Senior Science Advisor for Earthquake and Geologic Hazards and by the Associate Coordinator for the GSN at the USGS headquarters in Reston.

The collective leadership provided by the GSN Program Manager, the GSN Standing Committee, and the management of the USGS and IDA network operations groups is key to making the GSN structure work. This structure brings both scientific- and mission-centric perspectives to the operations, and leverages both government and academic R&D environments.

9.2 Budget

Figure 9.2-1 shows the history of NSF and USGS GSN funding and documents the substantial investment that both organizations have made. The figure shows the ongoing annual core funding from both IRIS and USGS, though for historical reasons, the IRIS core funding in this graph does not include the IDA DCC activity. Special funding augmentations have contributed to the periodic recapitalization of the network. Since 2005 (post Sumatra earthquake), there has been over $22 M in external recapitalization funding. This total may, in fact, be an underestimate. In the early 1990s, there was additional DoD funding that was used as part of the IRIS Joint Seismic Program for activities in the Former Soviet Union. Because these funds covered a variety of activities (some PASSCAL-like, others more GSN and DMC related), they were not strictly tracked against the GSN. More recently, the President's 2016 budget also contains a proposed ~$5 M increase in the USGS GSN budget to assist in the installation of next generation borehole sensors (see details in Section 8).

Tables 9.2-1 to 9.2-3 provide a more detailed view of how the core IRIS and USGS budgets are allocated and expended. Labor makes up the biggest component of both the IRIS expenditures (via the subaward to UCSD) and USGS expenditures. Note that Tables 9.2-1 and 9.2-2 do include the costs of the IDA DCC activity. During this five-year period (July 1, 2009, to June 30, 2014), an augmentation of $5 M was received (beginning in FY10) by IRIS, and these funds were used to fund the upgrade to next generation data loggers. The augmentation funds were used both to acquire data loggers and to implement a deployment campaign to get these instruments into the field in a timely fashion. The USGS received an ARRA augmentation of ~$5 M as well, to similarly procure and deploy next generation equipment. The "next generation" recapitalization plan was formulated after the Great Sumatra Earthquake. When the ARRA funds became available, the GSN recapitalization plan was deemed "shovel ready" and was funded in part. In 2011, the Department of Energy National Nuclear Security Administration provided $5.7 M to develop and procure next generation primary borehole sensors. These funds were distributed to the USGS and can only be used for the purchase of equipment and not for enhanced deployment activities.

Table 9.2-1 summarizes the IRIS GSN expenditures. Most costs for operating the IRIS/IDA portion of the GSN are included within the IDA subaward, which is further detailed in Table 9.2-2. Among IRIS' non-subaward costs are funds for "ASL", which is a small pool of funds that are used when, for various reasons, it is most efficient to have IRIS purchase items for the IRIS/USGS component of the network. The "communications" costs cover routine, recurring satellite telemetry costs. The "site prep" funds are used to perform civil works at station sites—typically to repair aging infrastructure. The "hardware" funds cover equipment (items that cost more than $5 K) and materials and supplies, and these items may include sensors, power

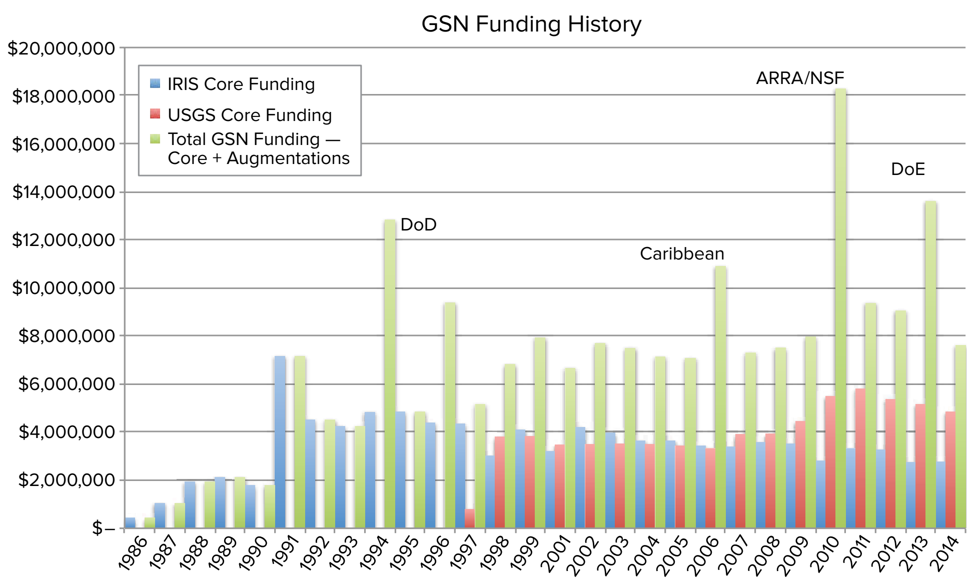


Figure 9.2-1. Funding of the GSN over time. The green bars show the total GSN funding, which is the sum of IRIS and USGS core funding plus any special augmentations. The major augmentations of the GSN budget are labeled, and total $20.5 M over the past ten years.

systems, communications equipment, data loggers, and other ancillary equipment. The "array workshop" was held as an adjunct to the 2013 EarthScope National Meeting to bring global seismologists together to discuss the state-of-the-art in international array seismology.

The IDA subaward budget expenditures cover two primary activities, GSN operations and the Data Collection Center. Within these two tasks, the majority of the budget goes into labor, then equipment and travel. As **Table 9.2-2** indicates, during the five-year period presented here, some of the augmentation funds were spent directly by IDA, via their subaward.

Table 9.2-3 presents the USGS core GSN expenditures. Station O&M comprises almost 75% of the budget, with the Data Collection Center and data QC activities ("Data QC" in the table) being the next largest item.

Table 9.2-1. Summary of the IRIS core GSN expenditures for the past five years.

Category	YR 1 7/1/09-6/30/10	YR 2 7/1/10-6/30/11	YR 3 7/1/11-6/30/12	YR 4 7/1/12-6/30/13	YR 5 7/1/13-6/30/14	Total 7/1/09-6/30/14
Program Management and Governance	$548,909	$422,705	$293,966	$318,106	$308,401	**$1,892,088**
ASL	$224,265	$-	$7,918	$150,384	$144,428	**$526,995**
Communications	$48,716	$120,452	$60,833	$38,326	$57,581	**$325,908**
Site Work (ASL/IDA)	$24,424	$55,247	$149,543	$30,153	$74,797	**$334,164**
Hardware	$-	$-	$89,250	$5,325	$229,447	**$324,022**
Array Workshop	$-	$-	$-	$42,609	$-	**$42,609**
QC Enhancements	$-	$-	$-	$-	$22,002	**$22,002**
IDA - GSN Operations	$2,396,356	$1,897,905	$2,118,272	$2,049,685	$2,535,766	**$10,997,984**
IDA - Data Collection Center	$754,998	$729,305	$608,738	$638,572	$508,055	**$3,239,668**
Augmentation	$2,488,652	$1,489,467	$976,103	$353,852	$-	**$5,308,074**
Total	**$6,486,320**	**$4,715,081**	**$4,304,624**	**$3,627,012**	**$3,880,477**	**$23,013,513**

Table 9.2-2. Summary of the IDA expenditures for the past five years.

Category	YR 1 7/1/09-6/30/10	YR 2 7/1/10-6/30/11	YR 3 7/1/11-6/30/12	YR 4 7/1/12-6/30/13	YR 5 7/1/13-6/30/14	Total 7/1/09-6/30/14
Operations	$2,390,826	$1,854,089	$2,107,253	$2,043,862	$2,523,260	**$10,919,290**
Site Work	$-	$-	$21,397	$22,756	$21,429	**$65,582**
DCC	$754,998	$729,305	$608,738	$638,572	$508,055	**$3,239,668**
Augmentation	$247,393	$339,611	$304,884	$6,039	$-	**$612,477**
Total	**$3,393,217**	**$2,923,005**	**$3,042,271**	**$2,711,229**	**$3,052,744**	**$15,122,467**

Table 9.2-3. Summary of the USGS core GSN expenditures for the past five years.

Category	FY11	FY12	FY13	FY14	FY15	Total
GSN station O&M	$2,688,690	$3,086,005	$2,991,401	$2,838,143	$2,844,423	**$14,448,662**
Data QC	$624,933	$745,328	$755,645	$489,130	$489,948	**$3,104,984**
ASL facilities	$300,460	$256,440	$317,114	$343,795	$339,279	**$1,557,088**
Instrument Testing	$314,073	$377,600	$240,381	$283,684	$283,152	**$1,498,890**
Total (net)	**$4,000,143**	**$4,496,261**	**$4,304,540**	**$3,954,752**	**$3,956,803**	**$20,712,499**
Net allocation	$4,271,326	$4,114,658	$3,989,735	$3,980,801	$3,974,743	$20,331,263
Gross Allocation	$5,379,220	$5,321,490	$4,852,969	$4,853,000	$4,853,000	$25,259,679

Note: Actual expenditures can differ from net allocation from year to year due to funds being carried over from one fiscal year (FY) to the next.

The core operating budgets do not have any large-scale investment in recapitalization for the GSN. As noted above, these funds have successfully been obtained from external sources. A lower bound estimate for the replacement value of the equipment deployed at GSN sites is $15 M to $20 M. Assuming an optimistic estimate of 10 to 15 year lifespan for most of this equipment, the annualized investment in recapitalization should be $1 M to $2 M or more. This is roughly in line with the external recapitalization funding rate shown in Figure 9.2-1. Another item of note is the IRIS and USGS budgets do not have a specific line item for research and development (R&D). R&D activities are funded at a very modest level as part of operational activities and testing.

In addition to the USGS and IRIS/IDA budgets, in-kind contributions come from other organizations, particularly station host organizations that provide services related to station operations at no cost.

9.3 Governance

Figure 9.3-1 shows the IRIS governance structure. Governance for the GSN is provided first and most directly by the GSN Standing Committee, which meets in person twice per year. The GSN Standing Committee advises the Board of Directors and the GSN program managers at IRIS and USGS on policies to deploy and operate the GSN, to ensure its integrity and long-term viability, to rapidly disseminate data collected by it, and coordinate linkages with other networks around the world. The GSN Standing Committee includes nine members selected from the IRIS community and rotates one-third of this membership per year. The IRIS Board of Directors appoints incoming members to three-year terms based on recommendations developed by the GSN Standing Committee. Members are selected to provide diverse community representation—in terms of disciplines, gender, and institution and geography.

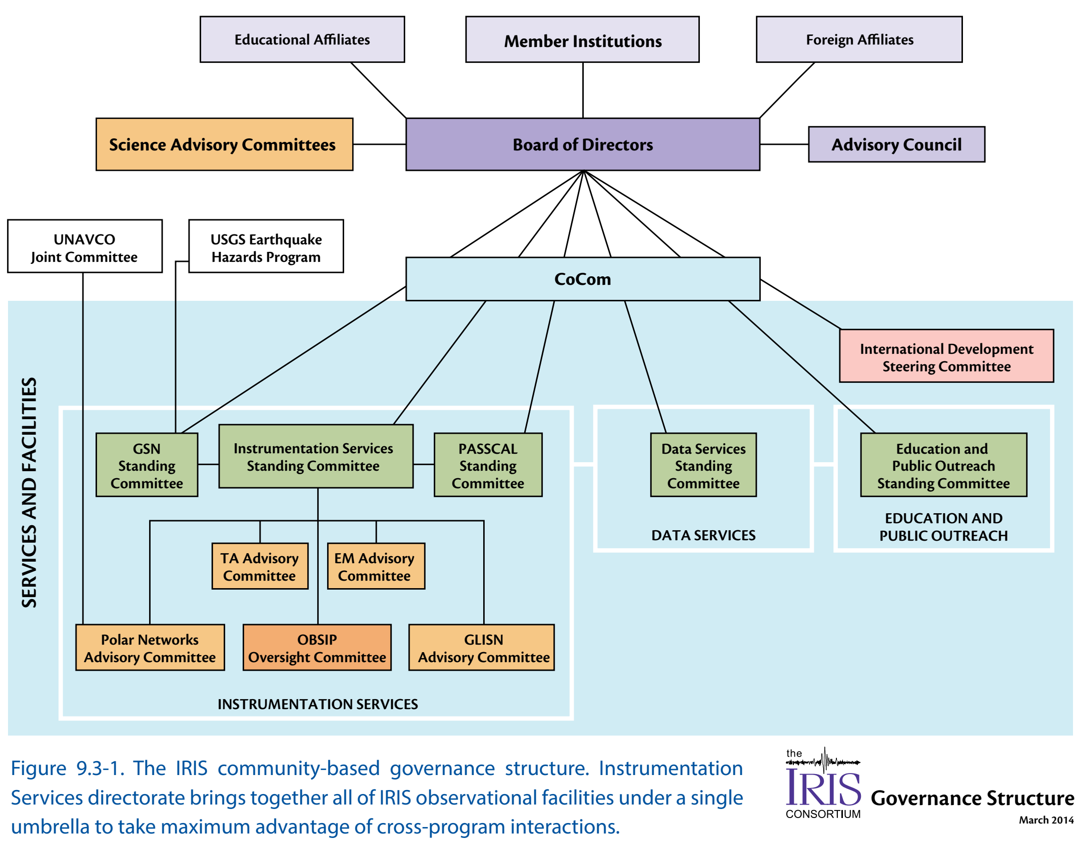


Figure 9.3-1. The IRIS community-based governance structure. Instrumentation Services directorate brings together all of IRIS observational facilities under a single umbrella to take maximum advantage of cross-program interactions.

The charge for the GSN Standing Committee is provided on the IRIS website (http://www.iris.edu/hq/about_iris/governance/gsn) and includes a number of very specific activities as well as this broad direction:

> *…advises the Board of Directors and the GSN program managers at IRIS and USGS on policies to deploy and operate the Global Seismographic Network, to ensure its integrity and long-term viability, to rapidly disseminate data collected by the GSN, and coordinate GSN linkages with other networks around the world.*

A key aspect of the GSN Standing Committee is that it serves a dual role—advising both the IRIS Board of Directors and the USGS with respect to operation of the GSN. The USGS participates directly in the GSN Standing Committee via an ex officio, voting member (Appendix C), a position held by the USGS ANSS Coordinator and Associate Coordinator for Earthquake Hazards, Global Seismographic Network, and Geomagnetism Programs (Cecily Wolfe). IRIS-USGS coordination is further strengthened by having the USGS ASL Director sit as an observer on the GSN Standing Committee and via a long tradition of appointing a staff member of the USGS NEIC as a regular committee member.

The GSN Standing Committee interacts closely with the recently established Instrumentation Services Standing Committee to ensure that GSN activities are coordinated with the rest of IRIS' instrumentation activities, and vice versa. The GSN Standing Committee chair is an ex officio member of the IS Standing Committee. The first IS Standing Committee meeting took place in October of 2014 and will continue to convene in person twice per year. The two standing committees interact with other programs, committees, and directorates through the Coordinating Committee. Budgets and key decisions are forwarded to the IRIS Board of Directors for approval, but the GSN Standing Committee reports directly to the IRIS Board of Directors.

The IS Standing Committee was created as part of a restructuring of the IRIS governance when its traditional (core) programs and USArray activities were merged under the SAGE award. IRIS recognized that it has a broad range of observing programs (PASSCAL, Transportable Array, OBSIP) that were making similar observations, in many cases with similar (or the same) equipment, installation techniques, and the like. This new standing committee is intended to leverage better, and derive synergy from, these multiple capabilities. The committee's terms of reference state that the IS Standing Committee will:

> *… identify crosscutting instrumentation needs and services, develop activities and initiatives across Instrumentation Services programs, and ensure effective and efficient use of resources. The committee will undertake strategic planning to ensure the best use of existing resources and to identify future needs and opportunities.*

As noted earlier, the managers within the Instrumentation Services directorate have already derived significant benefit from sharing expertise across programs, and it is expected that the same will be true of the new governance structure. As this updated IRIS governance proceeds, it will be evaluated and modified to ensure that it is fulfilling its role.

All service by community members on IRIS governance committees is on a pro bono, volunteer basis. As other organizations have emulated IRIS' community governance model, many community members find themselves serving on committees for multiple organizations. Thus, a continuing challenge for IRIS governance is not overtaxing community members. However, community governance is critical to effective management of the GSN. As part of the restructuring of IRIS governance, the Board of Directors paid careful attention to the requirements for meeting attendance, trying to balance in-person meetings and Web-based meetings.

9.4 Partnerships

A variety of national and international partnerships are vital to achieving GSN objectives. The GSN is itself a partnership between NSF, IRIS, and the USGS. At the operations and mission level, the partnerships with NOAA and CTBTO are intimately connected to data flow and data delivery. Through the FDSN there are partnerships with global and national networks operated by other countries that are essential to achieving the GSN's worldwide coverage.

At the individual station level, the network operators have cultivated long-standing relationships with local hosts. The hosts provide access to the land and are key to site security, infrastructure, and communications, and are essential in allowing permanent installation permits and customs clearances. There are numerous MoUs related to the station host relationships. These MoUs are executed by the GSN with agencies/departments of foreign governments as well as public and private universities and other institutions. On the GSN side, the signatories to these MoUs and agreements include various combinations of IRIS, NSF, USGS, and IDA (e.g., IRIS plus IDA plus the foreign institution, or sometimes just IRIS and the foreign institution, or sometimes just IDA and the foreign institution).

10.0 Summary

The preceding sections have provided an overview of the GSN to facilitate the 2015 review of the GSN program. The information that has been provided makes clear that the GSN fulfills both scientific and operational missions via a multifaceted international program that is operated as a partnership between NSF/IRIS and the USGS.

The design goals of the GSN have largely been met. The GSN generates high dynamic range, very broadband, continuous, real time data from a global network of stations. The GSN is a standard for international, national, and regional network design, capability, and operations. The GSN coordinates coverage, instrumentation, and practices with network operators worldwide by participating in international efforts, like the FDSN. GSN stations often serve as key elements in national and regional observing capabilities. Continued well-established host country relationships at all GSN stations have allowed multi-decadal scale observations from high quality stations around the world.

A review of the current state of instrumentation in the GSN highlighted the success of the recent upgrade to a "next generation" standardized data logger. Current hardware upgrade plans are focused on the VBB borehole instruments. The challenges of operating aging hardware were discussed, though the overall network uptime is good. In particular, the upgrade of the data loggers demonstrated the positive impact that upgrading aging equipment can have on uptime. Further, quality-related measurements are now being incorporated into the network operations metrics to go beyond uptime as a measure of network performance. Station performance at GSN sites, as measured by background noise levels, compares very well with peer networks. This result is notable since global coverage sometimes necessitates favoring station location and distribution over optimizing site noise. A review of GSN coverage indicates that the planet is generally well-covered, though stubborn gaps remain in the coverage of the ocean basins. There is significant reliance on international partners in some key areas of the globe (particularly in the southern Indian Ocean region).

The management of GSN data works well and is successfully archiving and distributing a large volume of data. The data are distributed to a large number of users both nationally and internationally, with the entire GSN data volume being distributed multiple times over. The data distribution statistics indicate that the research and operational utilization of the data is healthy and vibrant and the GSN has the highest volume of requested data from the entire IRIS DMC archive.

The management and operational partnership between NSF/IRIS and the USGS is an inter-governmental collaboration success story. Through this partnership the GSN serves the interests and needs of both research and operational communities, to the benefit of both. The dual network operator structure has provided the flexibility, adaptability, and redundancy necessary to deal with unique circumstances and has increased the resilience of the GSN.

The utilization of GSN data for scientific research is broad and deep. Studies have focused on the entire planet, or a single earthquake, and from the Earth's crust to core. Studies have used the entire multi-decade record of the GSN, or single narrow windows of time. Yet the science research vignettes presented in Section 5 are only a small sampling of the range of research that is based on GSN data, as the extensive bibliography in the appendix makes clear. While some of the science results from GSN data were considered as part of the original science justification for the GSN, there have been numerous unanticipated uses of the GSN (e.g., glacial earthquakes or the teleseismic detection of landslides) and this report made no attempt to identify or catalog these.

Data from the GSN are used every day as part of the operational missions of the USGS NEIC, tsunami warning centers, the Comprehensive Nuclear-Test-Ban-Treaty Organization, and other organizations. The characteristics of the GSN that are so critical for research, such as high quality, global distribution, real time telemetry, are no less important to these operational activities.

Data quality has been a significant focus of the GSN in recent years. The GSN has responded to quality challenges by developing new processes, procedures, tools, and metrics to better manage quality in all aspects of network operation. The tools, practices, and results developed for the GSN are being shared, and it is hoped that the GSN will be seen as an international gold standard in data quality process and practice, as it already is in technology and operations.

It is an important concept that an international network must be resilient. There are many difficulties, large and small, that must be overcome on an almost continuous basis. In many aspects of the GSN resilience is built in—dual operators, dual DCCs, multiple telemetry paths, multiple sensors, and so on. The operational structure that is fundamental to the GSN is fundamental to its resilience.

Network renewal is key to resilience, to quality, and to the continued evolution that is essential to remain a state-of-the-art global network. Renewal of the GSN requires careful attention to instrument replacement needs, evolving requirements, new technology, as well as the recapitalization that is essential to pay for these activities. The GSN has been almost continuously engaged in renewal, has critical renewal activities under way at present (such as the borehole sensor replacement), and has a governance structure that is engaged on the topic. But renewal is not easy and several challenges exist, such as establishing the optimum level of standardization and developing an ongoing process for projecting equipment needs and capabilities into the future.

This report identified the management structures of the IRIS, Project IDA, and USGS organizations that are responsible for the GSN. These structures benefit the GSN by bringing the research and monitoring objectives to bear in a coordinated, mutually beneficial fashion. The successful funding history of the GSN—both the internal core funding from NSF/IRIS and the USGS, and the external recapitalization funding—has enabled stable operations throughout the GSN's life. A well-established common structure, the GSN Standing Committee, advises both IRIS and the USGS. This Standing Committee leverages IRIS' robust community governance model, and has benefited from wide participation within the IRIS community as well as broader national and international research and operational monitoring activities. The diverse IRIS community has been able to engage with and respond to congressional interest in funding the GSN for the benefit of the research community, the USGS, and other agencies and partners. Both the management and governance of the GSN benefit from synergies with IRIS' other instrumentation activities.

Taken together, the aforementioned structures and activities ensure that the GSN is a state-of-the-art facility for observational seismology. The results from the research and operational activities that rely on GSN data are a testament to this. But improvements are always possible. In fact, a key feature of the GSN over the decades is that it has evolved and adapted to improve its capabilities and operation.

References

Aster, R.C., D.E. McNamara, and P.D. Bromirski (2010), Global trends in extremal microseism intensity, *Geophysical Research Letters,* **37**, L14303, doi:10.1029/2010GL043472.

Ekström, G., C.A. Dalton, and M. Nettles (2006), Observations of time-dependent errors in long-period instrument gain at global seismic stations, *Seismological Research Letters*, **77**, 12–22.

Ekström, G., M. Nettles, and A.M. Dziewonski (2012), The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes, *Physics of the Earth and Planetary Interiors,* **200–201**,1–9.

Dziewonski, A.M., and D.L. Anderson (1981), Preliminary Reference Earth Model, *Physics of the Earth and Planetary Interiors*, 25, 297–356.

French, S., and B. Romanowicz (2014), Whole mantle radially anisotropic shear-velocity structure from spectral-element waveform tomography, *Geophysical Journal International*, **199**, 1303–1327.

Gaherty, J.B., and R.A. Dunn (2007), Evaluating hot spot–ridge interaction in the Atlantic from regional-scale seismic observations, *Geochemistry, Geophysics, Geosystems*, **8**, Q05006, doi: 10.1029/2006GC001533.

Gee, L., M. Nettles, G. Ekström, J. Davis, A. Ringler, T. Storm, D. Wilson, and K. Anderson (2014), Five years on: Revisiting GSN data quality, AGU Fall Meeting abstract.

Hayes, G.P., M.W. Herman, W.D. Barnhart, K.P. Furlong, S. Riqyelme, H.M. Benz, S. Barrientos, P.S. Earle, and S. Samsonov (2014), Continuing megathrust earthquake potential in Chile after the 2014 Iquique earthquake, *Nature*, **512**, 295–298, doi: 10.1038/nature13677.

Ide, S., A. Baltay, and G.C. Beroza (2011), Shallow dynamic overshoot and energetic deep rupture in the 2011 M_w 9.0 Tohoku-Oki earthquake, *Science*, **332** (6036), doi: 10.1126/science.1207020.

IRIS (1984). Design considerations for a new Global Seismographic Network. Appendix 1C in *Imaging the Earth's Interior: Detailed Studies of the Earth and of the Seismic Source with the New Global and Transportable Arrays*, A proposal to the National Science Foundation, the Incorporated Research Institutions for Seismology, Washington, DC, http://www.iris.edu/hq/files/programs/gsn/documents/historical/IRIS_Rainbow_proposal_1984_App1C.pdf.

Kiser, E., and M. Ishii (2011), The 2010 Mw 8.8 Chile earthquake: Triggering on multiple segments and frequency-dependent rupture behavior. *Geophysical Research Letters*, **38**, L07301, doi: 10.1029/2011GL047140.

Koper, K.D., and C.J. Ammon (2013), Planning a global array of broadband seismic arrays, *Eos Transactions, AGU*, **94**(34), 300, doi: 10.1002/2013EO340005.

Kumar, P., X. Yuan, R. Kind, and G. Kosarev (2005), The lithosphere-asthenosphere boundary in the Tien Shan-Karakoram region from S receiver functions: Evidence for continental subduction, *Geophysical Research Letters*, **32**, L07305, doi: 10.1029/2004GL022291.

Kustowski, B., G. Ekstrom, and A.M. Dziewonski (2008), Anisotropic shear-wave velocity structure of the Earth's mantle: A global model, *Journal of Geophysical Research,* **113,** B06306, doi: 10.1029/2007JB005169.

Leith, W. (2008), Challenges ahead for the Global Seismographic Network*, Seismological Research Letters,* **79**(2), 155–157.

Lekic, V., S. Cottaar, A.M. Dziewonski, and B. Romanowicz (2012), Cluster analysis of global lower mantle tomography: A new class of structure and implications for chemical heterogeneity, *Earth and Planetary Science Letters*, **357–358**, 68–77, doi: 10.1016/j.epsl.2012.09.014.

Lin, F.-C., and V.C. Tsai (2013), Seismic interferometry with antipodal station pairs, *Geophysical Research Letters,* **40**, 4609–4613, doi: 10.1002/grl.50907.

Nettles M., and G. Ekström (2009), Some observations of data quality at global seismic stations, IRIS Seismic Instrument Technology Symposium, Palm Springs, CA.

Panning, M.P., and B. Romanowicz (2006), A three-dimensional radially anisotropic model of shear velocity in the whole mantle, *Geophysical Journal International*, **167**, 361–379, doi: 10.1111/j.1365-246X.2006.03100.x.

Park, J., A. Amoruso, L. Crescentini, and E. Boschi (2008), Long-period toroidal earth free oscillations from the great Sumatra-Andaman earthquake observed by paired laser extensometers in Gran Sasso, Italy, *Geophysical Journal International*, **173**, 887–905, doi: 10.1111/j.1365-246X.2008.03769.x.

Pasyanos, M.E., and W.R. Walter (2009), Improvements to regional explosion identification using attenuation models of the lithosphere, *Geophysical Research Letters*, **36**, L14304, doi:10.1029/2009GL038505.

Peterson, J. (1993), *Observation and Modeling of Seismic Background Noise*, U.S. Geological Survey Technical Report 93-322.

Ringler, A.T., M.T. Hagerty, J. Holland, A. Gonzales, L.S. Gee, J.D. Edwards, D. Wilson, and A.M. Baker (2014), The data quality analyzer: A quality control program for seismic data, *Computers and Geosciences*, doi: 10.1016/j.cageo.2014.12.006.

Ritsema, J., A. Deuss, H.J. van Heijst, and J.H. Woodhouse (2011), S40RTS: A degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements, *Geophysical Journal International*, **184**, 1223–1236.

Roessler, D., F. Krueger, M. Ohrnberger, and L. Ehlert (2010), Rapid characterisation of large earthquakes by multiple seismic broadband arrays, *Natural Hazards and Earth System Science*, **10**, 923–932.

Rychert, K., and P. Shearer (2009), A global view of the lithosphere-asthenosphere boundary, *Science*, **324**, 495–498, doi: 10.1126/science.1169754.

Schmerr, N., E. Garnero, and A. McNamara (2010), Deep mantle plumes and convective upwelling beneath the Pacific Ocean, *Earth and Planetary Science Letters*, **294**, 143–151.

Simmons, N.A., A.M. Forte, and S.P. Grand (2009), Joint seismic, geodynamic and mineral physical constraints on three-dimensional mantle heterogeneity: Implications for the relative importance of thermal versus compositional heterogeneity, *Geophysical Journal International*, **177**, 1284–1304, doi: 10.1111/j.1365-246X.2009.04133.x.

Trampert, J., and H.J. van Heijst (2002), Global azimuthal anisotropy in the transition zone, *Science*, **296**(5571), 1297–1299.

Visser, K., J. Trampert, and B.L.N. Kennett (2008), Global anisotropic phase velocity maps for higher mode Love and Rayleigh waves. *Geophysical Journal International*, **172**(3), 1016–1032, doi: 10.1111/j.1365-246X.2007.03685.x.

Yuan, H., and B. Romanowicz (2010), Lithospheric layering in the North American Craton, *Nature*, **466**, 1063–1068, doi: 10.1038/nature09332.

Yuan, K., and C. Beghein (2013), Seismic anisotropy changes across upper mantle phase transitions, *Earth and Planetary Science Letters*, **374**, 132–144, doi: 10.1016/j.epsl.2013.05.031.

Yuan, K., and C. Beghein (2014), Three dimensional variations in Love and Rayleigh wave azimuthal anisotropy for the upper 800km of the mantle, *Journal of Geophysical Research,* **119**, 3232–3255, doi: 10.1002/2013JB010853.

Zhan, Z., D.V. Helmberger, and D. Li (2014a), Imaging subducted slab structure beneath the Sea of Okhotsk with teleseismic waveforms, *Physics of the Earth and Planetary Interiors,* **232**, 30–35.

Zhan, Z., D.V. Helmberger, H. Kanamori, and P.M. Shearer (2014b), Supershear rupture in a M_w 6.7 aftershock of the 2013 Sea of Okhotsk earthquake, *Science*, **345**, 6193, 204–207.

Appendix A. Charge to the Review Committee for the Global Seismographic Network

GSN Review

The Review Committee for the Global Seismographic Network (GSN) is charged with providing a full external review of the GSN, including its goals and scope, its management and operations, its technology and data quality, and its costs. The Committee is asked to provide recommendations and advice to the IRIS Board of Directors and President, and to the National Science Foundation (NSF), on ways to maintain the quality and improve the operations, efficiency and scientific return of the network. The review should take a long-term perspective and consider how to ensure the continued viability of the network and quality of operations over the next decade.

While the primary purpose of the committee is to review and report on those activities that fall under the IRIS/NSF program, it is recognized that the GSN is a collaborative project that includes the U.S. Geological Survey (USGS) and international partners. It is also recognized that GSN data are used by other U.S. government agencies such as NOAA and DOE. NSF and IRIS will work closely with the USGS to ensure that the deliberations of the committee and the implementation of its recommendations are coordinated with those activities of the GSN that involve the USGS and other U.S. government agencies. International GSN partners and the Federation of Digital Seismographic Networks (FDSN) will be informed of the review, invited to provide input and provided with a summary of the Committee's recommendations.

Major emphasis will be placed on the Global Seismographic Network itself – i.e. "operations, personnel and instrument costs" as supported through the IRIS GSN Program. However, the review also should include those activities related to quality control and data management and distribution related to the GSN that fall under IRIS Data Services.

Mandate

The Cooperative Agreement (CA) between the IRIS Consortium and the National Science Foundation requires IRIS to: *"By the end of the second year of this CA, conduct a full external review of the GSN, including all associated subawards, and exploring alternative configurations, management approaches, and the possible* *scientific impacts. The review will be developed and carried out in collaboration with the USGS. The Awardee will keep the NSF Program Officer informed throughout the process."*

Membership

The committee will be appointed as specified under Article V, Section 4 of the IRIS By Laws, which states: "*The President may appoint advisory committees or panels to assist in carrying out the business of the Corporation*".

The Review Committee for the Global Seismographic Network will consist of a Chair plus six members. Members of the committee will be appointed by the IRIS President in consultation with the IRIS Board of Directors, the Program Director for SAGE (Seismological Facilities for the Advancement of Geoscience and Earthscope) award at the National Science Foundation and the Program Coordinator for the GSN program at the USGS.

Members will be chosen to minimize real or perceived conflicts of interest with IRIS or the GSN network operators

Schedule

It is anticipated that the committee will require one or more meetings in the first quarter of 2015. A final report will be presented to IRIS and NSF by April 15, 2015.

The committee will be briefed by IRIS Program staff and governance (including representatives of the Board of Directors, GSN and DMS Standing Committees), representatives of the GSN network operators, and other interested parties. If required, site visits will be arranged to network operations centers in San Diego and Albuquerque and the Data Management Center in Seattle.

The Committee will be provided with written documentation on the history and current status of the GSN and budgetary information.

Key Questions

In fulfilling its charge to conduct "a *full external review of the GSN, including all associated subawards, and exploring alternative configurations, management approaches, and the possible scientific impacts",* the committee is asked to address the following questions. The committee has the latitude to address other questions if they are relevant to this charge.

GSN Goals
The original concept for the GSN set forth the following goals: "*a global network of uniformly spaced stations (~2000 km spacing), capable of recording the full range of seismic signals, with data collection in real time*".

- Are these goals still appropriate in light of advances over the past 10 years in availability of new sensors and data types (e.g. availability of high-quality regional and international seismic networks, geodetic networks)?
- Are these goals appropriate given community research and monitoring needs for the next decade?
- How well does the GSN support/enable discovery science through long-term, high-quality data acquisition on a global scale?

Technology
The GSN technical specifications, established in 1985 and updated in 2002, established new standards for seismological instrumentation both nationally and internationally.

- Has GSN instrumentation kept pace with technological development?
- Are there investments in new technology that could enhance the scientific return, performance or efficiency of the GSN?
- What should be the process by which technology R&D is supported and new technology is brought into the GSN?

Management, Coordination and Oversight
The Global Seismographic Network includes two sub-networks, IDA and USGS, operated by IRIS and USGS respectively, plus a limited number of independent university-operated stations. Capital equipment, installation and operational costs are supported by the NSF and the USGS. Management coordination for IRIS is provided by the IRIS GSN Program Manager. Policy oversight is provided by the GSN Standing Committee. Both IRIS and the USGS accept the GSN Standing Committee as a joint advisory committee and agree to follow the advice of the committee in good faith and to the extent possible within the limits of practical considerations and available funding.

- Is the current management structure appropriate and efficient? Can it be improved, and if so, how?
- What significant advantages or disadvantages would there be to a substantially different management structure or mode of operation?

- Are subawards appropriately structured and adequately reviewed?
- How effective is the facility oversight by the scientific user community, especially in facilitating intermediate and long-term planning?

Data Quality
The quality of data provided by the GSN is critical to achieving the scientific goals motivating the operation of the GSN.

- Does the GSN provide data of sufficient quality to meet the scientific and monitoring needs of the community?
- Are quality assurance systems adequate?
- Are there new or different strategies the GSN should adopt to ensure high-quality data?

Costs
A major challenge for the long-term sustainability of the GSN will be to contain operational and maintenance costs.

- Are current costs appropriate and well substantiated?
- Are current staffing levels appropriate and well substantiated?
- Are there alternative management or operational models that could significantly reduce costs without negative impacts?
- Are there investments in new technologies that could help minimize future operational and maintenance costs?
- The current model for recapitalization is to obtain support outside regular core funding. Is this model adequate to meet the future needs of the network? Are there other models that should be considered?

Partnerships
In addition to the IRIS-USGS partnership, partnerships with other FDSN networks are essential to provide global coverage in areas not covered by the GSN. GSN data are also utilized by other U.S. government agencies, including NOAA and DOE.

- Are there ways in which improved collaborations between the GSN and other global or regional networks could enhance global seismological observations and/or improve the efficiency of the GSN?
- Are there other collaborations with U.S. government agencies (e.g. NOAA in

tsunami early warning) or international organizations that should be developed or improved?

Scope of GSN

The GSN now consists of 153 stations. Combined with stations of cooperating FDSN networks (especially GEOSCOPE, Pacific 21, GEOFON and MedNet) and cooperation with the CTBT IMS network, the coverage on land has reached that envisioned in the original GSN siting plan. Coverage in oceanic regions remains sparse.

- What are the most important challenges that the GSN faces over the next 10 years?
- Is the process for re-evaluation of the GSN siting plan adequate?
- What efforts, if any, should be undertaken to encourage the installation of sustained seismic observatories on the seafloor?
- Are activities to encourage the installation of other types of sensors at GSN sites adequate and appropriate?

Data Management and Services

IRIS Data Services (DS) has the responsibility to provide access to all GSN data. In addition, as part of its commitment to the FDSN, IRIS is a permanent FDSN archive for continuous data from the FDSN Backbone Network and provides coordinated access to data from many FDSN stations.

- Are there ways in which interaction between IRIS DS (including the Data Collection Centers operated by the USGS and IRIS) and the GSN program could improve data quality or accessibility?
- Could the data collection system be streamlined to reduce costs without serious negative impacts?
- Are there different or additional capabilities for data access or data quality that the GSN and DS should provide?
- How effective are the linkages between the IRIS DMC and other global, national and regional data centers?

Appendix B.
Global Seismographic Network Design Goals Update 2002

August 26, 2002

GSN ad hoc Design Goals Subcommittee

Thorne Lay, Chair
Jon Berger
Ray Buland
Rhett Butler
Goran Ekstrom
Bob Hutt
Barbara Romanowicz

FINAL VERSION –GSN Design Goals Subcommittee Report
Reviewed by GSN Standing Committee October, 2002

Introduction

The GSN Design Goals Subcommittee (DGS) agreed that the appropriate approach was for us to couch this effort in terms of an update of relevant portions of the 1985 document "The Design Goals for a New Global Seismographic Network" prepared by the SCGSN Instrumentation and Data Collection Subcommittees. That document was redistributed, and studied by the DGS. Our focus is directed at updating the GSN design goals to provide input to the Instrumentation Committee, which will then be tasked to develop technical specifications. Design goals are framed by the context of both scientific goals of the research community and by general philosophy of network design and recording system attributes that service the scientific applications of the data.

From the perspective of today's GSN, major elements of the 1985 Design Goals document have been implemented in several respects. That document emphasized 20 sample/sec broadband digital recording with real-time or near real-time data telemetry of all teleseismic ground motions (assuming about 20 degrees station spacing) for earthquakes as large as $M_w = 9.5$ (equivalent to the 1960 Chile earthquake) by a uniform global network of about 100 stations, with low noise instrumentation and environment, standardization of system modules, and linearity of response. The intent was for total system noise to be less than the ambient ground noise over the operating bandwidth.

Some provision was made for the possibility of additional short-period data channels to record local signals or high frequency teleseismic signals, as well as for low-gain channels, possibly with additional sensors, to record the largest accelerations experienced by the stations. Over the ensuing 17 years, the GSN has achieved significant global coverage (large gaps persist within oceanic regions and continental coverage is non-uniform), and high dynamic range, broadband instrumentation has been deployed at all formal GSN stations. Short-period recording has extended beyond the general statements of the 1985 document to encompass 40 sample/sec continuous recording at most stations, along with 80 to 125 sample/sec triggered recording, with short-period sensors supplementing the basic broadband instrumentation. Strong ground motion instrumentation and triggered channels have been added to stations in earthquake prone areas, and low-gain 1 sample/sec channels are continuously recorded.

Limitations

The driving motivation for the GSN has been to record with full fidelity and bandwidth all seismic signals above the Earth noise, accompanied by some efforts to reduce Earth noise by deployment strategies. The primary limitations at many GSN stations at this time are site noise related. Despite extensive effort, political and logistical situations have resulted in some GSN stations being located in noisy environments. The 1985 Design Goal framework does not address the reality of compromised site selection. The most useful stations are those that provide abundant high signal-to-noise ratio data, but there is always some trade-off with geographic coverage. While the goal should be to have low noise sites in general, there will be compromises. Site selection and site construction should be such that there is reasonable assurance of substantial data return, with the goal being to maximize the bandwidth and useful dynamic range of the GSN signals.

In particular, many stations with useful vertical component signals have horizontal components that are much lower in quality. Further development of strategies for improved horizontal component stability and noise reduction is recommended. Discussion of procedures for installation involving shielding of sensors from temperature and pressure variations should be undertaken to define practices that optimize horizontal component stability in vaults and boreholes.

A significant concern is that as new station deployment has given way to long-term operations and maintenance of the network, we find that there are significant non-uniformities in the instrumentation comprising the GSN today, largely as a result of the historical evolution of the network. This seriously complicates maintenance of the network. As GSN renews and expands its instrumentation, efforts toward network-wide standardization of instrument performance, if not instrumentation, should be a priority, even as flexibility is retained due to variable site attributes. The extent to which compromises in individual station performance are tolerated must be weighed against the scientific gains to be had and the increased complexity of network O&M.

Future Directions

So, is sustaining the status quo the recommendation of the DGS? There are actually several major concerns that warrant a re-articulation of the design goals for the network and a vigorous effort to develop next generation instrumentation for the GSN.

Adaptation of GSN design goals to accommodate emerging scientific directions has been, and should continue to be, an ongoing process. However, since 1984 there has not been a community-wide discussion of scientific directions to guide or modify a future vision of GSN instrumentation. Renewal proposals for IRIS funding from NSF have included updated applications of GSN data, but there has not been a forum for broad thinking on expanded roles or capabilities for GSN in the future. Thus, the present work of DGS is framed by a general sense that, at a minimum, the existing instrumentation strategy is serving the community rather well and the original design criteria need to be sustained.

Two sorts of network enhancements have been considered: enhancements improving network performance, maintainability, and flexibility within existing design goals and enhancements expanding the scope of the GSN design goals. The most obvious enhancement of maintainability is to select new instrumentation to replace aging and/or obsolete equipment currently in the field. The most obvious enhancement to performance and flexibility would be to seek equipment that can be operated under a wider variety of site conditions. Lower power equipment, in particular, would make many potentially lower noise sites viable as well as reducing power related maintenance problems.

For stations that are intrinsically excessively noisy (to the point where the advantage of geographic siting is outweighed by the paucity of useful signal recovered) it may prove viable to pursue noise suppression strategies. For example, if auxiliary channels for pressure, temperature and tilting need to be recorded to suppress noise on the horizontals, this should be pursued. Alternatively, mini-arrays may prove useful for signal enhancement in specific pass bands. The potential improvements in signal recovery using array deployments for GSN island stations and possibly for ocean bottom stations warrant detailed consideration in the context of specific scientific applications.

In addition, enhancements of the GSN may be intrinsically desirable. In particular, the exploration of geophysical platform concepts, modified station density design (e.g., the fixed NSN/GSN network accompanying USArray), and improved ocean environment coverage are all obvious candidates. Further, there is increasing scientific interest in ultra-long period signals, such as the Earth's spectrum of continuously excited modes and tides. For example, super conducting gravimeters have demonstrated superior response to existing GSN instrumentation for very long-period free oscillations, and inclusion of a subset of these gravimeters at very quiet sits in the GSN may prove very attractive in the future. The value of high fidelity recording throughout the tidal band is not self-evident, and community discussion of the role GSN should play in data collection at frequencies below the normal mode band (as for some ocean oscillations) should be undertaken.

Overall Criteria for the GSN

The current characterization of optimal GSN instrumentation capabilities is shown in the attached Figure 1. A combination of sensors is utilized to realize this full response, and if advances in sensor design can achieve greater performance (while retaining linearity, resolution, bandwidth and dynamic range) over the full seismic spectrum it would be attractive to incorporate such instrumentation into the GSN in the future. Definition of scientific enterprises that 'push' the margins of the GSN capabilities, such as in the very long period range, the very high frequency range, or the low noise range is worthy of discussion, but the DGS does not have a clear sense of major enterprises that are inadequately serviced by the existing level of instrumentation. The DGS recommends that in the best possible situation (not limited by local noise conditions), the GSN design goal is to achieve at least the bandwidth and dynamic range indicated in this figure, as is presently achieved by the optimal GSN instrumentation. This should guide the development of instrumentation specifications for all future GSN instrumentation.

Design Goals

The following design goals are derived from the scientific mission of the GSN.

1. Maintain a global network of at least 140 uniformly spaced stations (adequate to resolve lateral heterogeneity to about angular order 8). GSN stations are to be coordinated with other Federation of Digital Broadband Seismic Network stations.
2. Provide high fidelity digital recordings of all teleseismic ground motions (adequate to resolve at or near ambient noise up to the largest teleseismic signals over the bandwidth from free oscillations (10^{-4} Hz) to teleseismic body waves (up to approximately 15 Hz)).
3. Bandwidth to record regional earthquake waves at all stations (up to about 15 Hz or higher, as warranted by regional wave propagation considerations).
4. Extend the bandwidth and/or the clip level at selected stations (i.e. those with high probability of nearby activity) to include local events and/or strong ground motions.
5. Provide real-time or near real-time data telemetry (to support event monitoring, provide data for scientific analysis in a timely manner, and improve maintenance response time).

6. Equipment must be robust, sustaining high up-time performance.
7. Data return must be high.
8. System environmental requirements should not constrain site selection.

Extensions for ocean bottom stations:

1. Hydrophones should be included.
2. Bandwidth for both seismic sensors and hydrophones extended to about 100 Hz. (The upper limit has not been definitively determined. The few observations that exist suggest that P and S waves may propagate in the oceanic lithosphere to distances of 4000 km with frequencies of up to 35 Hz. Coupled seismoacoustic T waves in the seafloor have been observed with frequencies of 80 Hz at 2000 km distance. Local microearthquakes in the oceanic crust have frequency contents exceeding 80 Hz.)

Functional Specifications

The functional specifications are derived from the design goals by considering detailed limits of the general scientific goals. Note that at this stage, discussions of how well we can do are irrelevant. If the state-of-the-art isn't adequate, we need to improve it. It it's better than we need, we're paying for a capability we're not using. In general, it's worth making the instrumentation about an order of magnitude better than our ability to model the parameters being measured. Thus, if we hope to model amplitudes to 20%, the aggregate sources of amplitude error (gain stability, cross axis coupling, and cross talk) should be less than 2% and individual contributions should be less than that.

1. On-scale broadband recordings of earthquakes as large as $M_w = 9.5$ (equivalent to the 1960 Chile earthquake) at 30 degrees. On-scale low-gain recordings of all earthquakes at 1 sample/sec.
2. Noise below ambient earth noise.
3. Bandwidth spanning all solid earth free oscillations and regional body waves (up to 15 Hz or higher as regional wave propagation considerations dictate).
4. Linearity sufficient to record signals near ambient noise in the presence of signals near clipping at well separated frequencies.
5. Response known to 1% across the bandwidth (adequate for amplitude modeling which at best is good to about 20%).
6. Sensor cross axis coupling less than about 1% (adequate for amplitude modeling).
7. DAS channel cross talk less than about 1% accounting for the difference in gains between adjacent channels (adequate for amplitude modeling).
8. Timing adequate to measure teleseismic body wave arrivals to 0.01 s.
9. Optional high frequency sensors must record the full bandwidth of small local events.
10. Optional low gain sensors must record the largest expected free field ground motion.
11. System should provide robust, low cost telemetry of all data in real-time.

12. DAS should be sufficiently modular in design as to permit variable channel configuration for differing numbers of sensors at GSN sites.
13. Equipment must be isolated from environmental problems including corrosion, water damage, dust, radio frequency interference, electrical surges, atmospheric pressure changes, and to some extent temperature changes. The equipment should be highly reliable.
14. On-site data storage must be provided for telemetered sites and removable non-volatile storage must be provided for non-telemetered sites.
15. Equipment should be operable in extreme temperatures, corrosive environments, small vaults, and sites without mains power.

Trade-offs

The task of translating functional specifications into a finished system inevitably leads to compromises. In particular, the availability and cost of instruments as well as the cost of site preparation are always factors at some level.

1. Given digital data and precise transfer functions, it is no longer necessary for stations to provide uniform responses. Given the wide range of site conditions and ambient noise characteristics encountered throughout the GSN, the level of uniformity of equipment becomes a trade-off between the cost of capitalization and the cost of maintenance. Requiring uniform equipment at all sites increases capital costs because less capable and hence less expensive equipment would be adequate for the noisier sites (perhaps the majority of sites). Heterogeneous equipment requires stocking more spares and more training for maintenance personnel. Experience indicates that if the increase in capital costs is small for homogeneous equipment, the reduction in out-year costs and improved network stability is worthwhile. On the other hand, if the increase in capital cost is large, it may be that the cost of allowing some heterogeneity is offset by the lower cost of amortization. Customizing sensors to individual sites would require rather extensive site noise survey, and would add time to site deployment so it may be useful to define threshholds for different system configurations.
2. Providing the horizontal performance of the best broadband borehole sensors while retaining the vertical performance of the best surface mounted broadband sensors is a complex tradeoff. Boreholes and borehole sensors are expensive to procure, install, and maintain. However, tilt compensation for surface mounted sensors, while intriguing, has yet to be adequately developed. Ultimately, this trade-off will depend on the characteristics of available sensors and the development of compensation technologies.
3. Lower power systems are desirable because they make sites without mains power more accessible and reduce maintenance issues at all sites. However, lower power designs may compromise system performance and mixing high and low power equipment makes the network more heterogeneous.
4. Because long distance telemetry equipment (e.g., satellite) sometimes requires significant power, separating sensors from telemetry systems by short haul communications links is attractive. However, such systems add significant complexity and reduce reliability. In

some locations, lower power long distance telemetry options would reduce complexity, but might also require unattended operation.

5. At many sites, display and processing facilities are provided for the local host. While it is recognized that an interested host increases station up-time, not all stations have hosts or even caretakers. Developing systems that can operate unattended is desirable. The reliability of an unattended system can be enhanced by eliminating unused sub-systems (e.g., the operator workstation), however, this increases network heterogeneity.
6. Telemetry with suitable on-site storage can be as reliable as non-volatile, removable storage in some cases. It is attractive to consider eliminating removable storage in such cases to avoid the cost of maintaining the recording equipment, changing the media, and processing the media at a DCC. However, there will always be situations where on-site recording will result in higher data recovery.
7. In separated systems, data is currently recorded on a hard drive when the telemetry link to the recording facility is down. This results in improved data recovery, but requires frequent visits to the digitizer and special processing at the operator workstation. In designing a new system, the cost effectiveness of greater flexibility versus complexity in such situations needs to be carefully considered.

Suggested Technical Specifications

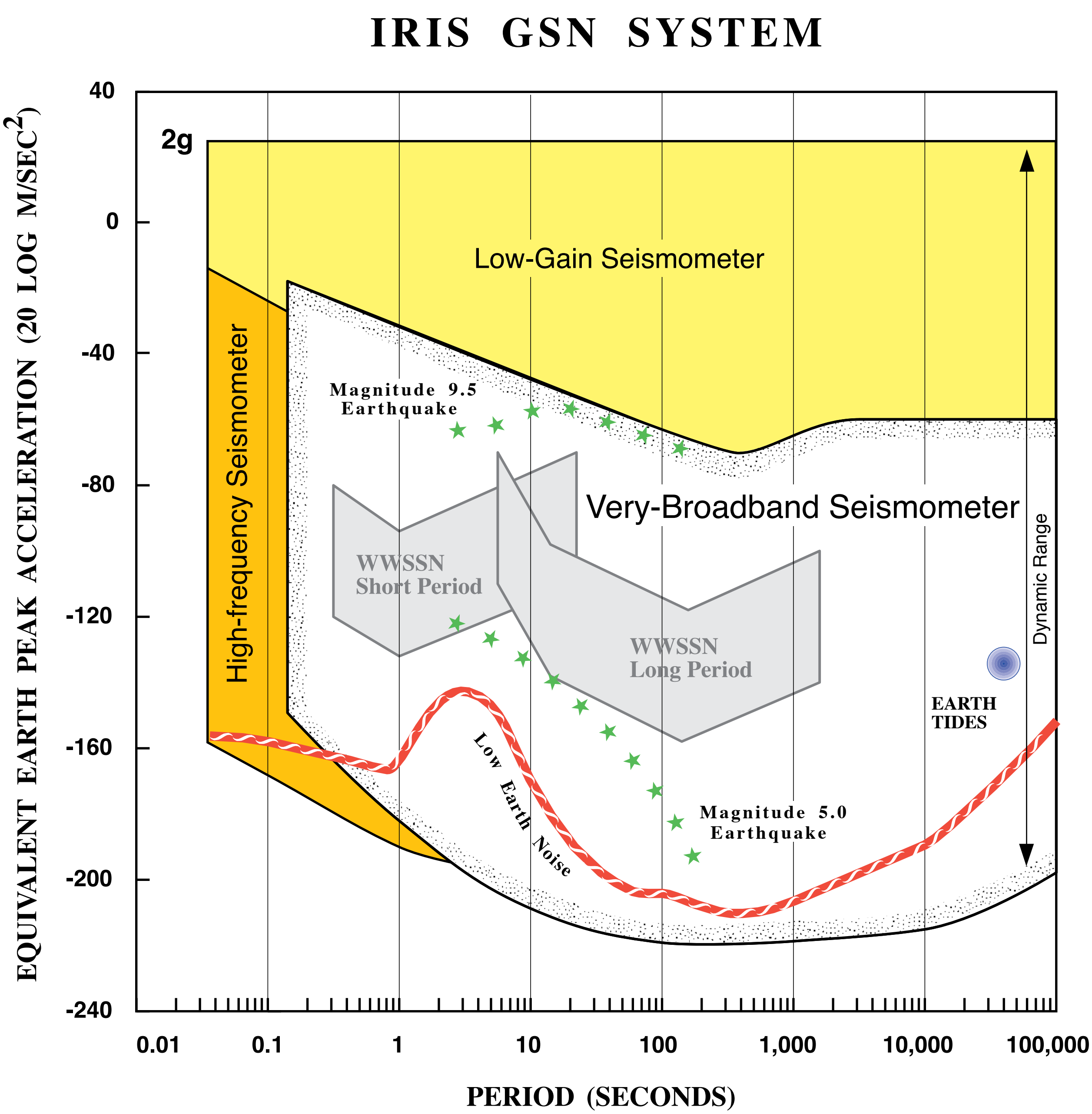
The Instrumentation Committee will derive technical specifications from the functional specifications after considering available technology and the relevant trade-offs. However, some of the technical specifications follow so directly from the functional specifications that it seems worthwhile to list them here.

1. Clip level of 5.8 mm/s rms over the band 10^{-4} (or below) to 15 Hz, while resolving the USGS low-noise model.
2. Resolution of 3 dB below the NLNM is sufficient, but not necessary at all sites (or at any site at all frequencies).
3. Bandwidth of 10^{-4} (or below, depending on priority for tide and very low frequency earth motion resolution) to about 15 Hz (or higher as warranted by regional wave propagation considerations).
4. Digitizer linearity of ~140 dB. Seismometer linearity of 90 dB or greater.
5. Calibrations good to 1% and gain stability of 1% between calibrations.
6. Sensor sensitive axis orientation accurate to 0.6 degrees (minimum). Note, cross axis coupling goes as the sine of the angular error between components. Three mutually orthogonal components of motion should be recorded.
7. DAS channel cross talk –135 dB (maximum). This is difficult to guesstimate because the shaping of the signals is different between the high gain and the low gain sensors.
8. The DAS must provide a free running oscillator sufficiently stable to maintain a timing accuracy of 1 ms across a 3 hour interval without absolute time (~.1 ppm). Note that a typical crystal oscillator will do .1 ppm/degree C and .1 ppm/year at constant temperature. So we either need a really good oscillator or really good temperature stability.

9. Optional high frequency sensors must provide a bandwidth of 1 to 35 Hz (at least 100 Hz for ocean sites).
10. Optional low gain accelerometers must provide a clip level of 2 g over a bandwidth of just above 0 to 50 Hz (From an operational point of view, an instrument with flat acceleration response all the way to DC is very nice because it lends itself to easy on-site calibration check: turn it upside-down and you should have a 2g change on the vertical component; turn it 90 degrees and you should have 1 g on the corresponding horizontal component.) Optional low gain velocity sensors must record the largest expected free field ground motion and be able to detect surface waves from teleseismic events as small as M6.0.
11. All intra- and inter-site communications must be by means of IP protocols.
12. Equipment must meet relevant standards for packaging and radio frequency interference. It must have no appreciable sensitivity to atmospheric pressure and temperature changes (except for clock sensitivity which is specified elsewhere). The equipment should have a MTBF of 10,000 to 20,000 hours.
13. Telemetered data must be buffered for 3 days (minimum), ~48 MBytes. Non-volatile, removable storage should have a capacity of at least 1 year, ~12 Gbytes.
14. Equipment must be operable over a temperature range of -25 to +75 degrees C. All sensors, the DAS, and (at least local) telemetry should be designed for low power requirements.

We hope that this input updates the GSN design goals that will guide development of specifications for the next generation GSN systems. We encourage SCGSN to consider workshop activities that may extend the vision of GSN instrumentation beyond the current concept, as warranted by evolving scientific applications and priorities.

Figure 1 (adapted from Figure 2 of Peterson, USGS OFR 89471). Idealized recording range of the GSN system. The approximate recording ranges of the WWSSN LP and SP channels are shown for comparison. Earthquake spectra from sources at 30 degrees distance were provided by H. Kanamori, California Institute of Technology. The low Earth Noise model is from Jon Peterson [Observations and Modeling of Seismic Background Noise, USGS Open File Report 93-322, 1993]. The lowest and highest acceleration levels shown are for an ideal combination of Very Broad Band (STS-1), High Frequency Broad Band, Low Gain Seismometers, and 24-bit digitizers. While Low-Gain Seismometer response may be flat all the way to DC offset, the very large displacements implied for long period high acceleration motions are not achieved in normal Earth motions.



Appendix C.

Annex on the Global Seismographic Network to the Memorandum of Understanding between the National Science Foundation and the United States Geological Survey

on

Cooperation in Development and Support of Research Activities, Facilities, Education and Outreach For the Earth Sciences

this Annex being between

The National Science Foundation, the United States Geological Survey, and the Incorporated Research Institutions for Seismology

1. Purpose

The purpose of this Annex is to set down the roles and responsibilities of the Incorporated Research Institutions for Seismology (IRIS), the U.S. Geological Survey (USGS), and the National Science Foundation (NSF) in matters related to the Global Seismographic Network (GSN).

2. Background

2.1 General

The GSN is a worldwide network of more than 100 modern seismograph stations and the network is expected to expand to about 140 sites. Each station consists of a seismometer or seismometers, recording and communications equipment, and facilities necessary for the operation and security of this equipment. The GSN is a multi-use facility serving the interests of scientific research, nuclear explosion monitoring, earthquake monitoring, assessment of earthquake hazards, and education. The development of the GSN was possible through funding provided by NSF, and the through a special Congressional appropriation to the Department of Defense, and through private Foundation support. The GSN is a joint effort of NSF, IRIS, USGS, and GSN station host institutions.

This Annex updates and takes precedent over prior agreements regarding the Global Seismographic Network: IRIS/USGS Cooperative Agreement (1984), Interagency Accord on

Implementation of the Committee on Science, Engineering, and Public Policy (COSEPUP) Recommendations for Research Initiatives in Seismology (NSF/USGS/DARPA 1986), USGS and NSF Roles and Responsibilities in the Global Digital Seismic Array and Data Management (1986), and Technical Plan for a New Global Seismographic Network (USGS/NSF/IRIS 1990).

2.2 Functions of IRIS and NSF in the GSN

NSF provides IRIS funding for the GSN and oversight for the IRIS program. NSF funding is provided to IRIS through a Cooperative Agreement. IRIS is responsible for archiving and distributing GSN data through the IRIS Data Management System. The Parties recognize that the extent to which NSF and IRIS can support these functions depends on the availability of funding.

2.3 Functions of the USGS in the GSN

The USGS is responsible for the maintenance of GSN equipment it has installed at various sites and supporting GSN operations at these sites. The USGS modernizes existing stations and installs new stations in cooperation with and with funding support from IRIS/NSF. The USGS Albuquerque Seismological Laboratory (ASL) carries out most GSN activities within the USGS. Funding for USGS operation and maintenance activities is provided by a separate Congressional appropriation to the USGS through the Department of Interior budget. The Parties recognize the number of GSN stations the USGS can maintain, or the level of support available to the stations, depends on the level of Congressional funding.

3. GSN Goals

3.1 Stable Base of High Quality Data

The goal of the GSN is to establish and maintain a global network of modern seismographic stations operating continuously and providing open data as quickly as possible to the scientific community, national and international agencies, and the general public.

3.2 Network Design--Number of Stations and Coverage

The network design goal is about 140 seismic stations globally distributed with a spacing of 2000 km to provide uniform coverage of the Earth. Station siting is coordinated with other networks of the Federation of Digital Seismic Networks.

3.3 Station Equipment

GSN station equipment includes one or several types of data acquisition systems, seismometers, power supplies, communications and telemetry systems, and environmental isolation and protection. It may also include ancillary sensors such as geophysical sensors for non-seismic data and meteorological sensors.

3.4 Data Access

All parties agree that all data from the GSN are openly and freely available without restriction or delay.

3.5 Station Maintenance Goals

The operations and maintenance goal for the GSN is to have all of the stations fully functional all of the time. All Parties realize that this goal, although desirable, may be impossible to achieve without very high cost and considerable effort, so that the average performance level of the GSN will likely be less than 100%.

Another national or international agency may request higher than overall GSN average performance for a subset of GSN stations. Extraordinary maintenance requirements above and beyond the basic GSN maintenance must be funded by the requesting agency, and implemented in a way as not to interfere with the basic operations and maintenance of the GSN.

3.6 Operational and Maintenance Practices

Operational and Maintenance (O&M) practices for the GSN will be common to all stations. Routine GSN O&M practices are listed in Appendix 1.

4. Joint NSF/IRIS and USGS Responsibilities in the GSN

As a fully collaborative effort in support of the research and monitoring missions of the National Science Foundation, the US Department of the Interior, and other government agencies, NSF/IRIS and USGS are jointly committed in partnership to and responsible for the continued success of the GSN. The joint responsibilities are based on the underlying principle that NSF/IRIS is responsible for procurement and upgrade of capital equipment at IRIS/USGS GSN stations and the USGS is responsible for the on-going operational support and maintenance of that equipment. The following sections provide details of the specific responsibilities of each of the partners.

5. USGS Responsibilities in the GSN

5.1 Stations

A GSN station usually consists of GSN equipment installed in or at a facility of a local host institution. The operation of GSN equipment and maintenance of physical facilities at IRIS/USGS GSN stations (including vaults, piers, boreholes, and structures housing GSN equipment) are covered under various agreements the USGS establishes and maintains with host organizations. The USGS will support GSN station operations and GSN station facilities in accordance with these agreements. The USGS responsibilities for IRIS/USGS GSN stations given in this Annex refer only to those stations given in the most current version of Table A1. The Parties to this agreement will review and update this list at periodic GSN Standing Committee meetings.

5.2 Station Equipment

The USGS is responsible for the maintenance of station equipment installed at IRIS/USGS GSN stations in accordance with GSN goals. New equipment is installed only with the mutual agreement of IRIS and USGS.

5.3 Telecommunications

The USGS shall work to establish circuits between IRIS/USGS GSN stations and ASL using available communications resources. The USGS and IRIS shall approve and have access to any communications circuits installed at IRIS/USGS GSN sites by other interests. The operation and maintenance of this equipment is the responsibility of these other interests unless special arrangements are made with the USGS and IRIS.

5.4 Data Quality Control and Instrument Testing

The USGS is responsible for maintaining high standards for data quality control for all IRIS/USGS GSN stations and other GSN stations whose data pass through the ASL Data Collection Center. The USGS and IRIS jointly establish data quality control standards and methods. The USGS is responsible for testing and quality assurance of systems and equipment intended for deployment at IRIS/USGS GSN stations.

5.5 Data Access

The USGS will provide free and open access to IRIS for broadband data made available to USGS.

6. NSF/IRIS Responsibilities in the GSN

6.1 New stations

IRIS is responsible for GSN instrumentation plans, concepts, and development, for GSN siting plans, and for the establishment of new GSN stations. IRIS designates a Network Operator for installing, operating and maintaining a new GSN station. All stations designated for the USGS portion of the GSN will be so designated only with the written agreement of the USGS. IRIS shall bear the expense of equipment for new stations and their installation. IRIS may designate Affiliated GSN stations, which are installed, operated and maintained to meet GSN instrumentation design goals and data availability, but are not associated with IRIS or USGS.

6.2 New Equipment

IRIS is responsible for upgrading GSN equipment and facilities as appropriate for keeping the GSN a state-of-the-art scientific facility. New equipment at IRIS/USGS GSN stations shall be installed by and with the mutual agreement of the USGS. IRIS shall bear the expense of the new equipment and its installation.

6.3 Other Stations

IRIS is responsible for the installation, maintenance, and upgrade of all other GSN stations. A dated list of these sites is attached (Table A2). This site list will be updated at periodic meetings of the GSN Standing Committee.

6.4 Data Quality Control and Instrument Testing

To assure the accuracy of timing and response of instrumentation, IRIS is responsible for maintaining high standards for data quality control for all IRIS/IDA, IRIS/University, and Affiliated GSN stations and for other stations, whose data pass through IRIS Data Collection Centers. Data quality control standards and methods are established jointly by the USGS and IRIS. IRIS is responsible for testing and quality assurance of systems and equipment intended for other GSN stations that complement the IRIS/USGS GSN.

6.5 Data Distribution

IRIS is responsible for the distribution, in a free and open manner, of all GSN data through its Data Management System. IRIS will provide access to the USGS to all GSN data.

7. Changing Stations, Equipment, and Practices

7.1 Assigning New Stations and Changing Stations

The designation of the USGS as the responsible Party for a new or existing GSN station may be changed with the mutual agreement of USGS and IRIS. USGS shall accept or decline responsibility for a new station in writing within 30 days.

IRIS and the USGS must mutually agree to the closing of an IRIS/USGS GSN station.

7.2 Changing Equipment

IRIS and the USGS official representatives must mutually agree to the installation of new or replacement, major GSN equipment at IRIS/USGS GSN sites. By agreeing to new equipment the USGS accepts maintenance and operational support responsibility for this equipment.

Additional, new scientific instrumentation may be added to GSN stations as they expand to become more general geoscientific observatories. The broadening of the scientific scope of the GSN will require the concurrence of IRIS and NSF. USGS concurrence is required at IRIS/USGS GSN sites.

7.3 Changing Practices

Operation and maintenance practices for USGS/ GSN stations may be changed with the mutual agreement of IRIS and USGS.

8. Equipment Ownership

The NSF holds title to most of the equipment at GSN stations under a Cooperative Agreement with IRIS. This includes all equipment purchased directly by IRIS or indirectly through an IRIS subaward. IRIS maintains an inventory of permanent equipment purchased with NSF funds. IRIS and NSF are responsible for the final disposition of GSN equipment to which NSF holds title. Some equipment is owned by the organization (e.g., University or USGS) that installed it, having been purchased through other arrangements. At a few cooperative international GSN sites, some seismometers or data acquisition systems are owned wholly or partly by the international partner and contributed to the GSN. IRIS and NSF reserve the right to remove, or abandon in place, GSN equipment to which they hold title.

9. Acknowledgement Policy

Recognizing the importance of the attribution of support for the GSN for achieving its long-term stability and success, the Parties agree to the following acknowledgement, which shall be used in all media referring to the GSN:

"The Global Seismographic Network (GSN) is a cooperative scientific facility operated jointly by the Incorporated Research Institutions for Seismology (IRIS), the United States Geological Survey (USGS), and the National Science Foundation (NSF)."

10. Management Considerations and Procedures

10.1 General

The Parties acknowledge that each has its own management policies, regulations, and procedures that shall be recognized and respected by the other Parties.

10.2 External Guidance

Both IRIS and USGS management policies require external advisory or consultative committees for the GSN program. Both sides recognize that their institutions and the scientific community as a whole will not be well served with two such bodies offering possibly conflicting guidance. Therefore, all Parties agree to accept the IRIS GSN Standing Committee as a joint advisory committee for the GSN. IRIS shall consult with NSF and the USGS in the appointment of the membership of the GSN Standing Committee. There shall be a permanent, voting seat on the GSN Standing Committee for the official representative of the USGS, in addition to a non-voting seat for the USGS Network Operator filled by a representative of ASL.

Both IRIS and the USGS recognize that the ultimate responsibility for the GSN matters rests with the management structures in their respective organizations. The guidance issued of the IRIS GSN Standing Committee shall be considered by both sides to be advisory in nature. However, both IRIS and the USGS mutually agree to follow the advice of the IRIS GSN Standing Committee in good faith and to the extent possible within the limits of practical considerations and available funding.

10.3 Management Contacts

The official representative of IRIS and NSF to the USGS on GSN matters shall be the IRIS GSN Program Manager or his or her designee. The official representative of the USGS to IRIS and NSF on GSN matters shall be the GSN Program Coordinator or his or her designee.

The technical points of contact between IRIS and USGS shall be the IRIS GSN Program Manager and the USGS Chief of Albuquerque Seismological Laboratory.

Working Groups or *ad hoc* technical bodies may be established through mutual agreement of representatives of all Parties. These bodies shall be guided by terms of reference mutually agreed to by the Parties

11. Procedures and Timetable for Review, Alteration, and Termination of this Annex.

11.1 Review

The official representatives of the Parties jointly shall review this Annex once a year.

11.2 Alteration

The Parties may agree to alter this Annex at any time.

11.3 Termination

Any Party may withdraw from this Annex three months after having notified, in writing, the other Parties of its intention to do so.

For the U.S. Geological Survey	For the Incorporated Research Institutes for Seismology	For the National Science Foundation
P. Patrick Leahy Assoc. Director for Geology	David W. Simpson President	Margaret S. Leinen Asst. Director for Geosciences
Date: 10/17/02	Date: 9/11/02	Date: 8/27/02

Appendix 1.

Routine GSN operation and maintenance concepts include but are not limited to:

- Monitoring GSN system performance, and developing, testing, and evaluating changes that will improve data quality and reliability.

- Calibration of sensors, verification of sensor performance, and quality assurance of accurate system transfer functions.

- Maintaining GSN station equipment (hardware and software) as needed, and supporting GSN station operations by working with host institutions.

- Providing all operating supplies for equipment, including: magnetic tapes or other data recording media, mailing cartons and labels, and operational forms.

- Providing a depot with a reasonable inventory of operating supplies and spare parts stocked to minimize station down time.

- Forward stocking logistically difficult stations with critical on-site spares as funding allows.

- Shipping parts and materials to and from GSN stations.

- Providing all data to the IRIS Data Management Center immediately after quality control.

- Communicating with GSN station hosts and keeping station and telecommunications agreements up to date as necessary.

- Training GSN station personnel.

- Keeping accurate station files including station information and correspondence, station equipment, hardware and software configurations, maintenance problems and their solutions, and other station activities.

- Coordinating operation and maintenance activities where possible for network efficiency.

Appendix 2.

Table A1. List of 94 IRIS/USGS GSN Stations (May 1, 2002).

North America			
Sondre Stromfjord	Greenland	SFJ	Existing
Isla Socorro	Isla Socorro, Mexico	SRR	Planned
Tepich	Yucatan, Mexico	TEIG	Existing
San Juan	Puerto Rico	SJG	Existing
Adak Island	Alaska, U.S.A.	ADK	Existing
College Geophysical Observatory	Alaska, U.S.A.	COLA	Existing
Tucson	Arizona, U.S.A.	TUC	Existing
Disney Wilderness Preserve	Florida, U.S.A.	DWPF	Existing
Wyandotte Cave	Indiana, U.S.A.	WCI	Existing
Harvard	Massachusetts, U.S.A.	HRV	Existing
Cathedral Caves	Missouri, U.S.A.	CCM	Existing
Albuquerque	New Mexico, U.S.A.	ANMO	Existing
Corvallis	Oregon, U.S.A.	COR	Existing
Standing Stone	Pennsylvania, U.S.A.	SSPA	Existing
Black Hills	South Dakota, U.S.A	RSSD	Existing
Waverly	Tennessee, U.S.A.	WVT	Existing
Hockley	Texas, U.S.A.	HKT	Existing
South America			
Tornquist	Argentina	TRQA	Existing
Riachuelo	Brazil	RCBR	Existing
Pitinga	Brazil	PTGA	Existing
Samuel Dam	Brazil	SAML	Planned
Limon Verde	Chile	LVC	Existing
Otavalo	Ecuador	OTAV	Existing
Santo Domingo	Venezuela	SDV	Existing
Atlantic Ocean			
Bermuda	Bermuda	BEC	Planned
Taburiente (replacement site in Canary Islands to be determined)	Canary Islands	TBT	Closed for relocation
Trindade	Trindade Island, Brazil	TRIN	Planned
Tristan da Cunha	Tristan da Cunha	TRIS	Planned
Europe			
Kevo	Finland	KEV	Existing
Graefenberg Array	Germany	GRFO	Existing
Ny-Alesund	Spitsbergen, Norway	KBS	Existing
Kongsberg	Norway	KONO	Existing
San Pablo	Spain	PAB	Existing
Kiev	Ukraine	KIEV	Existing
Africa			
Furi	Ethiopia	FURI	Existing
Masuku	Gabon	MSKU	Existing

Kilima Mbogo	Kenya	KMBO	Existing
Kowa	Mali	KOWA	Existing
Tsumeb	Namibia	TSUM	Existing
Lusaka	Zambia	LSZ	Existing
Asia			
Garni	Armenia	GNI	Existing
Baijiatuan (Beijing)	China	BJT	Existing
Enshi	China	ENH	Existing
Hailar	China	HIA	Existing
Kunming	China	KMI	Existing
Lhasa	China	LSA	Existing
Mudanjiang	China	MDJ	Existing
Sheshan	China	SSE	Existing
Urumqi	China	WMQ	Existing
Xi'an	China	XAN	Existing
Qiongzhong	China	QIZ	Existing
Kodaikanal	India	KOD	Proposed
New Delhi	India	NDI	Proposed
Shillong	India	SHIO	Proposed
Matsushiro	Japan	MAJO	Existing
Makanchi	Kazakhstan	MAKZ	Existing
Ulaan Baatar	Mongolia	ULN	Existing
Quetta	Pakistan	QUE	Planned
Davao	Philippines	DAV	Existing
Magadan	Russia	MA2	Existing
Petropavlovsk-Kamchatskiy	Russia	PET	Existing
Bilibino	Russia	BILL	Existing
Tiksi	Russia	TIXI	Existing
Yakutsk	Russia	YAK	Existing
Yuzhno-Sakhalinsk	Russia	YSS	Existing
Inchon	South Korea	INCN	Existing
Taipei	Taiwan	TATO	Existing
Chiang Mai	Thailand	CHTO	Existing
Ankara	Turkey	ANTO	Existing
Australia			
Charters Towers	Queensland	CTAO	Existing
Marble Bar	Western Australia	MBWA	Existing
Narrogin	Western Australia	NWAO	Existing
Pacific Ocean			
Rarotonga	Cook Islands	RAR	Existing
Puerto Ayora, Santa Cruz Is.	Galapagos Is., Ecuador	PAYG	Existing
Pohakuloa	Hawaii, U.S.A.	POHA	Existing
Kipapa	Hawaii, U.S.A.	KIP	Existing
Johnston Atoll	Johnston Atoll	JOHN	Existing
Raoul Island	Kermadec Islands	RAO	Planned
Kiritimati	Kiribati	XMAS	Existing
Tarawa	Kiribati	TARA	Planned
Kanton	Kiribati	KANT	Planned

Guam	Marianas Islands	GUMO	Existing
Midway	Midway Islands	MIDW	Existing
South Karori	New Zealand	SNZO	Existing
Port Moresby	Papua New Guinea	PMG	Existing
Pitcairn	Pitcairn Island	PTCN	Existing
Afiamalu	Samoa Islands	AFI	Existing
Honiara	Solomon Islands	HNR	Existing
Funafuti	Tuvalu	FUNA	Planned
Wake	Wake Island	WAKE	Existing
Antarctica			
Casey	Antarctica	CASY	Existing
Palmer Station, Palmer Peninsula	Antarctica	PMSA	Existing
Scott Base	Antarctica	SBA	Existing
South Pole	Antarctica	SPA	Existing

Table A2. List of 45 IRIS GSN Stations (May 1, 2002).

North America			
Flin Flon	Manitoba, Canada	FFC	Existing
Alert	N.W.T., Canada	ALE	Existing
Las Juntas de Abangares	Costa Rica	JTS	Existing
Kodiak Island	Alaska, U.S.A.	KDAK	Existing
Columbia	California, U.S.A.	CMB	Existing
Pasadena	California, U.S.A.	PAS	Existing
Piñon Flat	California, U.S.A.	PFO	Existing
South America			
Las Campanas	Chile	LCO	Existing
Naña	Peru	NNA	Existing
Atlantic Ocean			
Ascension	Ascension Island	ASCN	Existing
Cha de Marcela	Azores	CMLA	Existing
East Falkland Island	Falkland Islands	EFI	Existing
Borgarnes	Iceland	BORG	Existing
Santiago Is.	Cape Verde Islands	SACV	Existing
South Georgia	South Georgia Island	HOPE	Existing
St. Helena	St. Helena Island	SHEL	Existing
Europe			
Lovozero	Russia	LVZ	Existing
Obninsk	Russia	OBN	Existing
Eskdalemuir	Scotland, U.K.	ESK	Existing
Africa			
Sutherland	South Africa	SUR	Existing
Mbarara	Uganda	MBAR	Existing
Indian Ocean			
Diego Garcia	Chagos Archipelago	DGAR	Planned
West Island	Cocos (Keeling) Islands	COCO	Existing
Fianarantsoa	Madagascar	FIAN	Proposed

Mahe	Seychelles Islands	MSEY	Existing
Pallekele	Sri Lanka	PALK	Existing
Asia			
Sulawesi	Indonesia	KAPI	Existing
Erimo	Japan	ERM	Existing
Borovoye	Kazakhstan	BRVK	Existing
Kurchatov	Kazakhstan	KURK	Existing
Ala-Archa	Kyrghyzstan	AAK	Existing
Wadi Sarin	Oman	WSAR	Proposed
Nilore	Pakistan	NIL	Existing
Arti	Russia	ARU	Existing
Kislovodsk	Russia	KIV	Existing
Norilsk	Russia	NRIL	Existing
Talaya	Russia	TLY	Existing
Ar Rayn	Saudi Arabia	RAYN	Existing
Alibek	Turkmenistan	ABKT	Existing
Australia			
Tennant Creek	Northern Territory	WRAB	Existing
Hobart	Tasmania	TAU	Existing
Pacific Ocean			
Rapa Nui	Easter Island, Chile	RPN	Existing
Monasavu	Viti Levu, Fiji	MSVF	Existing
Kwajalein Atoll	Marshall Islands	KWAJ	Existing
Hawaii-2 Observatory	Northeast Pacific	H2O	Existing

Table A3. List of 3 GSN Affiliate Stations and responsible organization (May 1, 2002).

Europe			
Black Forest Observatory	Germany	BFO	Black Forest Observatory
Africa			
Lobatse	Botswana	LBTB	Geological Survey of Botswana
Asia			
Bukit Timah Dairy Farm	Singapore	BTDF	Meteorological Service Singapore

Table A4. List of IRIS University GSN Stations and responsible organizations (May 1, 2002).

North America			
Tucson	Arizona	TUC	University of Arizona & USGS
Columbia	California	CMB	UC Berkeley
Pasadena	California	PAS	Caltech
Wyandotte Cave	Indiana	WCI	St. Louis University & USGS
Harvard	Massachusetts	HRV	Harvard & USGS
Cathedral Caves	Missouri	CCM	St. Louis University & USGS
Corvallis	Oregon	COR	Oregon State University & USGS
Standing Stone	Pennsylvania	SSPA	Penn State University & USGS
Waverly	Tennessee	WVT	St. Louis University & USGS

Hockley	Texas	HKT	University of Texas at Austin & USGS
South America			
Las Campanas	Chile	LCO	Carnegie Institution of Washington & IRIS
Pacific Ocean			
Hawaii-2 Observatory	NE Pacific	H2O	University of Hawaii & IRIS

Appendix D. IRIS Quality Principles for Data Collection, Distribution, and Use

Quality Principles, v3, October 19, 2014
Draft – Draft – Draft

The goal of the following IRIS Quality Principles is to address the whole process of collecting and distributing high-quality data, as this impacts the eventual quality and usability of the waveforms that are the end product. These quality principles are intended to be organization / operator neutral, and may be promulgated both nationally and internationally as a means of improving all data. Organizations that adhere to these principles provide a means of "quality assurance" to their data users. To achieve greatest impact, the mechanisms and tools used to implement these quality principles should be efficient, easy to operate, and scalable. Here, IRIS commits to adopting these principles, and indicates which part of the organization is primarily responsible for their implementation.

1. All users shall have information available to them that identifies the processes and methods by which the data were collected. (responsibility: IS)
2. All users shall have information available to them that identifies the data quality assurance process utilized by the facility. (responsibility: IS, DS)
3. There shall be mechanisms for operators to pass through to data users key information obtained as part of their data collection and quality assessment processes, including information that quantifies the integrity and state of the data time series and the validity and goodness of metadata and data time series. (responsibility: IS, DS)
4. All users of data shall have metrics describing data quality available to them, in a manner that allows use either directly by humans (e.g., web browser) or through computer interfaces (e.g., web services) where metrics can be directly included in workflows. (responsibility: DS)
5. The facility shall always strive to provide the most accurate metadata possible, and will update metadata when new information becomes available. (responsibility: IS, DS)
6. There shall be a mechanism for data users who register to report data quality information into the system. (responsibility: DS)
7. There shall be a mechanism for data users to obtain updates regarding data or metadata changes. (responsibility: DS)
8. IRIS-sponsored network / station operators shall have a quality plan, and implement quality processes that adhere to the larger facility-wide plan. [1] (responsibility: IS)

[1] The quality plan will at least include these sensor-specific requirements: Data providers shall maintain acceptance-testing protocols to verify instrument operational parameters prior to deployment; Regular in-situ calibrations will be conducted to validate key operational parameters.

Appendix E. GSN Standing Committee Membership History

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Committee Count	7	8	8	7	8	8	8	8	6	5	9	9	6	7	7	8	8	9	8	10	10	10	10	9	9	10	10	10	10
Staff + Observer Count	2	2	2	1	3	4	4	4	5	5	5	5	5	5	5	5	5	5	5	7	7	9	11	8	11	8	8	7	7
Total	9	10	10	8	11	12	12	12	11	10	14	14	11	12	12	13	13	14	13	17	17	19	21	17	20	18	18	17	17

Name		**Affiliation**	**Years of Service**	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Jonathan	Berger	UCSD	4	X	X	X		X																								
Adam	Dziewonski	Harvard	8	C	C												X	X	X								X	X	X			
Hiroo	Kanamori	Caltech	2	X	X																											
Thorne	Lay	UCSC	8	X	X	X											X	X	X		C	C										
Thomas	McEvilly	Berkeley	1	X																												
Brian	Mitchell	SLU	2	X	X																											
Ta-Liang	Teng	USC	3	X	X	X																										
Sean	Solomon	Carnegie	3		X	C	C																									
Terry	Wallace	UofAz	5		X	X	X				X	X																				
Kazuya	Fujita	Mich St	6			X	X	X				X	X	X																		
Donald	Helmberger	Caltech	3			X	X	X																								
Arthur	Lerner-Lam	LDEO	3			X	X	X																								
Charles	Langston	UM CERI	6				X	X	X	X	X	X																				
Emile	Okal	NW	4				X	X	X																	X						
Donald	Forsyth	Brown	4					C	C	C	C																					
Stephen	Grand	UTIG	6					X	X	X								X	X	X												
Gregory	Beroza	Stanford	3						X	X	X																					
Heidi	Houston	UW	3						X	X	X																					
Barbara	Romanowicz	Berkeley	7						X	X	X						C	C	C	C												
Stuart	Sipkin	USGS	4						X	X	X				X																	
Douglas	Wiens	WUSTL	3							X	X	X																				
Lane	Johnson	Berkeley	2									C	C																			
Robert	North	CMR	3									X	X	X																		
Duncan	Agnew	UCSD	3										X	X	X																	
Eric	Bergmann	USGS	3										X	X	X																	
Susan	Beck	ASU	3											X	X	X																
Alan	Chave	WHOI	3											X	X	X																
Douglas	Dreger	Berkeley	3											X	X	X																
Göran	Ekström	Harvard	3											C	C	C																
Thomas	Heaton	Caltech	4											X	X	X	X															
Anne	Sheehan	CU	3												X	X	X															
Charles	Ammon	Penn St	7														X	X	X				X						C	C	C	
John	Orcutt	UCSD	2														X	X														
Harley	Benz	USGS	3															X	X	X												
James	Gaherty	LDEO	3																X	X	X											
Cecily	Wolfe	UH Manoa	5																X	X	X										U	U
Kenneth	Creager	UW	3																	X	X	X										
Gabi	Laske	UCSD	3																	X	X	X										
Jeroen	Tromp	Caltech	6																	X	X	X	X	X	X							
Paul	Earle	USGS	6																		X	X	X							X	X	X
Jeffrey	Park	Yale	6																		X	X	C	C	C							X
Lianxing	Wen	SUNY SB	3																		X	X	X									
Karen	Fischer	Brown	1																			X										
Xiaodong	Song	Illinois	5																				X	X		C	C	C				
Mike	Ritzwoller	CU	2																				X	X								
Robert	Detrick	WHOI	3																				X	X	X							

X = Voting Committee Member; C = Committee Chair; U = USGS Member

Name		Affiliation	Years of Service	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Ed	Garnero	ASU	2																				X	X								
William	Leith	USGS	8																				U	U	U	U	U	U	U	U		
Miaki	Ishii	Harvard	3																					X	X	X						
Laura	Kong	ICO	3																					X	X	X						
Fenglin	Niu	Rice	3																					X	X	X						
Susan	Bilek	NMT	3																						X	X	X					
David	McCormack	NRC	3																						X	X	X					
Jeroen	Ritsema	Umich	3																						X	X	X					
Jeff	McGuire	WHOI	3																							X	X	X				
Gavin	Hayes	USGS	3																								X	X	X			
Colleen	Dalton	BU	3																								X	X	X			
Caroline	Beghein	UCLA	3																									X	X	X		
Meredith	Nettles	LDEO	4																									X	X	X		C
Gerardo	Suarez	UNAM	3																									X	X	X		
Mike	Thorne	Utah	3																										X	X	X	
Michael	Hedlin	UCSD	3																										X	X	X	
Andy	Newman	Georgia	3																											X	X	X
Mark	Panning	Florida	3																											X	X	X
Sebastien	Rost	Leeds	2																												X	X
Bob	Herrmann	SLU	2																												X	X
Vedran	Lekic	Maryland	2																												X	X
John	Vidale	Washington	1																													X

X = Voting Committee Member; C = Committee Chair; U = USGS Member

Other Participants

Name		Affiliation	Years of Service	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Rhett	Butler	IRIS	25	X	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P				
Jonathan	Berger	IDA	28	X	X	X		X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Charles	Hutt	ASL	19					O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O						
Holly	Given	IDA	7						O	O	O	O	O	O	O																	
Kent	Anderson	ASL/IRIS	21									O	O	O	O	O	O	O	O	O	O	O	M	M	M	M	M	A	A	P	P	P
Pete	Davis	IDA	17													O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
John	Dwyer	AFTAC	2																				O	O								
Alena	Leeds	USGS	4																				O	O	O	O						
Harley	Benz	USGS	8																						O	O	O	O	O	O	O	O
Bruce	Varnum	AFTAC	1																						O							
David	Green	NOAA	2																						O	O						
Shirley	Baher	AFTAC	4																							O	O	O	O			
Lind	Gee	ASL	7																							O	O	O	O	O	O	O
John	Derr	ASL	3																							O	O	O				
Charles	McCreery	NOAA	1																									O				
Jenifer	Rhoades	NOAA	2																									O	O			
Bob	Woodward	IS director	5																									O	O	O	O	O
Andy	Frassetto	IS	1																											O		
Dave	Wilson	USGS/ASL	3																											O	O	O

X = Voting Committee Member; P = Program Manager; O = Observer; M = Operations Manager; A = Acting Program Manager

Appendix F. GSN Selected Bibliography

This list results from a term-based search of selected journals and is not meant to a comprehensive list.

Abd el-aal, A.K., and M.S. Soliman (2013), New seismic noise models obtained using very broadband stations, *Pure and Applied Geophysics*, **170**(11), 1849–1857, doi: 10.1007/s00024-013-0640-7.

Adam, J. M.-C., and S. Lebedev (2012), Azimuthal anisotropy beneath southern Africa from very broad-band surface-wave dispersion measurements, *Geophysical Journal International*, **191**(1), 155–174, doi: 10.1111/j.1365-246X.2012.05583.x.

Adams, A., R. Brazier, A. Nyblade, A. Rodgers, and A. Al-Amri (2009), Source parameters for moderate earthquakes in the Zagros Mountains with implications for the depth extent of seismicity, *Bulletin of the Seismological Society of America*, **99**(3). 2044–2049, doi: 10.1785/0120080314.

Adams, A., and A. Nyblade (2011), Shear wave velocity structure of the southern African upper mantle with implications for the uplift of southern Africa, *Geophysical Journal International*, **186**(2), 808–824, doi: 10.1111/j.1365-246X.2011.05072.x.

Adams, A., A. Nyblade, and D. Weeraratne (2012), Upper mantle shear wave velocity structure beneath the East African plateau: Evidence for a deep, plateau-wide low velocity anomaly, *Geophysical Journal International*, **189**(1), 123–142, doi: 10.1111/j.1365-246X.2012.05373.x.

Al-Amri, A., D. Harris, M. Fnais, A. Rodgers, and M. Hemaida (2012), A regional seismic array of three-component stations in central Saudi Arabia, *Seismological Research Letters*, **83**(1), 49–58, doi: 10.1785/gssrl.83.1.49.

Allmann, B.P., and P.M. Shearer (2009), Global variations of stress drop for moderate to large earthquakes, *Journal of Geophysical Research*, **114**, B01310, doi: 10.1029/2008JB005821.

Ammon, C.J., T. Lay, and D.W. Simpson (2010), Great earthquakes and global seismic networks, *Seismological Research Letters*, **81**(6) 965–971, doi: 10.1785/gssrl.81.6.965.

Antolik, M., R.E. Abercrombie, and G. Ekström (2004), The 14 November 2001 Kokoxili (Kunlunshan), Tibet, Earthquake: Rupture transfer through a large extensional step-over, *Bulletin of the Seismological Society of America*, **94**(4), 1173–1194.

Ardhuin, F., E. Stutzmann, M. Schimmel, and A. Mangeney (2011) Ocean wave sources of seismic noise, *Journal of Geophysical Research*, **116**, C09004, doi: 10.1029/2011JC006952.

Assumpçao, M., J.C. Dourado, L.C. Ribotta, W.U. Mohriak, F.L. Dias, and J.R. Barbosa (2011), The Sao Vicente earthquake of 2008 April and seismicity in the continental shelf off SE Brazil: Further evidence for flexural stresses, *Geophysical Journal International*, **187**(3), doi: 10.1111/j.1365-246X.2011.05198.x.

Assumpçao, M., M. Feng, A. Tassara, and J. Julià (2013), Models of crustal thickness for South America from seismic refraction, receiver functions and surface wave tomography, *Tectonophysics*, **609**, 82–96, doi: 10.1016/j.tecto.2012.11.014.

Bao, X., E. Sandvol, E. Zor, S. Sakin, R. Mohamad, R. Gok, R. Mellors, T. Godoladze, G. Yetirmishli, and Niyazi Turkelli (2011), Pg Attenuation tomography within the northern Middle East, *Bulletin of the Seismological Society of America*, **101**(4), 1496–1506, doi: 10.1785/0120100316.

Baranov, A., and A. Morelli (2013), The Moho depth map of the Antarctica region, *Tectonophysics*, **609**, 299–313, doi: 10.1016/j/tecto.2012.12.023.

Bastow, I.D. (2012), Relative arrival-time upper-mantle tomography and the elusive background mean, *Geophysical Journal International*, **190**(2), 1271–1278, doi: 10.1111/j.1365-246X.2012.05559.

Bedle, H., and S. van der Lee (2009), Velocity variations beneath North America, *Journal of Geophysical Research*, **114**, B07308, doi: 10.1029/2008JB005949.

Behn, Mark D., Clinton P. Conrad, and Paul G. Silver (2004), Detection of upper mantle flow associated with the African Superplume, *Earth and Planetary Science Letters*, **224**(3–4), 259–274.

Berger, J., P. Davis, and G. Ekström (2004) Ambient Earth noise: A survey of the Global Seismographic Network, *Journal of Geophysical Research*, **109**, B11307, doi:10.1029/2004JB003408.

Besana, G.M., Y. Tanioka, M. Ando, M.H. Mirabueno, J. Manahan, J. De Ocampo, J. Perez, and B. Bautista (2004), The May 17, 1992 earthquakes in southeastern Philippines, *Geophysical Research Letters*, **31**, L24618, doi:10.1029/2004GL020917.

Bezada, M.J., and E.D. Humphreys (2012), Contrasting rupture processes during the April 11, 2010 deep-focus earthquake beneath Granada, Spain, *Earth and Planetary Science Letters*, **353–354**(38–46), doi: 10.1016/j.epsl.2012.08.001.

Bilek, S.L., T. Lay, and L.J. Ruff (2004), Radiated seismic energy and earthquake source duration variations from teleseismic source time functions for shallow subduction zone thrust earthquakes, *Journal of Geophysical Research*, **109**, B09308, doi:10.1029/2004JB003039.

Boatwright, J., and L. Seekins (2011), Regional spectral analysis of three moderate earthquakes in northeastern North America, *Bulletin of the Seismological Society of America*, **101**(4), 1769–1782, doi: 10.1785/0120100225.

Bodin, P., and S. Horton (2004), Source parameters and tectonic implications of aftershocks of the M_w 7.6 Bhuj earthquake of 26 January 2001, *Bulletin of the Seismological Society of America*, **94**(3), 818–827.

Boettcher, M.S., and J.J. McGuire (2009) Scaling relations for seismic cycles on mid-ocean ridge transform faults, *Geophysical Research Letters*, **36**, L21301, doi:10.1029/2009GL040115.

Boomer, K.B., R.A. Brazier, and A.A. Nyblade (2010), Empirically based ground truth criteria for seismic events recorded at local distances on regional networks with application to southern Africa, *Bulletin of the Seismological Society of America*, **100**(4), 1785–1791, doi: 10.1785/0120090237.

Bormann, P., and J. Saul (2009), A Fast, Non-saturating magnitude estimator for Great Earthquakes, *Seismological Research Letters*, **80**(1), 128–133, doi: 10.1785/gssrl.80.5.808.

Bromirski, P.D. (2009) Earth vibrations, *Science*, **324**(5030), 1026–1027.

Cao, A., and B. Romanowicz (2004), Hemispherical transition of seismic attenuation at the top of the Earth's inner core, *Earth and Planetary Science Letters*, **228**(3–4), 243–253.

Castellaro, S., and F. Mulargia (2012), A statistical low noise model of the Earth, *Seismological Research Letters*, **83**(1), 39–48, doi: 10.1785/gssrl.83.1.39.

Chambers, K., A. Deuss, and J.H. Woodhouse (2005), Reflectivity of the 410-km discontinuity from PP and SS precursors, *Journal of Geophysical Research*, **110**, B02301, doi:10.1029/2004JB003345.

Chambers, K., J.H. Woodhouse, and A. Deuss (2005), Topography of the 410-km discontinuity from PP and SS precursors, *Earth and Planetary Science Letters*, **235**(3), 610–622.

Chen, W., D. Wang, and S. Wei (2013), A study on the uncertainties of the centroid depth of the 2013 Lushan earthquake from teleseismic body wave data, *Earthquake Science*, **26**(3-4), 161–168, doi: 10.1007/s11589-013-0042-z.

Chen, Y., and F. Niu (2013), Ray-parameter based stacking and enhanced pre-conditioning for stable inversion of receiver function data, *Geophysical Journal International*, **194**(3), 1682–1700, doi: 10.1093/gji/ggt179.

Chi, W.-Ch., W.-J. Chen, D. Dolenc, B.-Y. Kuo, Chin-ren Lin, and J. Collins (2010), Seismological report on the 2006 Typhoon Shanshan that lit up seismic stations along its way, *Seismological Research Letters*, **81**(4), 592–596, doi: 10.1785/gssrl.81.4.592.

Choy, G.L., and J. Boatwright (2009) Differential energy radiation from two earthquakes in Japan with identical M_w: The Kyushu 1996 and Tottori 2000 earthquakes, *Bulletin of the Seismological Society of America*, **99**(3), 1815–1826, doi: 10.1785/0120080078.

Chu, R., L. Zhu, and D.V. Helmberger (2009), Determination of earthquake focal depths and source time functions in central Asia using teleseismic waveforms, *Geophysical Research Letters*, **36**, L17317, doi:10.1029/2009GL039494.

Chun, Kin-Yip, and G.A. Henderson (2009), Lg attenuation near the North Korean border with China, Part II: Model development from the 2006 nuclear explosion in North Korea, *Bulletin of the Seismological Society of America*, 99(5), 3030–3038, doi: 10.1785/0120080341.

Cleveland, K.M., and C.J. Ammon (2013), Precise relative earthquake location using surface waves, *Journal of Geophysical Research*, **118**, 2893–2904, doi: 10.1002/jgrb.50146.

Corchete, V. (2013), Shear-wave velocity structure of Antarctica from Rayleigh-wave analysis, *Tectonophysics*, **583**, 1–15, doi: 10.1016/j.tecto.2012.10.013.

Cupillard, P., E. Delavaud, G. Burgos, G. Festa, J.-P. Vilotte, Y. Capdeville, and J.-P. Montagner (2012), RegSEM: a versatile code based on the spectral element method to compute seismic wave propagation at the regional scale, *Geophysical Journal International*, **188**(3), 1203–1220, doi: 10.1111/j.1365-246X.2011.05311.

D'Oreye, N., P.J. González, A. Shuler, A. Oth, L. Bagalwa, G. Ekström, D. Kavotha, F. Kervyn, C. Lucas, F. Lukaya, E. Osodundu, C. Wauthier, and J. Fernández (2011), Source parameters of the 2008 Bukavu-Cyangugu earthquake estimated from InSAR and teleseismic data, *Geophysical Journal International*, **184**(2), 934–948, doi: 10.1111/j.1365-246X.2010.04899.x.

Darbyshire, F.A., T.B. Larsen, K. Mosegaard, T. Dahl-Jensen, O. Gudmundsson, T. Bach, S. Gregersen, H.A. Pedersen, and W. Hanka (2004), A first detailed look at the Greenland lithosphere and upper mantle, using Rayleigh wave tomography, *Geophysical Journal International*, **158**(1), 267–286, doi: 10.1111/j.1365-246X.2004.02316.x.

Davis, M.W., N.J. White, K.F. Priestley, B.J. Baptie, and F.J. Tilmann (2012), Crustal structure of the British Isles and its epeirogenic consequences, *Geophysical Journal International*, **190**(2), 705–725 doi: 10.1111/j.1365-246X.2012.05485.x.

Davis, P., M. Ishii, and G. Masters (2005), An assessment of the accuracy of GSN sensor response information, *Seismological Research Letters*, **76**(6), 678–683.

Davis, P.M., and J. Berger (2012), Initial Impact of the Global Seismographic Network Quality Initiative on Metadata Accuracy, *Seismological Research Letters*, **83**(4), 697–703, doi: 10.1785/0220120021.

De la Torre, T.L., and A.F. Sheehan (2005), Broadband seismic noise analysis of the Himalayan Nepal Tibet Seismic Experiment, *Bulletin of the Seismological Society of America*, **95**(3), 1202–1208, doi: 10.1785/0120040098.

Debayle, E., and Y. Ricard (2012), A global shear velocity model of the upper mantle from fundamental and higher Rayleigh mode measurements, *Journal of Geophysical Research*, **117**, B10308, doi: 10.1029/2012JB009288.

Delouis, B., M. Vallée, M. Meghraoui, E. Calais, S. Maouche, K. Lammali, A. Mahsas, P. Briole, F. Benhamouda, and K. Yelles (2004), Slip distribution of the 2003 Boumerdes-Zemmouri earthquake, Algeria, from teleseismic, GPS, and coastal uplift data, *Geophysical Research Letters*, **31**, L18607, doi:10.1029/2004GL020687.

DeShon, H.R., and S.Y. Schwartz (2004), Evidence for serpentinization of the forearc mantle wedge along the Nicoya Peninsula, Costa Rica, *Geophysical Research Letters*, **31**, L21611, doi:10.1029/2004GL021179.

Di Leo, J.F., J. Wookey, J.O.S. Hammond, J.M. Kendall, S. Kaneshima, H. Inoue, T. Yamashina, and P. Harjadi (2012), Deformation and mantle flow beneath the Sangihe subduction zone from seismic anisotropy, *Physics of the Earth and Planetary Interiors*, **194–195**, 38–54, doi: 10.1016/j.pepi.2012.01.008.

Duputel, Z., L. Rivera, H. Kanamori, and G. Hayes (2012), W phase source inversion for moderate to large earthquakes (1990–2010), *Geophysical Journal International*, **189**(2), 1125–1147, doi: 10.1111/j.1365-246X.2012.05419.

Eakin, C.M., and M.D. Long (2013), Complex anisotropy beneath the Peruvian flat slab from frequency-dependent, multiple-phase shear wave splitting analysis, *Journal of Geophysical Research*, **118**, 4794–4813, doi:10.1002/jgrb.50349..

Ebeling, C.W., and E.A. Okal (2012), An extension of the E/M0 tsunami earthquake discriminant Θ to regional distances, *Geophysical Journal International*, **190**(3), 1640–1656, doi: 10.1111/j.1365-246X.2012.05566.x.

Ebeling, C.W., and S. Stein (2011), Seismological identification and characterization of a large hurricane, *Bulletin of the Seismological Society of America*, **101**(1), 399–403, doi: 10.1785/0120100175.

Ekström, G., M. Nettles, and A.M. Dziewonski (2012), The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes, *Physics of the Earth and Planetary Interiors*, **200–201**, 1–9, doi: 10.1016/j.pepi.2012.04.002.

Ekström, G., and C.P. Stark (2013), Simple Scaling of Catastrophic landslide dynamics, *Science*, **339**(6126), 1416–1419, doi: 10.1126/science.1232887.

Elliott, J.R., E.K. Nissen, P.C. England, J.A. Jackson, S. Lamb, Z. Li, M. Oehlers, and B. Parsons (2012), Slip in the 2010-2011 Canterbury earthquakes, New Zealand, *Journal of Geophysical Research*, **117**, B03401, doi: 10.1029/2011JB008868.

Feng, M., M. Assumpcao, and S. Van der Lee (2004), Group-velocity tomography and lithospheric S-velocity structure of the South American continent, *Physics of the Earth and Planetary Interiors*, **147**(4), 315–331, doi: 10.1016/j.pepi.2004.07.008.

Fielding, E.J., A. Sladen, Z. Li, J.-P. Avouac, R. Bürgmann, and I. Ryder (2013), Kinematic fault slip evolution source models of the 2008 M7.9 Wenchuan earthquake in China from SAR interferometry, GPS and teleseismic analysis and implications for Longmen Shan tectonics, *Geophysical Journal International*, **194**(2), 1138–1166, doi: 10.1093/gji/ggt155.

Fishwick, S., B.L.N. Kennett, and A.M. Reading (2005), Contrasts in lithospheric structure within the Australian craton-insights from surface wave tomography, *Earth and Planetary Science Letters*, **231**(3), 163–176, doi:10.1016/j.epsl.2005.01.009.

Forbriger, T., R. Widmer-Schnidrig, E. Wielandt, M. Hayman, and N. Ackerley (2010), Magnetic field background variations can limit the resolution of seismic broad-band sensors, *Geophysical Journal International*, **183**(1), 303–312, doi: 10.1111/j.1365-246X.2010.04719.x.

Ford, S.R., D.S. Dreger, and W.R. Walter (2009), Source analysis of the Memorial Day explosion, Kimchaek, North Korea, *Geophysical Research Letters*, **36**, L21304, doi:10.1029/2009GL040003.

Ford, S.R., W.R. Walter, and D.S. Dreger (2012), Event Discrimination using Regional Moment Tensors with Teleseismic-P Constraints, *Bulletin of the Seismological Society of America*, **102**(2), 867–872, doi: 10.1785/0120110227.

Fox, B.D., N.D. Selby, R. Heyburn, and J.H. Woodhouse (2012), Shallow seismic source parameter determination using intermediate-period surface wave amplitude spectra, *Geophysical Journal International*, **191**(2), 601–615, doi: 10.1111/j.1365-246X.2012.05612.x.

Frassetto, A., and H. Thybo (2013), Receiver function analysis of the crust and upper mantle in Fennoscandia – isostatic implications, *Earth and Planetary Science Letters*, **381**, 234–246, doi: 10.1016/j.epsl.2013.07.001.

Frederiksen, A.W., T. Bollmann, F. Darbyshire, and S. van der Lee (2013) Modification of continental lithosphere by tectonic processes: A tomographic image of central North America, *Journal of Geophysical Research*, **118**(3), 1051-1066, doi: 10.1002/jgrb.50060.

Gaherty, J.B. (2004), A surface wave analysis of seismic anisotropy beneath eastern North America, *Geophysical Journal International*, **158**(3), 1053–1066, doi: 10.1111/j.1365-246X.2004.02371.x.

Gaite, B., A. Iglesias, A. Villaseñor, M. Herraiz, and J.F. Pacheco (2012), Crustal structure of Mexico and surrounding regions from seismic ambient noise tomography, *Geophysical Journal International*, **188**(3), 1413–1424, doi: 10.1111/j.1365-246X.2011.05339.x.

Gao, S.S., K.H. Liu, and M.G. Abdelsalam (2010), Seismic anisotropy beneath the Afar Depression and adjacent areas: Implications for mantle flow, *Journal of Geophysical Research*, **115**, B12330, doi: 10.1029/2009JB007141.

Gao, S.S., K.H. Liu, and C. Chen (2004), Significant crustal thinning beneath the Baikal rift zone: New constraints from receiver function analysis, *Geophysical Research Letters*, **31**, L20610, doi:10.1029/2004GL020813.

García-Jerez, A., F. Luzón, F.J. Sánchez-Sesma, E. Lunedei, D. Albarello, M.A. Santoyo, and J. Almendros (2013), Diffuse elastic wavefield within a simple crustal model. Some consequences for low and high frequencies, *Journal of Geophysical Research*, **118**, 5577–5595, doi:10.1002/2013JB010107.

Garnero, E.J., M.M. Moore, T. Lay, and M.J. Fouch (2004), Isotropy or weak vertical transverse isotropy in D beneath the Atlantic Ocean, *Journal of Geophysical Research*, **109**, B08308, doi: 10.1029/2004JB003004.

Geissler, W.H., F. Sodoudi, and R. Kind (2010), Thickness of the central and eastern European lithosphere as seen by S receiver functions, *Geophysical Journal International*, **181**(2), 604–634, doi: 10.1111/j.1365-246X.2010.04548.x.

Godey, S., F. Deschamps, J. Trampert, and R. Snieder (2004), Thermal and compositional anomalies beneath the North American continent, *Journal of Geophysical Research*, **109**, B01308, doi:10.1029/2002JB002263.

Gök, R., R.J. Mellors, E. Sandvol, M. Pasyanos, T. Hauk, R. Takedatsu, G. Yetirmishli, U. Teoman, N. Turkelli, T. Godoladze, and Z. Javakishvirli (2011), Lithospheric velocity structure of the Anatolian plateau-Caucasus-Caspian region, *Journal of Geophysical Research*, **116**, B05303, doi:10.1029/2009JB000837.

Granville, J.P., P.G. Richards, W.-Y. Kim, and L.R. Sykes (2005), Understanding the differences between three teleseismic mb scales, *Bulletin of the Seismological Society of America*, **95**(5), 1809–1824, doi: 10.1785/0120040159.

Groos, J.C., S. Bussat, and J.R.R. Ritter (2012), Performance of different processing schemes in seismic noise cross-correlations, *Geophysical Journal International*, **188**(2), 498–512, doi: 10.1111/j.1365-246X.2011.05288.

Gu, Y.J., F.H. Webb, A. Lerner-Lam, and J.B. Gaherty (2005), Upper mantle structure beneath the eastern Pacific Ocean ridges, *Journal of Geophysical Research*, **110**, B06305, doi: 10.1029/2004JB003381.

Guo, Z., X. Gao, H. Shi, and W. Wang (2013), Crustal and uppermost mantle S-wave velocity structure beneath the Japanese islands from seismic ambient noise tomography, *Geophysical Journal International*, **193**(1), 394–406, doi: 10.1093/gji/ggs121.

Häfner, R., and R. Widmer-Schnidrig (2013), Signature of 3-D density structure in spectra of the spheroidal free oscillation 0S2, *Geophysical Journal International*, **192**(1), 285–294, doi: 10.1093/gji/ggs013.

Hanson, J.A., and J.R. Bowman (2005), Dispersive and reflected tsunami signals from the 2004 Indian Ocean tsunami observed on hydrophones and seismic stations, *Geophysical Research Letters*, **32**, L17606, doi:10.1029/2005GL023783.

Hao, J., C. Ji, W. Wang, and Z. Yao (2013), Rupture history of the 2013 Mw 6.6 Lushan earthquake constrained with local strong motion and teleseismic body and surface waves, *Geophysical Research Letters*, **40**, 5371–5376, doi:10.1002/2013GL056876.

Hayes, G.P., P.S. Earle, H.M. Benz, D.J. Wald, R.W. and Briggs, and the USGS/NEIC Earthquake Response Team (2011), 88 Hours: The U.S. Geological Survey National Earthquake Information Center Response to the 11 March 2011 M_w 9.0 Tohoku Earthquake, *Seismological Research Letters*, **82**(4), 481–493, doi: 10.1785/gssrl.82.4.481.

He, Y., and L. Wen (2009), Structural features and shear-velocity structure of the Pacific Anomaly, *Journal of Geophysical Research*, **114**, B02309, doi: 10.1029/2008JB005814.

Heintz, M., V.P. Kumar, V.K. Gaur, K. Priestley, S.S. Rai, and K.S. Prakasam (2009), Anisotropy of the Indian continental lithospheric mantle, *Geophysical Journal International*, **179**(3), 1341–1360, doi: 10.1111/j.1365-246X.2009.04395.x.

Helffrich, G., B. Faria, João F.B.D. Fonseca, A. Lodge, and S. Kaneshima (2010), Transition zone structure under a stationary hot spot: Cape Verde, *Earth and Planetary Science Letters*, **289**(1–2), 156–161, doi: 10.1016/j.epsl.2009.11.001.

Herrmann, F.J., and Y. Bernabe (2004), Seismic singularities at upper-mantle phase transitions: a site percolation model, *Geophysical Journal International*, 159(3), 949–960, doi: 10.1111/j.1365-246X.2004.02464.x.

Hirshorn, B., S. Weinstein, and S. Tsuboi (2013), On the application of Mwp in the near field and the March 11, 2011 Tohoku earthquake, *Pure and Applied Geophysics*, **170**(6–8), 975–991 doi: 10.1007/s00024-012-0495-3.

Hjörleifsdóttir, V., and G. Ekström (2010), Effects of three-dimensional Earth structure on CMT earthquake parameters, *Physics of the Earth and Planetary Interiors*, **179**(3–4), 178–190, doi: 10.1016/j.pepi.2009.11.003.

Hjörleifsdóttir, V., H. Kanamori, and J. Tromp (2009), Modeling 3-D wave propagation and finite slip for the 1998 Balleny Islands earthquake, *Journal of Geophysical Research*, 114, B03301, doi:10.1029/2008JB005975.

Hu, X.G., L.T. Liu, C. Kroner, and H.P. Sun (2009), Observation of the seismic anisotropy effects on free oscillations below 4 mHz, *Journal of Geophysical Research*, **114**, B07301, doi:10.1029/2008JB005713.

Huang, G.-C. D., S.W. Roecker, and V. Levin (2011), Lower-crustal earthquakes in the West Kunlun range, *Geophysical Research Letters*, **38**, L01314, doi: 10.1029/2010GL045893.

Huang, G.-C. (D.), F.T. Wu, S.W. Roecker, and A.F. Sheehan (2009), Lithospheric structure of the central Himalaya from 3-D tomographic imaging, *Tectonophysics*, **475**(3–4), 524–543, doi:10.1016/j.tecto.2009.06.023.

Huerta, A.D., A.A. Nyblade, and A.M. Reusch (2009), Mantle transition zone structure beneath Kenya and Tanzania: more evidence for a deep-seated thermal upwelling in the mantle, *Geophysical Journal International*, **177**(3), 1249–1255, doi: 10.1111/j.1365-246X.2009.04092.x.

Hung, S.H., W.P. Chen, and L.Y. Chiao (2011), A data-adaptive, multiscale approach of finite-frequency, traveltime tomography with special reference to P and S wave data from central Tibet, *Journal of Geophysical Research*, **116**, B06307, doi: 10.1029/2010JB008190.

Hung, S.H., Y. Shen, and L.Y. Chiao (2004), Imaging seismic velocity structure beneath the Iceland hot spot: A finite frequency approach, *Journal of Geophysical Research*, **109**, B08305, doi: 10.1029/2003JB002889.

Husson, R., F. Ardhuin, F. Collard, B. Chapron, and A. Balanche (2012), Revealing forerunners on Envisat's wave mode ASAR using the Global Seismic Network, *Geophysical Research Letters*, **39**, L15609, doi:10.1029/2012GL052334.

Hwang, Y.K., and J. Ritsema (2011), Radial Qμ structure of the lower mantle from teleseismic body-wave spectra, *Earth and Planetary Science Letters*, **303**(3–4), 369–375, doi: 10.1016/j.epsl.2011.01.023.

Ide, S., A. Baltay, and G.C. Beroza (2011), Shallow dynamic overshoot and energetic deep rupture in the 2011 M_w 9.0 Tohoku-Oki earthquake, *Science*, **332**(6036), 1426–1429, doi: 10.1126/science.1207020.

Igarashi, Y., L. Kong, M. Yamamoto, and C.S. McCreery (2011), Anatomy of historical ysunamis: Lessons learned for tsunami warning, *Pure and Applied Geophysics*, **168**(11), 2043–2063, doi: 10.1007/s00024-011-0287-1.

Isse, T., H. Shiobara, Y. Fukao, K. Mochizuki, T. Kanazawa, H. Sugioka, S. Kodaira, R. Hino, and D. Suetsugu (2004), Rayleigh wave phase velocity measurements across the Philippine sea from a broad-band OBS array, *Geophysical Journal International*, **158**(1), 257–266, doi: 10.1111/j.1365-246X.2004.02322.x.

Ji, C., K.M. Larson, Y. Tan, K.W. Hudnut, and K. Choi (2004), Slip history of the 2003 San Simeon earthquake constrained by combining 1-Hz GPS, strong motion, and teleseismic data, *Geophysical Research Letters*, **31**, L17608, doi: 10.1029/2004GL020448.

Kanamori, H., and L. Rivera (2008), Source inversion of W phase: speeding up seismic tsunami warning, *Geophysical Journal International*, **175**, 222–238, doi: 10.1111/j.1365-246X.2008.03887.x.

Kaneshima, S., K. Kanjo, T. Ohtaki, and I. Purwana (2004), Surface wave tomography for southeastern Asia using IRIS-FARM and JISNET data, *Physics of the Earth and Planetary Interiors*, **146**(1–2), 101–112, doi: 10.1016/j.pepi.2003.06.009.

Katsumata, K., M. Kasahara, M. Ichiyanagi, M. Kikuchi, R.-Se Sen, C.-Un Kim, A. Ivaschenko, and R. Tatevossian (2004), The 27 May 1995 Ms 7.6 Northern Sakhalin earthquake: An earthquake on an uncertain plate boundary, *Bulletin of the Seismological Society of America*, **94**(1), 117–130.

Keir, D., I.D. Bastow, C. Pagli, and E.L. Chambers (2013), The development of extension and magmatism in the Red Sea rift of Afar, *Tectonophysics*, **607**, 98–114, doi: 10.1016/j.tecto.2012.10.015.

Kgaswane, E.M., A.A. Nyblade, R.J. Durrheim, J. Julià, Paul H.G.M. Dirks, and S.J. Webb (2012), Shear wave velocity structure of the Bushveld Complex, South Africa, *Tectonophysics*, **554–557**, 83–104, doi: 10.1016/j.tecto.2012.06.003.

Kgaswane, E.M., A.A. Nyblade, J. Julià, P.H.G.M. Dirks, R.J. Durrheim, and M.E. Pasyanos (2009), Shear wave velocity structure of the lower crust in southern Africa: Evidence for compositional heterogeneity within Archaean and Proterozoic terrains, *Journal of Geophysical Research*, **114**, B12304, doi:10.1029/2008JB006217.

Kilb, D., Z. Peng, D. Simpson, A. Michael, M. Fisher, and D. Rohrlick (2012), Listen, Watch, Learn: SeisSound video products, *Seismological Research Letters*, **83**(2), 281–286, doi: 10.1785/gssrl.83.2.281.

Kim, K.-Hee, Jer-M. Chiu, H. Kao, Q. Liu, and Yih-H. Yeh (2004), A preliminary study of crustal structure in Taiwan region using receiver function analysis, *Geophysical Journal International*, **159**(1), 146–164, doi: 10.1111/j.1365-246X.2004.02344.x.

Kim, T.S., I.B. Kang, and G.Y. Kim (2009), Yield ratio estimates using regional P and P from North Korea's underground nuclear explosions, *Geophysical Research Letters*, **36**, L22302, doi:10.1029/2009GL040495.

Kim, W-Y, and M. Chapman (2005), The 9 December 2003 Central Virginia Earthquake Sequence: A Compound Earthquake in the Central Virginia Seismic Zone, *Bulletin of the Seismological Society of America*, **95**(6), 2428–2445.

Kobayashi, R., and D. Zhao (2004), Rayleigh-wave group velocity distribution in the Antarctic region, *Physics of the Earth and Planetary Interiors*, **141**(3), 167–181, doi: 10.1016/j.pepi.2003.11.011.

Koch, F.W., D.A. Wiens, A.A. Nyblade, P.J. Shore, R. Tibi, B. Ateba, C.T. Tabod, and J.M. Nnange (2012), Upper-mantle anisotropy beneath the Cameroon Volcanic Line and Congo Craton from shear wave splitting measurements, *Geophysical Journal International*, **190**(1), 75–86, doi: 10.1111/j.1365-246X.2012.05497.

Köhler, A., C. Weidle, and V. Maupin (2011), Directionality analysis and Rayleigh wave tomography of ambient seismic noise in southern Norway, *Geophysical Journal International*, **84**(1), 287–300, doi: 10.1029/2011GL046855.

Köhler, A., C. Weidle, and V. Maupin (2012), Crustal and uppermost mantle structure of southern Norway: results from surface wave analysis of ambient seismic noise and earthquake data, *Geophysical Journal International*, **191**(3), 1441–1456, doi: 10.1111/j.1365-246X.2012.05698.x.

Koketsu, K., Y. Yokota, N. Nishimura, Y. Yagi, S. Miyazaki, K. Satake, Y. Fujii, H. Miyake, S. Sakai, Y. Yamanaka, and T. Okada (2011), A unified source model for the 2011 Tohoku earthquake, *Earth and Planetary Science Letters*, **310**(3–4), 480–487, doi: 10.1016/j.epsl.2011.09.009.

Koper, K.D., and M.L. Pyle (2004), Observations of PKiKP / PcP amplitude ratios and implications for Earth structure at the boundaries of the liquid core, *Journal of Geophysical Research*, **109**, B03301, doi: 10.1029/2003JB002750.

Kosarev, G.L., S.I. Oreshin, L.P. Vinnik, S.G. Kiselev, R.S. Dattatrayam, G. Suresh, and P.R. Baidya (2013), Heterogeneous lithosphere and the underlying mantle of the Indian subcontinent, *Tectonophysics*, **592**, 175–186, doi: 10.1016/j.2013.02.023.

Kraeva, N. (2004) Tikhonov's regularization for deconvolution in the empirical Green function method and vertical directivity effect, *Tectonophysics*, **383**(1–2), 29–44, doi: 10.1016/j.tecto.2004.02.003.

Kuenza, K., and C. Soon-Hoe (2010), Anatomy of the 17 July 2006 Java earthquake reveals its tsunamigenic nature, *Seismological Research Letters*, Vol. 81, No. 1, p.99–112, doi: 10.1785/gssrl.81.1.99.

Kumar, P., R. Kind, and X. Yuan (2010), Receiver function summation without deconvolution, *Geophysical Journal International*, **180**(3), 1223–1230, doi: 10.1111/j.1365-246X.2009.04469.x.

Kuo, B.Y., and C.W. Chen (2005) A seismological determination of the temperature gradient in D' beneath the western Pacific, *Journal of Geophysical Research*, **110**, B05304, doi:10.1029/2004JB003291.

Laske, G., A. Markee, J.A. Orcutt, C.J. Wolfe, J.A. Collins, S.C. Solomon, R.S. Detrick, D. Bercovici, and E.H. Hauri (2011), Asymmetric shallow mantle structure beneath the Hawaiian Swell—evidence from Rayleigh waves recorded by the PLUME network, *Geophysical Journal International*, **187**(3), 1725–1742, doi: 10.1111/j.1365-246X.2011.05238.x.

Lawrence, J.F., D.A. Wiens, A.A. Nyblade, S. Anandakrishan, P.J. Shore, and D. Voigt (2006), Upper mantle thermal variations beneath the Transantarctic Mountains inferred from teleseismic S-wave attenuation, *Geophysical Research Letters*, **333**, L03303, doi:10.1029/2005GL024516.

Lay, T., H. Kanamori, C. J. Ammon, M. Nettles, S.N. Ward, R.C. Aster, S.L. Beck, S.L. Bilek, M.R. Brudzinski, R. Butler, H.R. DeShon, G. Ekstrom, K. Satake, and S. Sipkin (2005), The Great Sumatra-Andaman Earthquake of 26 December 2004, *Science*, **308**(5725), 1127–1133, doi: 10.1126/science.1112250.

Leahy, G.M. (2009), Local variability in the 410-km mantle discontinuity under a hotspot, *Earth and Planetary Science Letters*, **288**(1–2), 158–163, doi: 10.1016/j.epsl.2009.09.018.

Leahy, G.M., and J.A. Collins (2009), Improved statistical processing for common-conversion-point stacked receiver functions, *Bulletin of the Seismological Society of America*, **99**(2A), 914–921, doi: 10.1785/0120080263.

Leahy, G.M., J.A. Collins, C.J. Wolfe, G. Laske, and S.C. Solomon (2010), Underplating of the Hawaiian Swell: evidence from teleseismic receiver functions, *Geophysical Journal International*, **183**(1), 313–329, doi: 10.1111/j.1365-246X.2010.04720.x.

Legendre, C.P., T. Meier, S. Lebedev, W. Friederich, and L. Viereck-Götte (2012), A shear wave velocity model of the European upper mantle from automated inversion of seismic shear and surface waveforms, *Geophysical Journal International*, **191**(1), 282–304, doi: 10.1111/j.1365-246X.2012.05613.

Leidig, M.R., D.T. Reiter, J.L. Bonner, and A.J. Rodgers Jr (2004), Applicability of 3D Modeling Techniques in Creating Single-Station Locations: A Test Case in Southern Asia, *Bulletin of the Seismological Society of America*, **94**(2), 753–759.

Lekić, V., and B. Romanowicz (2011), Inferring upper-mantle structure by full waveform tomography with the spectral element method, *Geophysical Journal International*, **185**(2), 799–831, doi: 10.1111/j.1365-246X.2011.04969.x.

Lentas, K., A.M.G. Ferreira, and M. Vallée (2013), Assessment of SCARDEC source parameters of global large (Mw ≥ 7.5) subduction earthquakes, *Geophysical Journal International*, **195**(3), 1989–2004, doi: 10.1093/gji/ggt364.

Levin, V., D. Droznin, J. Park, and E. Gordeev (2004), Detailed mapping of seismic anisotropy with local shear waves in southeastern Kamchatka, *Geophysical Journal International*, **158**(3), 1009–1023, doi: 10.1111/j.1365-246X.2004.02352.x.

Levin, V., Guo-chin D. Huang, and S. Roecker (2013), Crust–mantle coupling at the northern edge of the Tibetan plateau: Evidence from focal mechanisms and observations of seismic anisotropy, *Tectonophysics*, **584**, 221–229, doi: 10.1016/j.tecto.2012.05.013.

Leykam, D., H. Tkalčić, and A.M. Reading (2010), Core structure re-examined using new teleseismic data recorded in Antarctica: evidence for, at most, weak cylindrical seismic anisotropy in the inner core, *Geophysical Journal International*, Vol. 180, No. 3, p.1329–1343, doi: 10.1111/j.1365-246X.2010.04488.x.

Li, A. (2011), Shear wave model of southern Africa from regional Rayleigh wave tomography with 2-D sensitivity kernels, *Geophysical Journal International*, **185**(2), 832–844, doi: 10.1111/j.1365-246X.2011.04971.x.

Li, J., and F. Niu (2010), Seismic anisotropy and mantle flow beneath northeast China inferred from regional seismic networks, *Journal of Geophysical Research*, **115**, B12327, doi: 10.1029/2010JB007470.

Li, J., X. Wang, and F. Niu (2011), Seismic anisotropy and implications for mantle deformation beneath the NE margin of the Tibet plateau and Ordos plateau, *Physics of the Earth and Planetary Interiors*, **189**(3–4), 157–170, doi: 10.1016/j.pepi.2011.08.009.

Li, J., Xin Wang, X. Wang, and D.A. Yuen (2013), P and SH velocity structure in the upper mantle beneath Northeast China: Evidence for a stagnant slab in hydrous mantle transition zone, *Earth and Planetary Science Letters*, **367**, 71–81, doi: 10.1016/j.epsl.2013.02.026.

Li, X., R. Kind, X. Yuan, I. Wölbern, and W. Hanka (2004), Rejuvenation of the lithosphere by the Hawaiian plume, *Nature*, **427**(7004), 827–829, doi: 10.1038/nature02349.

Liang, X., E. Sandvol, Y.J. Chen, T. Hearn, J. Ni, S.L. Klemperer, Y. Shen, and F.J. Tilmann (2012), A complex Tibetan upper mantle: A fragmented Indian slab and no south-verging subduction of Eurasian lithosphere, *Earth and Planetary Science Letters*, **333–334**, 101–111, doi: 10.1016/j.epsl.2012.03.036.

Lin, F.-Chi, and V.C. Tsai (2013), Seismic interferometry with antipodal station pairs, *Geophysical Research Letters*, **40**, 4609–4613, doi:10.1002/grl.50907.

Long, H., and L. Wen (2012), Using repeated sources to quantitatively determine temporal change of medium properties: Theory and an example, *Journal of Geophysical Research*, **117**, B09303, doi: 10.1029/2012JB009302.

Long, M.D., and P.G. Silver (2009), Mantle flow in subduction systems: The subslab flow field and implications for mantle dynamics, *Journal of Geophysical Research*, **114**, B10312, doi: 10.1029/2008JB006200.

Long, M.D., and E.A. Wirth (2013) Mantle flow in subduction systems: The mantle wedge flow field and implications for wedge processes, *Journal of Geophysical Research*, **118**, 583–606, doi:10.1002/jgrb.50063.

Mancinelli, N.J., and P.M. Shearer (2013), Reconciling discrepancies among estimates of small-scale mantle heterogeneity from PKP precursors, *Geophysical Journal International*, **195**(3), 1721–1729 doi: 10.1093/gji/ggt319.

Marone, F., S. van der Lee, and D. Giardini (2004), Three-dimensional upper-mantle S-velocity model for the Eurasia-Africa plate boundary region, *Geophysical Journal International*, **158**(1), 109–130, doi: 10.1111/j.1365-246X.2004.02305.x.

Martinez-Arevalo, C., Flor de Lis Mancilla, G. Helffrich, and A. Garcia (2013) Seismic evidence of a regional sublithospheric low velocity layer beneath the Canary Islands, *Tectonophysics*, **608**, 586–599, doi: 10.1016/j.tecto.2013.08.021.

Masy, J., F. Niu, A. Levander, and M. Schmitz (2011), Mantle flow beneath northwestern Venezuela: Seismic evidence for a deep origin of the Mérida Andes, *Earth and Planetary Science Letters*, **305**(3–4), 396–404, doi: 10.1016/j.epsl.2011.03.024.

McNamara, D., M. Meremonte, J.Z. Maharrey, S-L Mildore, J.R. Altidore, D. Anglade, S.E. Hough, D. Given, H. Benz, L. Gee, and A. Frankel (2012), Frequency-Dependent Seismic Attenuation within the Hispaniola Island Region of the Caribbean Sea, *Bulletin of the Seismological Society of America*, **102**(2), 773–782, doi: 10.1785/0120110137.

McNamara, D.E., C.R. Hutt, L.S. Gee, H.M. Benz, and R.P. Buland (2009), A Method to Establish Seismic Noise Baselines for Automated Station Assessment, *Seismological Research Letters*, **80**(4), 628–637, doi: 10.1785/gssrl.80.4.628.

Megawati, K., and Tso-Ch. Pan (2009), Regional seismic hazard posed by the Mentawai Segment of the Sumatran megathrust, *Bulletin of the Seismological Society of America*, **99**(2A), 566–584, doi: 10.1785/0120080109.

Mellors, R.J., J. Jackson, S. Myers, R. Gok, K. Priestley, G. Yetirmishli, N. Turkelli, and T. Godoladze (2012), Deep Earthquakes beneath the Northern Caucasus: Evidence of Active or Recent Subduction in Western Asia, *Bulletin of the Seismological Society of America*, **102**(2), 862–866, doi: 10.1785/0120110184.

Mendoza, C., and S. Hartzell (2013) Finite-Fault Source Inversion Using Teleseismic P Waves: Simple Parameterization and Rapid Analysis, *Bulletin of the Seismological Society of America*, **103**(2A), 834–844, doi: 10.1785/0120120069.

Miyatake, T., Y. Yagi, and T. Yasuda (2004), The dynamic rupture process of the 2001 Geiyo, Japan, earthquake, *Geophysical Research Letters*, **31**, L12612, doi:10.1029/2004GL019721.

Molodenskii, D.S., and M.S. Molodenskii (2013), On the possibilities of determination of small changes in the tidal response of the medium at short time intervals, *Seismic Instruments*, **49**(1), 22–26, doi: 10.3103/S0747923913010076.

Mulibo, G.D., and A.A. Nyblade (2013), The P and S wave velocity structure of the mantle beneath eastern Africa and the African superplume anomaly, *Geochemistry, Geophysics, Geosystems*, **14**(8), 2696–2715, doi: 10.1002/ggge.20150.

Mulibo, G.D., and A.A. Nyblade (2013), Mantle transition zone thinning beneath eastern Africa: Evidence for a whole-mantle superplume structure, *Geophysical Research Letters*, **40**, 3562–3566, doi:10.1002/grl.50694.

Nakano, M., T. Yamashina, H. Kumagai, H. Inoue, and Sunarjo (2010), Centroid moment tensor catalogue for Indonesia, *Physics of the Earth and Planetary Interiors*, **183**(3–4), 456–467, doi: 10.1016/j.pepi.2010.10.010.

Nettles, M., and V. Hjörleifsdóttir (2010), Earthquake source parameters for the 2010 January Haiti main shock and aftershock sequence, *Geophysical Journal International*, **183**(1), 375–380, doi: 10.1111/j.1365-246X.2010.04732.x.

Newman, A.V., G. Hayes, Y. Wei, and J. Convers (2011), The 25 October 2010 Mentawai tsunami earthquake, from real-time discriminants, finite-fault rupture, and tsunami excitation, *Geophysical Research Letters*, **38**, L05302, doi: 10.1029/2010GL046498.

Niu, F., and A.M. Perez (2004), Seismic anisotropy in the lower mantle: A comparison of waveform splitting of SKS and SKKS, *Geophysical Research Letters*, **31**, L24612, doi:10.1029/2004GL021196.

O'Donnell, J.P., A. Adams, A.A. Nyblade, G.D. Mulibo, and F. Tugume (2013), The uppermost mantle shear wave velocity structure of eastern Africa from Rayleigh wave tomography: constraints on rift evolution, *Geophysical Journal International*, **194**(2), 961–978, doi: 10.1093/gji/ggt135.

Obayashi, M., D. Suetsugu, and Y. Fukao (2004), PP-P differential traveltime measurement with crustal correction, *Geophysical Journal International*, **157**(3), 1152–1162, doi: 10.1111/j.1365-246X.2004.02233.x.

Obrebski, M., F. Ardhuin, E. Stutzmann, and M. Schimmel (2013), Detection of microseismic compressional (P) body waves aided by numerical modeling of oceanic noise sources, *Journal of Geophysical Research*, **118**, 4312–4324, doi:10.1002/jgrb.50233.

Ohtaki, T., S. Kaneshima, and K. Kanjo (2012), Seismic structure near the inner core boundary in the south polar region, *Journal of Geophysical Research*, **117**, B03312, doi: 10.1029/2011JB008717

Okada, T., T. Yaginuma, N. Umino, T. Kono, T. Matsuzawa, S. Kita, and A. Hasegawa (2005), The 2005 M7.2 MIYAGI-OKI earthquake, NE Japan: Possible rerupturing of one of asperities that caused the previous M7.4 earthquake, *Geophysical Research Letters*, **32**, L24302, doi:10.1029/2005GL024613.

Okal, E.A., S. Hongsresawat, and S. Stein (2012), Split-Mode Evidence for No Ultraslow Component to the Source of the 2010 Maule, Chile, Earthquake, *Bulletin of the Seismological Society of America*, **102**(1), 391–397, doi: 10.1785/0120100240.

Oki, S., Y. Fukao, and M. Obayashi (2004), Reference frequency of teleseismic body waves, *Journal of Geophysical Research*, **109**, B04304, doi:10.1029/2003JB002821.

Panning, M.P., A. Cao, A. Kim, and B.A. Romanowicz (2012), Non-linear 3-D Born shear waveform tomography in Southeast Asia, *Geophysical Journal International*, **190**(1), 463–475, doi: 10.1111/j.1365-246X.2012.05489.x.

Park, J., R. Butler, K. Anderson, J. Berger, H. Benz, P. Davis, C.R. Hutt, C.S. McCreery, T. Ahern, G. Ekstrom, and R.C. Aster (2005), Performance Review of the Global Seismographic Network for the Sumatra-Andaman megathrust earthquake, *Seismological Research Letters*, **76**(3), 332–343.

Park, J., H. Yuan, and V. Levin (2004), Subduction zone anisotropy beneath Corvallis, Oregon: A serpentinite skid mark of trench-parallel terrane migration? *Journal of Geophysical Research*, **109**, B10306, doi:10.1029/2003JB002718.

Park, Y., K. Kim, J. Lee, H.J. Yoo, and M.P. Plasencia L (2012), P-wave velocity structure beneath the northern Antarctic Peninsula: Evidence of a steeply subducting slab and a deep-rooted low-velocity anomaly beneath the central Bransfield Basin, *Geophysical Journal International*, **191**(3), 932–938, doi: 10.1111/j.1365-246X.2012.05684.x.

Pasyanos, M.E. (2013), A Lithospheric Attenuation Model of North America, *Bulletin of the Seismological Society of America*, **103**(6), 3321–3333, doi: 10.1785/0120130122.

Pasyanos, M.E., E.M. Matzel, W.R. Walter, and A.J. Rodgers (2009) Broadband Lg attenuation modelling in the Middle East, *Geophysical Journal International*, **177**(3), 1166–1176.

Pavlenko, O.V. (2013), Simulation of Ground Motion from Strong Earthquakes of Kamchatka Region (1992–1993) at Rock and Soil Sites, *Pure and Applied Geophysics*, **170**(4), 571–595, doi: 10.1007/s00024-012-0529-x.

Persh, S.E., and H. Houston (2004), Deep earthquake rupture histories determined by global stacking of broadband P waveforms, *Journal of Geophysical Research*, **109**, B04311, doi:10.1029/2003JB002762.

Petersen, M.D., J. Dewey, S. Hartzell, C. Mueller, S. Harmsen, A.D. Frankel, and K. Rukstales (2004), Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the Southern Malaysian Peninsula, *Tectonophysics*, **390**(1–4), 141–158, doi:10.1016/j.tecto.2004.03.026.

Pilidou, S., K. Priestley, O. Gudmundsson, and E. Debayle (2004), Upper mantle S-wave speed heterogeneity and anisotropy beneath the North Atlantic from regional surface wave tomography: The Iceland and Azores plumes, *Geophysical Journal International*, **159**(3), 1057–1076, doi: 10.1111/j.1365-246X.2004.02462.x.

Quintanar, L., M. Rodríguez-González, and Campos-Enríquez (2004), A shallow crustal earthquake doublet from the Trans-Mexican Volcanic Belt (Central Mexico), *Bulletin of the Seismological Society of America*, **94**(3), 845–855, doi: 10.1785/0120030057.

Rastin, S.J., C.P. Unsworth, K.R. Gledhill, and D.E. McNamara (2012), A Detailed Noise Characterization and Sensor Evaluation of the North Island of New Zealand Using the PQLX Data Quality Control System, *Bulletin of the Seismological Society of America*, **102**(1), 98–113, doi: 10.1785/0120110064.

Rawlinson, N., S. Pozgay, and S. Fishwick (2010), Seismic tomography: A window into deep Earth, *Physics of the Earth and Planetary Interiors*, **178**(3–4), 101–135, doi: 10.1016/j.pepi.2009.10.002.

Revets, S.A., M. Keep, and B.L.N. Kennett (2009), NW Australian intraplate seismicity and stress regime, *Journal of Geophysical Research*, **114**, B10305, doi: 10.1029/2008JB006152.

Richards, P.G., and W-Y. Kim (2005), Equivalent Volume Sources for Explosions at Depth: Theory and Observations, *Bulletin of the Seismological Society of America*, **95**(2), 401–407, doi: 10.1785/0120040034.

Ringler, A., L.S. Gee, C.R. Hutt, and D.E. McNamara (2010), Temporal variations in Global Seismic Station ambient noise power levels, *Seismological Research Letters*, **81**(4), 605–613, doi: 10.1785/gssrl.81.4.605.

Ringler, A.T., L.S. Gee, B. Marshall, C.R. Hutt, and T. Storm (2012), Data Quality of Seismic Records from the Tohoku, Japan, Earthquake as Recorded across the Albuquerque Seismological Laboratory Networks, *Seismological Research Letters*, **83**(3), 575–584, doi: 10.1785/gssrl.83.3.575.

Ringler, A.T., C.R. Hutt, R. Aster, H. Bolton, L.S. Gee, and T. Storm (2012), Estimating Pole-Zero Errors in GSN-IRIS/USGS Network Calibration Metadata, *Bulletin of the Seismological Society of America*, **102**(2), 836–841, doi: 10.1785/0120110195.

Robinson, D.P., and L.T. Cheung (2010), Source process of the Mw 8.3, 2003 Tokachi-Oki, Japan earthquake and its aftershocks, *Geophysical Journal International*, **181**(1), 334–342, doi: 10.1111/j.1365-246X.2010.04513.x.

Rosat, S., and J. Hinderer (2011), Noise Levels of Superconducting Gravimeters: Updated Comparison and Time Stability, *Bulletin of the Seismological Society of America*, **101**(3), 1233–1241, doi: 10.1785/0120100217.

Roult, G., J.-P. Montagner, B. Romanowicz, M. Cara, D. Rouland, R. Pillet, J.-F. Karczewski, L. Rivera, E. Stutzmann, A. Maggi, and the Geoscope team (2010), The GEOSCOPE program: Progress and challenges during the past 30 Years, *Seismological Research Letters*, **81**(3), 427–452, doi: 10.1785/gssrl.81.3.427.

Roult, G., J. Roch, and E. Clévédé (2010), Observation of split modes from the 26th December 2004 Sumatra-Andaman mega-event, *Physics of the Earth and Planetary Interiors*, **179**(1–2), 45–59, doi: 10.1016/j.pepi.2010.01.001.

Roumelioti, Z., C. Benetatos, and A. Kiratzi (2009), The 14 February 2008 earthquake (M6.7) sequence offshore south Peloponnese (Greece): Source models of the three, *Tectonophysics*, **471**(3), 272–284, doi:10.1016/j.tecto.2009.02.028.

Roy, J. (2009), MRS: A new geophysical technique for groundwater work, *The Leading Edge*, **28**(10), 1226–1233, doi: 10.1190/1.3249779.

Ruhl, C., S.L. Bilek, and J. Stankova-Pursley (2010), Relocation and characterization of the August 2009 microearthquake swarm above the Socorro magma body in the central Rio Grande Rift, *Geophysical Research Letters*, **37**, L23304, doi: 10.1029/2010GL045162.

Ruiz, S., R. Grandin, V. Dionicio, C. Satriano, A. Fuenzalida, Ch. Vigny, E. Kiraly, C. Meyer, J.C. Baez, S. Riquelme, R. Madariaga, and J. Campos (2013), The Constitución earthquake of 25 March 2012: A large aftershock of the Maule earthquake near the bottom of the seismogenic zone, *Earth and Planetary Science Letters*, **377–378**, 347–357, doi: 10.1016/j.epsl.2013.07.017.

Ruppert, N.A., N.P. Kozyreva, and R.A. Hansen (2012), Review of crustal seismicity in the Aleutian Arc and implications for arc deformation, *Tectonophysics*, **522–523**, 150–157, doi: 10.1016/j.tecto.2011.11.024.

Russo, R.M. (2009), Subducted oceanic asthenosphere and upper mantle flow beneath the Juan de Fuca slab, *Lithosphere*, **1**(4), 195–205, doi: 10.1130/l41.1.

Russo, R.M., A. Gallego, D. Comte, V.I. Mocanu, R.E. Murdie, and J.C. VanDecar (2010), Source-side shear wave splitting and upper mantle flow in the Chile Ridge subduction region, *Geology*, **38**(8), 707–710, doi: 10.1130/g30920.1.

Russo, R.M., and V.I. Mocanu (2009), Source-side shear wave splitting and upper mantle flow in the Romanian Carpathians and surroundings, *Earth and Planetary Science Letters*, **287**(1–2), 205–216, doi: 10.1016/j.epsl.2009.08.028.

Salichon, J., A. Lemoine, and H. Aochi (2009), Validation of teleseismic inversion of the 2004 Mw 6.3 Les Saintes, Lesser Antilles, Earthquake by 3D finite-difference forward modeling, *Bulletin of the Seismological Society of America*, **99**(6), 3390–3401, doi: 10.1785/0120080315.

Salichon, J., P. Lundgren, B. Delouis, and D. Giardini (2004), Slip history of the 16 October 1999 M_w 7.1 Hector Mine earthquake (California) from the inversion of InSAR, GPS, and teleseismic data, *Bulletin of the Seismological Society of America*, **94**(6)0, 2015–2027, doi: 10.1785/0120030038.

Saltzer, R.L., E. Stutzmann, and R.D. van der Hilst (2004), Poisson's ratio in the lower mantle beneath Alaska: Evidence for compositional heterogeneity, *Journal of Geophysical Research*, Vol. 109, No. B6, 15 pp., doi: 10.1029/2003JB002712.

Schaeffer, A.J., and S. Lebedev (2013), Global shear speed structure of the upper mantle and transition zone, *Geophysical Journal International*, **194**(1), 417–449, doi: 10.1093/gji/ggt095.

Schaff, D.P., and P.G. Richards (2004), Repeating seismic events in China, *Science*, **303**, 1176–1178, doi: 10.1126/science.1093422.

Schaff, D.P., and P.G. Richards (2004) Lg-Wave cross correlation and double-difference location: Application to the 1999 Xiuyan, China, sequence, *Bulletin of the Seismological Society of America*, **94**(3), 867–879, doi:10.1785/0120030136.

Schellart, W. P., and N. Rawlinson (2013), Global correlations between maximum magnitudes of subduction zone interface thrust earthquakes and physical parameters of subduction zones, *Physics of the Earth and Planetary Interiors*, **225**, 41–67, doi: 10.1016/j.pepi.2013.10.001.

Schivardi, R., and A. Morelli (2009), Surface wave tomography in the European and Mediterranean region, *Geophysical Journal International*, **177**(3), 1050–1066, doi: 10.1111/j.1365-246X.2009.04100.x.

Selby, N.D., D. Bowers, A. Douglas, R. Heyburn, and D. Porter (2005), Seismic discrimination in southern Xinjiang: The 13 March 2003 Lop Nor earthquake, *Bulletin of the Seismological Society of America*, **95**(1), 197–211.

Selby, N. D., P.D. Marshall, and D. Bowers (2012), mb:Ms event screening revisited, *Bulletin of the Seismological Society of America*, **102**(1), 88–97, doi: 10.1785/0120100349.

Shearer, P.M., and P.S. Earle (2004), The global short-period wavefield modelled with a Monte Carlo seismic phonon method, *Geophysical Journal International*, **158**(3), 1103–1117.

Sherrington, H.F., G. Zandt, and A. Frederiksen (2004), Crustal fabric in the Tibetan Plateau based on waveform inversions for seimic anisotropy parameters, *Journal of Geophysical Research*, **109**, B02312, doi:10.1029/2002JB002345.

Shin, J.S., D.-H. Sheen, and G. Kim (2010), Regional observations of the second North Korean nuclear test on 2009 May 25, *Geophysical Journal International*, **180**(1), 243–250, doi: 10.1111/j.1365-246X.2009.04422.x.

Shuler, A., and M. Nettles (2012), Earthquake source parameters for the 2010 western Gulf of Aden rifting episode, *Geophysical Journal International*, **190**(2), 1111–1122, doi: 10.1111/j.1365-246X.2012.05529.x.

Shuler, A., M. Nettles, and G. Ekström (2013), Global observation of vertical-CLVD earthquakes at active volcanoes, *Journal of Geophysical Research*, **118**, 138–164, doi: 10.1029/2012JB009721.

Silveira, G., L. Vinnik, E. Stutzmann, V. Farra, S. Kiselev, and I. Morais (2010), Stratification of the Earth beneath the Azores from P and S receiver functions, *Earth and Planetary Science Letters*, **299**(1–2), 91–103, doi: 10.1016/j.epsl.2010.08.021.

Singh, S.C., N. Hananto, M. Mukti, H. Permana, Y. Djajadihardja, and H. Harjono (2011), Seismic images of the megathrust rupture during the 25th October 2010 Pagai earthquake, SW Sumatra: Frontal rupture and large tsunami, *Geophysical Research Letters*, **38**, L16313, doi: 10.1029/2011GL048935.

Sladen, A., H. Tavera, M. Simons, J.P. Avouac, A.O. Konca, H. Perfettini, L. Audin, E.J. Fielding, F. Ortega, and R. Cavagnoud (2010), Source model of the 2007 M_w 8.0 Pisco, Peru earthquake: Implications for seismogenic behavior of subduction megathrusts, *Journal of Geophysical Research*, **115**, B02405, doi: 10.1029/2009JB006429.

Sloan, R.A., and J.A. Jackson (2012), Upper-mantle earthquakes beneath the Arafura Sea and south Aru Trough: Implications for continental rheology, *Journal of Geophysical Research*, **117**, B05402, doi:10.1029/2011JB008992.

Sodoudi, F., X. Yuan, R. Kind, S. Lebedev, J.M.C. Adam, E. Kästle, and F. Tilmann (2013), Seismic evidence for stratification in composition and anisotropic fabric within the thick lithosphere of Kalahari Craton, *Geochemistry, Geophysics, Geosystems*, **14**(12), 5393–5412, doi: 10.1002/2013GC004955.

Stroujkova, A., and V.F. Cormier (2004), Regional variations in the uppermost 100 km of the Earth's inner core, *Journal of Geophysical Research*, **109**, B10307, doi:10.1029/2004JB002976.

Suetsugu, D., T. Saita, H. Takenaka, and F. Niu (2004), Thickness of the mantle transition zone beneath the South Pacific as inferred from analyses of ScS reverberated and Ps converted waves, *Physics of the Earth and Planetary Interiors*, **146**(1–2), 135–146.

Sugioka, H., D. Suetsugu, M. Obayashi, Y. Fukao, and Y. Gao (2010), Fast P- and S-wave velocities associated with the cold stagnant slab beneath the northern Philippine Sea, *Physics of the Earth and Planetary Interiors*, **179**(1–2), doi: 10.1016/j.pepi.2010.01.006.

Sukyoung, Y., S. Ni, M. Park, and W.S. Lee (2009), Southeast Indian Ocean-Ridge earthquake sequences from cross-correlation analysis of hydroacoustic data, *Geophysical Journal International*, **179**(1), 401–407.

Sun, W., and X. Zhou (2012), Coseismic deflection change of the vertical caused by the 2011 Tohoku-Oki earthquake (M_w 9.0), *Geophysical Journal International*, **189**(2), 937–955, doi: 10.1111/j.1365-246X.2012.05434.x.

Sutherland, F.H., F.L. Vernon, J.A. Orcutt, J.A. Collins, and R.A. Stephen (2004), Results from OSNPE: Improved teleseismic earthquake detection at the seafloor, *Bulletin of the Seismological Society of America*, **94**, 1868–1878.

Suzuki, M., and Y. Yagi (2011), Depth dependence of rupture velocity in deep earthquakes, *Geophysical Research Letters*, **38**, L05308, doi: 10.1029/2011GL046807.

Sykes, L.R., and G. Ekström (2012), Earthquakes along Eltanin transform system, SE Pacific Ocean: fault segments characterized by strong and poor seismic coupling and implications for long-term earthquake prediction, *Geophysical Journal International*, **188**(2), 421–434, doi: 10.1111/j.1365-246X.2011.05284.x.

Tajima, F., J. Mori, and B.L.N. Kennett (2013), A review of the 2011 Tohoku-Oki earthquake (M_w 9.0): Large-scale rupture across heterogeneous plate coupling, *Tectonophysics*, **586**, 15–34, doi: 10.1016/j.tecto.2012.09.014.

Takeuchi, N. (2012), Detection of ridge-like structures in the Pacific Large Low-Shear-Velocity Province, *Earth and Planetary Science Letters*, **319–320**, 55–64, doi: 10.1016/j.epsl.2011.12.024.

Takeuchi, N., and M. Kobayashi (2004), Improvement of seismological earth models by using data weighting in waveform inversion, *Geophysical Journal International*, **158**(2), 681–694.

Tanaka, S. (2004), Seismic detectability of anomalous structure at the top of the Earth's outer core with broadband array analysis of SmKS phases, *Physics of the Earth and Planetary Interiors*, Vol. 141, No. 3, p.141–152.

Tanimoto, T., and C. Ji (2010), Afterslip of the 2010 Chilean earthquake, *Geophysical Research Letters*, **37**, L22312, doi: 10.1029/2010GL045244.

Tanimoto, T., C. Ji, and M. Igarashi (2012), An approach to detect afterslips in giant earthquakes in the normal-mode frequency band, *Geophysical Journal International*, **190**(2), 1097–1110, doi: 10.1111/j.1365-246X.2012.05524.x.

Tauzin, B., E. Debayle, C. Quantin, and N. Coltice (2013), Seismoacoustic coupling induced by the breakup of the 15 February 2013 Chelyabinsk meteor, *Geophysical Research Letters*, **40**, 3522–3526, doi:10.1002/grl.50683.

Thorne, M.S., and E.J. Garnero (2004), Inferences on ultralow-velocity zone structure from a global analysis of SPdKS waves, *Journal of Geophysical Research*, **109**, B08301, doi:10.1029/2004JB003010.

Thorne, M.S., Y. Zhang, and J. Ritsema (2013), Evaluation of 1-D and 3-D seismic models of the Pacific lower mantle with S, SKS, and SKKS travel times and amplitudes, *Journal of Geophysical Research*, **118**, 985–995, doi: 10.1002/jgrb.50054.

Tibi, R., and D.A. Wiens (2005), Detailed structure and sharpness of upper mantle discontinuities in the Tonga subduction zone from regional broadband arrays, *Journal Geophysical Research*, **110**, B06313, doi:10.1029/2004JB003433.

Tkalčić, H., Y.J. Chen, R. Liu, H. Zhibin, L. Sun, and W. Chan (2011), Multistep modelling of teleseismic receiver functions combined with constraints from seismic tomography: Crustal structure beneath southeast China, *Geophysical Journal International*, **187**(1), 303–326, doi: 10.1111/j.1365-246X.2011.05132.x.

To, A., Y. Fukao, and S. Tsuboi (2011), Evidence for a thick and localized ultra low shear velocity zone at the base of the mantle beneath the central Pacific, *Physics of the Earth and Planetary Interiors*, **184**(3–4), 119–133, doi: 10.1016/j.pepi.2010.10.015.

To, A., B. Romanowicz, Y. Capdeville, and N. Takeuchi (2005), 3D effects of sharp boundaries at the borders of the African and Pacific superplumes: Observation and modeling, *Earth and Planetary Science Letters*, **233**(1)–2, 137–153.

Trabant, C., A.R. Hutko, M. Bahavar, R. Karstens, T. Ahern, and R. Aster (2012), Data Products at the IRIS DMC: Stepping Stones for Research and Other Applications, *Seismological Research Letters*, **83**(5), 846–854, doi: 10.1785/0220120032.

Uchide, T., H. Yao, and P.M. Shearer (2013), Spatio-temporal distribution of fault slip and high-frequency radiation of the 2010 El Mayor-Cucapah, Mexico earthquake, *Journal of Geophysical Research*, **118**, 1546–1555, doi:10.1002/jgrb.50144.

Umutlu, N., K. Koketsu, and C. Milkereit (2004), The rupture process during the 1999 Duzce, Turkey, earthquake from joint inversion of teleseismic and strong-motion data, *Tectonophysics*, **391**(1–4), p.315–324.

Utkucu, M. (2013), 23 October 2011 Van, Eastern Anatolia, earthquake (M_w 7.1) and seismotectonics of Lake Van area, *Journal of Seismology*, **17**(2), 783–805, doi: 10.1007/s10950-012-9354-z.

Vallée, M. (2004), Stabilizing the Empirical Green Function Analysis: Development of the Projected Landweber Method, *Bulletin of the Seismological Society of America*, **94**(2), 394–409.

Venkataraman, A., and H. Kanamori (2004), Observational constraints on the fracture energy of subduction zone earthquakes, *Journal of Geophysical Research*, 109, B05302, doi:10.1029/2003JB002549.

Villagómez, D.R., D.R. Toomey, E.E.E. Hooft, and S.C. Solomon (2011), Crustal structure beneath the Galápagos Archipelago from ambient noise tomography and its implications for plume-lithosphere interactions, *Journal of Geophysical Research*, 116, B04310, doi: 10.1029/2010JB007764.

Vinnik, L., G. Silveira, Se. Kiselev, V. Farra, M. Weber, and E. Stutzmann (2012), Cape Verde hotspot from the upper crust to the top of the lower mantle, *Earth and Planetary Science Letters*, **319–320**, 259–268, doi: 10.1016/j.epsl.2011.12.017.

Vuan, A., S.D. Robertson Maurice, D.A. Wiens, and G.F. Panza (2005), Crustal and upper mantle S-wave velocity structure beneath the Bransfield Strait (West Antarctica) from regional surface wave tomography *Tectonophysics*, **397**(3–4), 241–259.

Waldhauser, F., D.P. Schaff, P. G. Richards, and Won-Y Kim (2004), Lop Nor revisited: Underground nuclear explosion locations, 1976–1996, from double-difference analysis of regional and teleseismic data, *Bulletin of the Seismological Society of America*, **94**(5), 1879–1889.

Walker, K.T., M. Ishii, and P.M. Shearer (2005), Rupture details of the 28 March 2005 Sumatra M_w 8.6 earthquake imaged with teleseismic P waves, *Geophysical Research Letters*, **32**, L24303, doi:10.1029/2005GL024395.

Walker, K.T., A.A. Nyblade, S.L. Klemperer, G.H.R. Bokelmann, and T.J. Owens (2004), On the relationship between extension and anisotropy: Constraints from shear wave splitting across the East African Plateau, *Journal of Geophysical Research*, **109**, B08302, doi:10.1029/2003JB002866.

Wang, W., W. Sun, and Z. Jiang (2010), Comparison of fault models of the 2008 Wenchuan earthquake (Ms8.0) and spatial distributions of co-seismic deformations, *Tectonophysics*, **491**(1–4), 85–95, doi: 10.1016/j.tecto.2009.08.035.

Wang, Y., and L. Wen (2004), Mapping the geometry and geographic distribution of a very low velocity province at the base of the Earth's mantle, *Journal of Geophysical Research*, **109**, B10305, doi:10.1029/2003JB002674.

Wei, S., D.V. Helmberger, Z. Zhan, and R. Graves (2013), Rupture complexity of the Mw 8.3 Sea of Okhotsk earthquake: Rapid triggering of complementary earthquakes? *Geophysical Research Letters*, **40**, 5034–5039, doi:10.1002/grl.50977.

Winberry, J.P., and S. Anandakrishnan (2004), Crustal structure of the West Antarctic rift system and Marie Byrd Land hotspot, *Geology*, **32**(11), 977–980.

Yagi, Y., and Y. Fukahata (2011), Rupture process of the 2011 Tohoku-oki earthquake and absolute elastic strain release, *Geophysical Research Letters*, **38**, L19307, doi: 10.1029/2011GL048701.

Yagi, Y., T. Mikumo, J. Pacheco, and G. Reyes (2004), Source rupture process of the Tecomán, Colima, Mexico Earthquake of 22 January 2003, determined by joint inversion of teleseismic body-wave and near-source data, *Bulletin of the Seismological Society of America*, **94**(5), 1795–1807.

Yang, X., S.R. Taylor, and H.J. Patton (2004), The 20-s Rayleigh wave attenuation tomography for central and southeastern Asia, *Journal of Geophysical Research*, **109**, B12304, doi:10.1029/2004JB003193.

Yang, Y., M.H. Ritzwoller, Y. Zheng, W. Shen, A.L. Levshin, and Z. Xie (2012), A synoptic view of the distribution and connectivity of the mid-crustal low velocity zone beneath Tibet, *Journal of Geophysical Research*, **117**, B04303, doi:10.1029/2011JB008810.

Yao, H., G. Xu, L. Zhu, and X. Xiao (2005), Mantle structure from inter-station Rayleigh wave dispersion and its tectonic implication in western China and neighboring regions, *Physics of the Earth and Planetary Interiors*, **148**(1), 39–54.

Yeh, Yu-L., H. Kao, S. Wen, W.-Y. Chang, and C.-H. Chen (2013), Surface wave tomography and azimuthal anisotropy of the Philippine Sea Plate, *Tectonophysics*, **592**, 94–112, doi: 10.1016/j.tecto.2013.02.005.

Yokota, Y., K. Koketsu, Y. Fujii, K. Satake, S. Sakai, M. Shinohara, and T. Kanazawa (2011), Joint inversion of strong motion, teleseismic, geodetic, and tsunami datasets for the rupture process of the 2011 Tohoku earthquake, *Geophysical Research Letters*, **38**, L00G21, doi: 10.1029/2011GL050098.

Yoshida, Y., and D. Suetsugu (2004), Lithospheric thickness beneath the Pitcairn hot spot trail as inferred from Rayleigh wave dispersion, *Physics of the Earth and Planetary Interiors*, **146**(1–2), 75–85.

Yoshizawa, K., and B.L.N. Kennett (2004), Multimode surface wave tomography for the Australian region using a three-stage approach incorporating finite frequency effects, *Journal of Geophysical Research*, **109**, B02310, doi:10.1029/2002JB002254.

Young, M.K., H. Tkalcić, T. Bodin, and M. Sambridge (2013), Global P wave tomography of Earth's lowermost mantle from partition modeling, *Journal of Geophysical Research*, **118**, 5467–5486, doi:10.1002/jgrb.50391.

Youssof, M., H. Thybo, I.M. Artemieva, and A. Levander (2013), Moho depth and crustal composition in Southern Africa, *Tectonophysics*, **609**, 267–287, doi: 10.1016/j.tecto.2013.09.001.

Yu, W., and L. Wen (2012), Deep-Focus Repeating Earthquakes in the Tonga-Fiji Subduction Zone, *Bulletin of the Seismological Society of America*, **102**(4), 1829–1849, doi: 10.1785/0120110272.

Yu, W. (2013), Shallow-focus repeating earthquakes in the Tonga–Kermadec–Vanuatu subduction zones, *Bulletin of the Seismological Society of America*, **103**(1), 463–486, doi: 10.1785/0120120123.

Yu, Zh., S. Ni, S. Wei, X. Zeng, W. Wu, and Z. Li (2012), An iterative algorithm for separation of S and ScS waves of great earthquakes, *Geophysical Journal International*, **191**(2), 591–600, doi: 10.1111/j.1365-246X.2012.05603.

Yuan, X., R. Kind, and H.A. Pedersen (2005), Seismic monitoring of the Indian Ocean tsunami, *Geophysical Research Letters*, **32**, L15308, doi:10.1029/2005GL023464.

Zaroli, C., E. Debayle, and M. Sambridge (2010), Frequency-dependent effects on global S-wave traveltimes: wavefront-healing, scattering and attenuation, *Geophysical Journal International*, **182**(2), 1025–1042, doi: 10.1016/j.epsl.2010.06.002.

Zhan, Z., D.V. Helmberger, M. Simons, H. Kanamori, W. Wu, N. Cubas, Z. Duputel, R. Chu, V.C. Tsai, J.-P. Avouac, K.W. Hudnut, S. Ni, E. Hetland, and F.H. Ortega Culaciati (2012), Anomalously steep dips of earthquakes in the 2011 Tohoku-Oki source region and possible explanations, *Earth and Planetary Science Letters*, **353–354**, 121–133, doi: 10.1016/j.epsl.2012.07.038.

Zhang, Mi., and L. Wen (2013), High-precision location and yield of North Korea's 2013 nuclear test, *Geophysical Research Letters*, **40**, 2941–2946, doi:10.1002/grl.50607.

Zhang, W., T. Iwata, and K. Irikura (2010), Dynamic simulation of the 1999 Chi-Chi, Taiwan, earthquake, *Journal of Geophysical Research*, **115**, B04305, doi: 10.1029/2008JB006201.

Zhao, L., X. Xie, W. Wang, and Z. Yao (2012), Yield estimation of the 25 May 2009 North Korean nuclear explosion, *Bulletin of the Seismological Society of America*, **102**(2), 467-478, doi: 10.1785/0120110163.

Zhao, L., and T. Zheng (2005), Using shear wave splitting measurements to investigate the upper mantle anisotropy beneath the North China Craton: Distinct variation from east to west, *Geophysical Research Letters*, **32**, L10309, doi:10.1029/2005GL022585.

Zhao, L.-F., X.-Bi Xie, W.-Mi. Wang, J.-H. Zhang, and Z.-X. Yao (2013), Crustal Lg attenuation within the North China Craton and its surrounding regions, *Geophysical Journal International*, 195(1), 513–531, doi: 10.1093/gji/ggt235.

Zhao, L.F., X.-B. Xie, W.-M. Wang, J.-H. Zhang, and Z.-Xi. Yao (2010), Seismic Lg-wave Q tomography in and around Northeast China, *Journal of Geophysical Research*, **115**, B08307, doi: 10.1029/2009JB007157.

Zheng, Y., W. Shen, L. Zhou, Y. Yang, Z. Xie, and M.H. Ritzwoller (2011), Crust and uppermost mantle beneath the North China Craton, northeastern China, and the Sea of Japan from ambient noise tomography, *Journal of Geophysical Research*, **116**, B12312, doi: 10.1029/2011JB008637.