Preface to Focus Section on New Frontiers and Advances in Global Seismology

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Over the last century, many of the fundamental advances in our understanding of the solid Earth have been underpinned by seismic observations recorded on long-running networks of globally distributed seismic instruments (e.g., Agnew *et al.*, 1976; Romanowicz *et al.*, 1984; Hanka and Kind, 1994; Peterson and Hutt, 2014; Ringler *et al.*, 2022a). During this time, seismic data quality and the speed of dissemination have improved substantially from early analog paper records to digital, very broadband data transmitted in near-real time (Steim, 2015) and rapidly archived in online data repositories with associated metadata (e.g., Ahern, 2003; Suarez *et al.*, 2008). With these significant advances in data quality, dissemination, and storage, global seismic networks are poised to continue to aid in answering key scientific questions about the Earth.

For example, global velocity models and tomographic images of the Earth have continued to evolve from studies using distinct seismic phases (e.g., from surface waves, *P* waves, *S* waves, and normal modes) from analog and early digital global seismic networks (e.g., Dziewoński and Anderson, 1981; Woodhouse and Dziewoński, 1984; Grand, 1994) to full-waveform inversions utilizing modern broadband seismic data acquired from thousands of stations (e.g., Bozdağ *et al.*, 2016; Lei *et al.*, 2020; Thrastarson *et al.*, 2022). The long-running nature of global seismic networks in particular enables scientists to investigate long-term changes across a multitude of Earth processes ranging from volcanic eruptions (Kanamori and Mori, 1992; Matoza *et al.*, 2022), the rotation rate of the inner core (Song and Richards, 1996), and variations in ocean temperature (Wu *et al.*, 2020) and wave activity (Aster *et al.*, 2023). In addition, the instrumentation, infrastructure, and coverage of global seismographic networks (GSNs) allow for the high-fidelity recording of long-period signals, such as normal modes (e.g., Park *et al.*, 2005; Bogiatzis and Ishii, 2014; Ringler *et al.*, 2022b) and gravitational perturbations arising from great earthquakes (Vallée *et al.*, 2017).

In this Focus Section, we selected manuscripts that leveraged the exceptional capabilities of global seismic networks to advance knowledge of Earth processes and structure, from the inner core to the atmosphere and beyond. In total, this Focus Section encompasses six research articles along with three Data Mine articles about the GSN and GEOSCOPE networks.

Staats *et al.* (2023) provide a glimpse of the scientific utility of the GSN by considering data turnover rate and studies that either directly used seismograms from GSN stations or indirect data products (e.g., earthquake catalogs and tomographic models). Importantly, they find that citations of the GSN are underrepresented in the literature by a factor of 3. Correction of this problem would be helped by a culture shift in how scientists acknowledge the data that underpin their studies. In addition to encouraging researchers to cite network digital object identifiers from data used in the study, Staats *et al.* (2023) also encourage journals, editors, and reviewers to promote this policy to avoid underrepresented citations in the future.

One theme in this Focus Section is the use of highly automated methods to improve earthquake detection and characterization that can be applied to a global data set over long time spans. These methods leverage advances in seismological software, computational algorithms, and databases to handle large data sets. For instance, Poli (2023) conducts a comprehensive search of global seismic data to identify and catalog sources of long-period (>25 s) seismic energy for 2010–2022. This effort builds on previous studies (e.g., Shearer, 1994; Ekström, 2006) and focuses on identifying long-period seismic energy using a shift and stack algorithm combined with a detection and location algorithm. A significant number of previously unknown low-frequency events are identified. Most of the new events occur in polar regions, although some occur along oceanic ridges and other volcanic regions. A substantial improvement in event detection occurs in Antarctica, with these events likely due to glacial processes. This type of systematic processing may provide new ways to link seismic monitoring with environmental change.

A sophisticated computational approach is also applied by Münchmeyer *et al.* (2023) to improve event-depth estimates using a global catalog of earthquakes to train two deep-learning models to detect and pick depth phases. One model is applied to each station independently, whereas the second model jointly analyzes multiple seismograms. The models use a probabilistic

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backprojection approach that allows for the propagation of uncertainty estimates as part of the analysis. Their work highlights the potential improvements in global detection capabilities that can be realized through combining machine learning techniques with data from global seismic networks.

Global seismic networks offer a framework for rapid characterization of damaging earthquakes and improved timeliness of earthquake early warning alerts (e.g., Jaiswal *et al.*, 2010; Allen and Melgar, 2019). For very large earthquakes, prompt elastogravity signals (PEGS) can be observed even before the arrival of seismic *P* waves (Vallée *et al.*, 2017). Juhel *et al.* (2023) demonstrate the value of PEGS observations used in combination with more conventional low-frequency (*W* phase) recordings to establish the main fault parameters of large earthquakes in near-real time. For the 2011 M_w 9.1 Tōhoku–Oki earthquake, their approach would allow determination of a stable M_w and focal mechanism within as little as 5 min from origin time. This is at least twice as fast compared to inversions relying on regional *W* phase alone.

Advances in seismic instrumentation illustrate possible paths toward denser seismic networks and better signal detection. The advent of distributed acoustic sensing (DAS) has provided a new way to capture the Earth's seismic wavefield with an unprecedented spatial sampling, at the local and even regional scale. Wuestefeld *et al.* (2023) document the first effort made to gather data from DAS systems distributed all around the world to build a Global Fiber Sensing Network (GFSN). Earthquakes of February 2023 with magnitude above 5 were recorded by 32 DAS systems, with the corresponding data freely available for download (steps for accessing this data set are documented within Wuestefeld *et al.*, 2023). One day of continuous data was also collected. Much of this data were collected at very low cost by repurposing existing fiber originally installed for telecommunications. Besides this success, the study also highlights challenges for a fully operational GFSN due to massive data volumes and evolving metadata standards.

Existing stations benefit from new technology as well. Bès de Berc *et al.* (2023) documents improved performance of a GEOSCOPE station (CCD) at the permanent research facility in Concordia, Antarctica, by installing a borehole seismometer at 120 m depth. The combination of a remote location of the station with an innovative installation of a new borehole sensor has created one of the quietest stations in the world in the 0.1–0.2 s period band. The data from this remote station are openly available to the scientific community (Institut de Physique du Globe de Paris and École et Observatoire des Sciences de la Terre de Strasbourg [IPGP/EOST], 1982).

In addition to the earlier research articles, this issue contains three Data Mine articles describing the motivation, history, instrumentation, and future directions of the GSN (Davis *et al.*, 2023; Wilson *et al.*, 2023) and GEOSCOPE (Leroy *et al.*, 2023) seismic networks. We note that a similar review of the GEOFON network (Quinteros *et al.*, 2021) has recently been published in *Seismological Research Letters* outside of this Focus Section, and Ringler *et al.* (2022a) provide a review of some of the recent seismological studies enabled by global networks of seismographs.

Leroy *et al.* (2023) discuss the development and build out of the GEOSCOPE very broadband network. This network of 34 stations operates in 18 countries and provides data from some of the most remote locations on the globe. These stations are important for characterizing seismic sources, but they have also played a critical role, along with other stations, in imaging the interior of the Earth. The build-out of the GEOSCOPE network in the early 1980s happened at a time when several technological advances were achieved (e.g., the extended bandwidth of the Streckeisen STS-1 seismometer to being flat to velocity to 360 s, the development of digitization techniques that allowed for high-resolution digital data streams). The ability for GEOSCOPE to make use of these developments during the initial build-out helped pave the way for other networks to harness these new technologies.

Two articles address the two main components of the GSN. Wilson *et al.* (2023) focus on the U.S. Geological Survey-operated component of the GSN (two-thirds of the network), detailing its evolution since the founding of the network in the late 1980s through the present. In addition, potential future improvements through technological advances and opportunities are discussed. Aside from network operations, Wilson *et al.* (2023) highlight the major role played by the GSN in many of the world's fundamental operational systems (e.g., strong earthquakes information, tsunami early warning, monitoring of nuclear testing, etc.), as well as in major and more fundamental scientific advances made by the Earth science community. The remaining component of the GSN is operated by International Deployment of Accelerometers (IDA) at the University of California, San Diego. Davis *et al.* (2023) detail the inception of project IDA as a network of 24, digitally recorded LaCoste–Romberg gravimeters in the 1970s through to its expansion to the present network of 40 multisensor, very broadband stations. The data from these networks have led to fundamental discoveries about the structure of the Earth's deep interior as well as atmospheric-solid Earth coupling processes.

This Focus Section demonstrates the symbiotic relationship between global seismic network operations and data users spanning the range of university researchers to government agencies tasked with mitigating loss of life and property to damaging earthquakes. As illustrated by Staats *et al.* (2023), high-quality seismic data from GSNs underpin a broad swath of seismological research. Future enhancements in data processing and instrumentation could lead to several advances in event detection and characterization. One potential avenue would be the routine use of PEGS observations (Juhel *et al.*, 2023), which have the potential to improve the response time for both tsunami and earthquake warning systems.

These articles outline key objectives for the future evolution of global networks:

1. Continued improvements in seismic data quality and station reliability (Bès de Berc *et al.*, 2023; Juhel *et al.*, 2023; Leroy *et al.*, 2023; Wilson *et al.*, 2023).
2. More complete spatial coverage of seismic stations across the globe (Leroy *et al.*, 2023; Poli, 2023; Wilson *et al.*, 2023), including the future aspirational goal of extending high-quality observations of ground motions to seismometers emplaced on the ocean floor (Kohler *et al.*, 2020; Leroy *et al.*, 2023; Wilson *et al.*, 2023; Wuestefeld *et al.*, 2023) and within the oceans. New sensors, such as DAS (Wuestefeld *et al.*, 2023) and autonomous floating seismographs (Simons *et al.*, 2019), may play an important role in achieving this goal.
3. Leveraging emerging data processing techniques including machine learning (Leroy *et al.*, 2023; Münchmeyer *et al.*, 2023; Wilson *et al.*, 2023) and neural networks (Juhel *et al.*, 2023) to improve data quality and analysis.

In addition, the long-running and multiinstrument nature of the GSNs are fundamental for understanding interactions between the solid Earth and the hydrosphere, cryosphere, and atmosphere, a topic that is of increasing importance and interest. For instance, collocated pressure sensors at GSN and GEOSCOPE stations provided essential data for characterizing and understanding the complex acoustic-to-seismic coupling process that occurred following the 16 January eruption of Hunga Volcano, Tonga (e.g., Matoza *et al.*, 2022; Vergoz *et al.*, 2022; Anthony *et al.*, 2023; Ringler *et al.*, 2023). Furthermore, the decadal scale records from global seismic networks can be used to track changes in climate including ocean storms (Aster *et al.*, 2023), sea ice concentration (e.g., Grob *et al.*, 2011; Anthony *et al.*, 2017; Turner *et al.*, 2020), and glacial calving events (e.g., Ekström *et al.*, 2006; Nettles and Ekström, 2010; Poli, 2023). We look forward to continuing to work with the international seismological community to provide high-quality data and innovate our networks to enable the continued advancement of science.

Data and Resources

All data used in this article came from published sources listed in the references.

Declarations of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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