Rapid Response Science and Instrumentation:
A Community White Paper

I. Executive Summary

Geohazards, including earthquakes, volcanic eruptions, floods, and landslides, cause billions of dollars in U.S. economic losses, loss of life, injuries, and significant disruption to lives and livelihoods on an annual basis. The ability of the geoscience community to respond rapidly, within hours to days, after a hazardous event or at the signs of precursors to these events, provide critical data to understand the physical processes responsible for these destructive events. These data are only available while these events are happening or in their immediate aftermath and have the potential to significantly improve hazard assessment and mitigation strategies. The current instrumentation and infrastructure for rapid response efforts available in the SAGE facility lags behind in technology developments that have improved other types of instrumentation over the last decades. There is strong community interest in rapid response to geohazards science and wide recognition that multidisciplinary data are required; there are instrumentation needs that cut across multiple geohazards. Enhancing the geoscience community's capability to effectively respond rapidly to geohazards requires an investment in infrastructure, instrumentation, and human resources.

II. Preface

The community input and recommendations in this white paper were developed in support of the National Science Foundation (NSF) SAGE II award to IRIS (EAR-1851048) to develop and implement an enhanced capability to respond rapidly to geohazards as a Frontier Activity. While the process of developing this white paper was overseen by Justin Sweet (IRIS Project Associate), Kent Anderson (IRIS Portable Programs Manager), Bob Woodward (IRIS President), and Anne Meltzer (Lehigh University, Community Representative), the contents reflect community needs and priorities. This white paper was developed to assist IRIS in implementing its NSF SAGE II award and to serve as a springboard to seed additional opportunities to develop broader multidisciplinary capabilities to rapidly respond to geohazards. This white paper is being submitted to the IRIS PASSCAL Standing Committee, the IRIS Board of Directors, and the National Science Foundation Division of Earth Sciences Instrumentation and Facilities Program. In addition, this white paper will be forwarded to other interested agencies, including, but not limited to the U. S. Geological Survey (USGS), U.S. Department of Energy (DOE), U.S. Department of State (DOS) and other organizations requiring and/or developing rapid response capabilities. This will also be posted publicly on the IRIS rapid response website (www.iris.edu/rapid).

This white paper would not have been possible without the significant level of community input provided by participants, speakers, and organizers at events held in-person and online over the course of 2019 and 2020. In preparing this document, we have tried to capture as many of the community's needs as possible—most of which are beyond the scope of what can be addressed with current funding. In light of this fact, we organized the white paper recommendations into three tiers:

1. those we can address with funds awarded to IRIS in the NSF SAGE II award,
2. those we can address that do not require additional funds, and
3. those that require funding from future proposals for SAGE, GAGE, other appropriate organizations, and/or community proposals.

In this way we hope to address current pressing rapid response needs while also providing a community vision for future rapid response needs.

III. Introduction

Geohazards sit at the intersection of Earth science and society. The last decade has brought new insights into our understanding of the complexities associated with earthquake rupture and slip behavior, volcanic eruptions, flooding, and landslides, and highlights the need for fundamental research. Discrete hazardous events often occur with little to no advanced warning. Studying these events requires responding on very short notice with deployment of instrumentation to observe signals, cascading events, or transients caused by the main event, or at the sign of precursors to capture the main event. In either case, the ability to respond rapidly with appropriate instrument systems (i.e. sensors, dataloggers, power, and telemetry) is critical to capturing time sensitive data to fully characterize these events, and to unravel the processes responsible for the destruction they cause. Assessing and observing geohazards is essential to being able to better serve the general public with an improved understanding of mechanisms and threats that can then be used to develop mitigation strategies. The importance of geohazard science is noted in a number of community science and facility documents: *Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences* (Aster and Simons, 2015), *The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D* (McGuire et al, 2017), *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing* (National Academies of Science, Engineering, and Medicine, 2017), and *Challenges and opportunities for research in tectonics: Understanding deformation and the processes that link Earth systems, from geologic time to human time*, (Huntington, K. W., and K. A. Klepeis, 2018). Earthquakes, volcanoes, and geohazards are identified as science priorities in the recent National Academies Report, *A Vision for NSF Earth Sciences 2020-2030: Earth in Time,* and the need for rapidly deployable instruments for quick response is included under infrastructure and facility needs (National Academies of Sciences, Engineering, and Medicine, 2020).

The IRIS seismologic community has engaged in rapid response efforts for decades using a small dedicated pool of equipment from its Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) program. Instruments in this dedicated pool are held ready for rapid deployments, and are put at the front of the testing queue upon return from the field so that they can be quickly turned around and made ready for the next potential deployment. Unfortunately, the pool is small (~10 stations), in near constant use, and not always appropriate to the response required. It is composed of decades-old instrumentation that is time and labor intensive and logistically difficult to deploy compared to the latest generation instrumentation that is small, lightweight, and designed for rapid and otherwise efficient direct-bury emplacement. Currently IRIS PASSCAL typically responds to rapid response requests with instruments from our general pool– availability can vary depending on regular experiment demand. Expanding and upgrading the instrumentation in the PASSCAL rapid response pool will improve rapid response capabilities, allowing PIs to deploy appropriate instrumentation quickly and more easily.

The seismic and geodetic communities articulated the importance of a functional rapid response capability in a community report to NSF entitled Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences (Aster and Simons, 2015). In that report, the community authors concluded that future facilities “should have the capability to support and deploy small (tens) to large (hundreds to thousands) networks of appropriate instrumentation within hours to days of significant geophysical developments, such as volcano unrest, earthquake swarm or aftershock sequences, glacial surges or floods, or landslides.”

Responding to this need, both IRIS and UNAVCO proposed to the NSF a development and implementation effort for a rapid response to geohazards capability that would develop and procure a “rapid response equipment pool that is kept readily available, is easy to ship and deploy, and is fully capable of collecting critical research-grade data (i.e., high-signal-to-noise, on-scale seismograms), as well as a staff that can support these systems and assist with immediate training of PIs and deployment of the systems.” While the geodetic component of this proposal did not get funded, IRIS was funded to proceed with this effort. Our plan to move forward includes:

1. Gathering community input to understand rapid response science and observational needs,
2. Using community input, prioritize, test, and evaluate instrumentation for suitability and sustainability,
3. Procuring instrumentation and ancillary equipment,
4. Working with the community to establish policies governing usage, best practices, and maintenance strategies.

In the following sections, this document describes the process used to gather community input and the science justification and observational needs to respond rapidly to volcanic and earthquake hazards, induced seismicity, hydrologic and cryologic hazards, and geomagnetic hazards. We outline the instrumentation and functional requirements defined by the community, and review technologies to develop better capabilities to support rapid response to geohazards science. There is significant community interest in rapid ocean bottom deployments to complement observations on land, so we include community input on needs in this area as well. We conclude with a series of recommendations, both short term and long, to carry out the IRIS SAGE II award to enhance rapid response capabilities, and to advance rapid response capabilities more broadly beyond the scope of the NSF award to IRIS.

The development of enhanced capabilities to respond rapidly to geohazards must be grounded in the science and observational needs as assessed by the seismological community. To ensure that a rapid response pool is available and used effectively to support rapid response science, it's critical to distinguish between rapid response science and longer-term observations and monitoring. In addition, an effective rapid response capability requires partnerships, coordination and collaboration between the NSF, facility operators, operators of monitoring networks (regional, national, and international), and with state and government agencies tasked with geohazard monitoring, assessment, and response. It is important to avoid duplicating instrumentation and efforts, and to best augment existing groups and capabilities. For the U.S. geohazard community, the U.S. Geological Survey is an essential partner and usually the lead agency. Partnerships can be strengthened by building rapid response capacity and exercising protocols between rapid response events, and not just during them. Developing and maintaining connections and partnerships both nationally and internationally in advance of geohazard events is essential. Establishing a network of rapid response scientists and coordinating an annual rapid response drill, similar to the annual ShakeOut events, would help ensure that rapid response connections and procedures are in place, tested, and operating efficiently and effectively before the next event.

IV. Community Process

To engage a wide swath of the community, we convened both in-person and online gatherings to identify the science goals and observational needs for geohazard rapid response capabilities. These included:

- A special interest group (SIG) session held during the 2019 Seismological Society of America (SSA) meeting in Seattle, Washington. Over 100 people attended the SIG, and as part of the SIG completed an interactive poll yielding a total of 2,410 unique responses across 17 different polling questions. A high-level summary of survey responses is available on the IRIS rapid response page.
- A series of online "virtual" breakout sessions on six geohazard topics: large earthquakes, volcanoes, induced seismicity, hydrosphere/cryosphere, geomagnetic hazards, and rapid Ocean Bottom Seismometer (OBS) hazards response were held in fall 2019 and early 2020. Each session was chaired by a community member with subject-matter expertise (see acknowledgments), and included short invited talks, Q&A, and discussion. Between 25 and 50 individuals participated in each session. The sessions were recorded and posted to the IRIS Rapid Response webpage for on-demand viewing by community members who were unable to participate in the virtual breakouts.
- A Rapid Response "mini" workshop was held in advance of the SAGE/GAGE workshop in Portland, Oregon in October 2019. Approximately 60 people attended the mini workshop, which was also live streamed for those who could not attend in person. The mini workshop included presentations from four different geohazard case studies, summaries of the SSA SIG and the four virtual breakout sessions that took place prior to the mini workshop, and discussion of rapid response capabilities, operational models, and funding. Representatives from the National Science Foundation participated in the

mini workshop and spoke briefly about funding available through NSF RAPID awards. Presentations from the mini workshop are posted to the IRIS Rapid Response page.
- An initial draft of this white paper was broadly circulated, to break-out session chairs and participants, to community members via the IRIS email distribution list, and to members of partner organizations like the USGS for review and comment. The initial draft was also the focus of a Virtual Special Interest Group (SIG) meeting in August 2020 as part of the virtual 2020 GAGE/SAGE Science Workshop in advance of the full workshop deferred until August 2021.

As part of the community process and development of this white paper, direct engagement from partners and allied initiatives, GAGE, the U.S. Geological Survey, SZ4D, the Community Network for Volcanic Eruption Response (CONVERSE), and Community Volcano Experiments (COVE) was sought and incorporated.

V. Science Motivation and Observational Requirements

The community defined six topical areas that would benefit from enhanced rapid response capabilities: volcanic hazards, large earthquakes, induced seismicity, hydrologic/cryologic hazards, geomagnetic hazards, and rapid ocean-bottom deployments. The input received as part of the rapid OBS gathering is covered in section VI under required instrumentation. Full recordings of each virtual breakout group session are available for download.

1. Volcanic Hazards

Volcanoes provide the setting for a range of geohazards including eruptions, earthquakes, landslides, and lahars. In general, advances in understanding volcanic eruptions will come from instrumentation deployed *prior* to the eruptions themselves. In that sense, the real science advances and humanitarian benefits will come from rapid response to initial volcanic unrest, rather than to any subsequent eruption. Current efforts to understand volcanic unrest are often based on pattern matching, comparing current behavior with previous eruptive sequences to predict what will happen in the future. To better anticipate hazards, future efforts must understand and link processes at work within volcanic systems. This requires multidisciplinary observations using a variety of instrumentation to accurately measure and record how volcano unrest is developing. In addition to seismic instrumentation, the most often requested equipment includes: infrasound, Global Navigation Satellite System (GNSS), Digital Elevation Models (DEMs), and Interferometric Synthetic Aperture Radar (InSAR). Infrasound and GNSS can often be co-located with seismic instrumentation, and have modest power requirements. DEMs are most useful when they can be compared with a pre-eruptive baseline model. During unrest, new DEMs may be collected via satellite, aircraft, or drone.

A multidisciplinary dataset allows a better understanding of the processes at work inside the volcano, both spatially and temporally. Spatially, where is magma present, in what volumes, and what are its properties? Temporal observations of the evolution of volcanic systems and eruptive precursors are critical to understand the drivers of volcanic unrest and eruptions. To answer these questions, a variety of observations are needed, including: large, dense seismic networks (broadband and high frequency), additional geophysical and geochemical observations (infrasound, GNSS, gas) and DEMs, as well as long-term, baseline records of seismicity and DEMs. These long-term datasets require more permanent (monitoring) networks but, used in combination with rapidly deployed instrumentation, are essential in understanding volcanic behavior. Infrasound, in particular, is essential for full characterization of outgassing and eruptive processes. Small-aperture arrays of 3-4 infrasound sensors allow for source identification and modeling, vent location and migration tracking, source depth variation, eruption height estimates, as well as the detection and discrimination of non-eruption processes. Multi-gas observations provide some of the most exciting new real-time measurements with forecasting potential seen in a decade. Many volcanoes that have no seismic precursors may instead show gas precursors—rises in carbon dioxide or sulfur—weeks to months prior to an eruption (Werner et al., 2019). As real-time multi-gas instrumentation boxes become increasingly easy to use and operate autonomously, their inclusion with other types of geophysical instrumentation (seismic, geodetic, etc.) becomes more feasible than in the past.

The timeline for volcanic hazards is as varied as the volcanoes that produce them. In general, precursory activity will begin days to weeks prior to the first surface manifestations of unrest. It's often impossible to know in advance when a precursory phase will become an active/eruptive phase, so time is of the essence in getting additional instrumentation installed and operating before conditions become too dangerous to allow continued deployments. The duration of volcanic unrest is equally uncertain, as eruptive sequences can last from days to years. The most critical data to collect immediately after an eruption are geologic samples. These are often blown away or blended with the landscape and lost to science unless sampled immediately. We will never fully understand seismic and geodetic signals without knowing what was going on beneath the surface to generate them.

Telemetry is essential for rapidly responding to volcanic hazards. Real-time seismic data is one of the best tools available for assessing the changing state of a volcano building towards an eruption. Collecting seismic data after an eruption isn't without merit for investigating volcanic behavior and processes after-the-fact, but it does little to help with hazard monitoring or warning. The same is true of geodetic, infrasound, and other geophysical data collected on or near an active volcano. Having these data telemetered in real-time greatly increases their usefulness for both hazard assessment, as well as scientific analysis. Depending on where particular instruments are deployed, some of them may be destroyed by an eruption. In these cases, data must be telemetered or it will not be collected at all. By their very nature, volcanic terrain is often rugged and remote, which can limit many ground-based telemetry options. For this reason, satellite telemetry is often necessary to enable real-time data streams of critical geophysical observations.

2. Large Earthquakes

Large earthquakes are some of the most impactful geohazards that our community studies and responds to. Past large earthquakes have killed tens to hundreds of thousands of people, and can devastate economies and human populations on a regional scale. Associated geohazards like tsunamis, landslides, liquefaction, and large aftershocks can also result in significant additional damage and loss of life. Understanding how large earthquakes occur is a fundamental topic of research, both in terms of science and hazard mitigation efforts. Because these events cannot be predicted in advance, seismologists must be reactive to them when and where they occur. In order to gather crucial data that illuminate the processes associated with these large events, instrumentation must be deployed rapidly, within days (if possible) to weeks (if necessary) following the mainshock.

Key scientific targets when rapidly responding to large earthquakes include:

- *Accurate recordings of post-seismic deformation and afterslip*
  This includes phenomena like aftershocks (seismic), earthquake swarms (seismic), triggered seismicity, and slow slip (geodetic & seismic) which are essential for capturing and understanding the continuum of deformation mechanisms following a mainshock.
- *High-resolution imaging of the seismogenic zone*
  This includes information on physical properties, fault zone fluids, fault roughness, fault damage zones, and asperities. Data on these features is important for understanding the physical properties of the fault rupture and how they influenced the mainshock.
- *High-resolution imaging of the volume surrounding the earthquake*
  Numerous aftershocks allow the creation of high-resolution models in the region surrounding the mainshock and help illuminate stress accommodation as well as structural studies.

One of the benefits of rapidly responding to a large earthquake is the near-certainty of collecting valuable data. Aftershock sequences produce huge volumes of data with many events to analyze and to image Earth structure. These large datasets can be particularly important in regions that may not have been previously targeted for temporary deployments due to the time and effort required to obtain a viable dataset. In addition, these kinds of rapid response efforts are often able to get access to places that may otherwise be difficult to obtain, because people and governments are more motivated to help.

Large earthquake rapid response efforts significantly benefit from mixed weak and strong motion 3-component seismic sensors (e.g. broadband, short period, node, and accelerometers) for accurate recording of the full seismic wavefield. A moderate number of broadband seismometers are helpful for recording earthquakes at regional distances, low-frequency events, and for ambient noise studies. Larger numbers of short period sensors and nodes are needed to capture high-frequency signals at local distances. These sensors tend to be much smaller, lighter, easier-to-deploy, and require less power to operate than broadband sensors. Accelerometers are a critical component of aftershock deployments in order to capture on-scale recordings of near-field seismic accelerations of larger aftershocks. Strong ground motion data are of particular use to the engineering community in developing seismic safety standards for buildings and critical infrastructure. Distributed acoustic sensors (DAS) are becoming tenable and hold great promise for tracking seismicity and potentially aseismic deformation. (e.g., as recently demonstrated after the 2019 Ridgecrest earthquakes by Zhan et al., 2020). In addition to seismic sensors, geodetic observations (InSAR, LiDAR, GNSS) are central to observing and quantifying ground deformation. For subduction zone events offshore OBS and geodetic observations are critical.

Because aftershock sequences are prolonged processes; moderate-sized earthquake (M6-7) deployments may last several months to a year. For larger earthquakes (M8+) deployments of 1 or more years may be necessary to advance science goals.

For entities engaged in monitoring of aftershock sequences (e.g. USGS, state agencies and funded universities, and their international equivalents) real-time earthquake detection, assessment, and location are principal goals. This information is used in aftershock forecasting and provides situational awareness for communicating to various stakeholders, including: local, state, and federal governments; emergency responders; and the public. In these cases, having real-time telemetered data is essential since many stakeholders are seeking timely, actionable information following events of significant size.

3. Induced Seismicity

Recent years have seen a significant rise in the number and scientific understanding of induced earthquakes, particularly in the central and eastern U.S. where earthquake hazards have traditionally been considered to be low. In these environments, even moderate-sized earthquakes (M4-5) can cause damage to buildings and infrastructure that were not built with earthquake hazards in mind. Scientists, policy-makers, and the general public have had to adapt quickly to understand these events, and to quantify their risks.

Earthquake catalogs (time, location, magnitude) form the backbone of induced seismicity studies. Building these catalogs requires the deployment of seismic networks of sufficient scale to adequately cover the region of interest, with the right type and density of instruments to ensure detection thresholds are low enough to capture events that are often small, shallow, and high-frequency in nature. Beyond simply tabulating when and where events are occurring, the particular science targets and necessary capabilities depend on the deployment objectives. For entities engaged in monitoring of induced seismic sequences (e.g. USGS and state agencies), open access, real-time telemetered data is essential as stakeholders (local, state, and federal governments; emergency responders; and the public) are seeking timely, actionable information following an induced event of significant size. Open access, real-time data helps establish partnerships with various agencies and operators.

For research-focused studies (e.g. academics, USGS), the science targets focus on the relationship between seismicity and anthropogenic activities (e.g. oil, gas, and, geothermal production, CO_2 sequestration, mining, dam impoundment). In addition to data-driven models, these studies often seek to estimate expected magnitudes and resulting ground motions, and then use these findings to forecast hazards and inform operators and regulators on best practices moving forward. These studies may not require real-time telemetry, and station coverage can be adapted to maximize science return in a location of interest, rather than to ensure uniform coverage and detection thresholds over a particular region.

Beyond continuous 3-component weak-motion seismic data, induced seismicity deployments benefit from the inclusion of accelerometers for on-scale recordings of strong motions. Pressure transducers are required for measuring pore pressure changes at depth. Downhole strainmeters are helpful for tracking strain. Fiber optic distributed acoustic sensors (DAS) are useful for recording the seismic wavefield (Rayleigh scattering), while other fiber optic interrogators permit the measuring of long-period strain (Brillouin scattering). Geodetic observations (InSAR, LiDAR, GNSS) are helpful for observing and quantifying ground deformation.

4. Hydrologic/Cryologic/Climate Hazards

Seismology has increasingly been used to study geophysical phenomena and events of interest in the hydrosphere and cryosphere including glacial seismicity, fluvial and debris flow processes, and hurricane physics. While some of these hazards occur without warning, others can be forecast in advance over weeks and days with increasing accuracy. The sudden collapse of a landslide or glacier might come without any advance warning, while a hurricane can often be anticipated several days in advance allowing time for instrumentation to be deployed in order to fully record the event. Taken together, lead times to respond to and capture the event could vary from days to weeks, months, or even seasonally.

Observational and instrumentation needs for studying these kinds of hazards are diverse. Seismically, everything from broadband systems to geophones to accelerometers is useful in capturing and quantifying signals of interest. Many deployments can also benefit from nodal deployments, although current limited battery life and the lack of telemetry can limit applications in some cases. Additional geophysical observations are crucial to fully record and understanding these hazards, including meteorological, pressure sensors, GPS/InSAR/GNSS, force plates, video/camera imagery, laser scanners/DEMs, sediment traps—and can be co-located with seismic instrumentation and digitized via the same or similar systems. DAS has also been used successfully in glaciers to study glacial seismicity and other seismic sources (subglacial water flow, etc.). Telemetry needs depend on the particular hazard being studied. In some cases, such as debris flows or floods, having real-time data is required to provide advance warnings to the public, while in other research applications (e.g. seismic deployments in hurricanes) data telemetry is less useful.

5. Geomagnetic Hazards

Geomagnetic activity induces electric currents in the Earth, and in areas where the subsurface is highly resistive, these currents can pass into utility infrastructure such as pipelines and the electric power grid. When this happens, the excess current accelerates normal wear and tear, and may cause component damage or even catastrophic system failures. These hazards can be caused by natural events, like solar storms, or via electromagnetic pulses caused by high-altitude nuclear weapon detonations. Currents induced by geomagnetic activity and other sources can be modeled from measurements of subsurface resistivity provided by magnetotelluric (MT) surveys, which record the Earth's ambient electric and magnetic fields. From 2006-2018, the EarthScope MT Transportable Array surveyed approximately two-thirds of the Lower-48 US with long-period MT stations, allowing for risk of geomagnetically induced currents to be better characterized across the northern and eastern US (http://usarray.org/researchers/obs/magnetotelluric). A survey of the remaining contiguous US is currently being conducted with support from the USGS and NASA. Once complete, utility operators will have access to first-order information to help mitigate and prepare for a critical hazard to their networks.

Often, increased solar activity can be predicted several days in advance, allowing crucial lead time to prepare for geomagnetic hazards. On even longer timescales, solar activity follows a decade-scale cycle which allows planners to anticipate when increased solar activity is likely to occur. MT surveys can be prioritized in advance of these peak activity time periods, to ensure that relevant susceptibility information has been gathered and disseminated. Even during peak activity periods, only the largest solar storms pose a threat to critical electric grid infrastructure (kp>6); however, smaller storms do impact high-latitude countries more frequently. Understanding the physics of these solar storms and their potential impacts is a key scientific question of societal relevance.

Geomagnetic activity can also manifest as noise on seismometers deployed at high latitudes. The USGS geomagnetic program operates co-located magnetometers at a handful of existing seismic stations. These data are used to monitor geomagnetic activity, and, where necessary, can also be used to correct and filter seismic data that may have been affected.

VI. Functionality Requirements

Despite the diversity of geohazards and the variety of observations and instrumentation required a common set of needed capabilities emerges, many of which cut across different applications.

1. **Multi-modal seismic observations**
   The importance of recording both weak and strong ground motions cuts across a number of geohazards. Near-field on-scale strong motion records are lacking across many applications, and are important for source characterization and are critically important for modeling ground shaking and seismic hazard. In order to accurately record the full seismic wavefield, several types of seismic sensors—each suited to a particular portion of the frequency spectrum—are required, including broadband sensors (5-120 s), short period (5 Hz to 5 s), and high frequency (>5 Hz). For most rapid response efforts, broadband sensors can be spaced widely as appropriate to avoid aliasing the long-period signals they record, while short period and high frequency sensors need to be placed closer together because of the shorter wavelengths to which they are sensitive. What this means in terms of rapid response deployments is that accurate full wavefield recordings will require a mix of sensors: fewer broadband sensors (~10-20+), more short period sensors (10-50+), and even more high frequency sensors (100+), with exact numbers determined by the event and targets. In addition to instrument counts, instrument design is also an essential component of a successful rapid response deployment. Instruments that are small, rugged, low-power, and able to be directly buried in high tilt conditions for long periods are required to meet the need to respond within days.

2. **Co-located multidisciplinary instrumentation**
   Multidisciplinary observations are critical to rapid response science, and in some instances can benefit from co-location with seismic instrumentation. The three most common types of non-seismic instrumentation requested by the community include:
   - *Infrasound*
     Infrasound has obvious benefits for the detection and measurement of explosive events, rapid landslides, and lahars, and in conjunction with seismic observations can discriminate sources occurring at the surface from those beneath the surface.
   - *Meteorological*
     In addition to wind speed, measurements of temperature, pressure, and other environmental parameters benefit rapid response deployments studying hydrologic or cryologic events, and provide valuable information for studies of the atmosphere in the vicinity of a rapid response deployments for earthquakes and volcanoes. Atmospheric sensors can also provide a check for signals seen in seismic data. Recent seismic deployments near landfalling hurricanes have used nearby measurements of wind speed to calibrate seismic “noise” with storm intensity (Ebeling & Stein, 2011).
   - *Geodetic*
     Geodetic data are critically important for rapid response to geohazards, particularly for rapid deployments on or near volcanoes, earthquakes, induced seismicity and hydrologic/cryologic events. The types of geodetic capabilities requested included GNSS, as well as InSAR/LiDAR, and tiltmeters/strainmeters.

There is strong community interest in enhancing geodetic capabilities as part of an integrated rapid response instrument pool.

3. **Rapid Deployment of Ocean Bottom Seismic instrumentation**
   Two-thirds of the Earth's surface is covered by water, and the most destructive, largest-magnitude earthquakes occur substantially offshore in subduction zones. As on land, offshore earthquakes can have impacts far beyond the immediate vicinity of the mainshock. Large undersea earthquakes that offset the seafloor induce tsunamis, which in turn can cause fatalities and destruction far away from any perceived shaking. Island volcanoes (both above and below the water) are another important geohazard, particularly in the Aleutian Islands and Hawaii.

   One of the primary science targets for ocean-bottom deployments are recording and constraining the location of aftershocks and improving local velocity models for accurate relocation of the mainshock. Offshore aftershocks are often poorly located if the only available seismic data comes from land-based stations. Having offshore stations makes a huge difference in the ability to locate events, determine physical properties, and image structures that promote or inhibit rupture and influence slip behavior. The same is true of volcanic earthquakes seen at island volcanoes. These events are often tied to eruptive activity at the surface, and monitoring their frequency can assist with hazard forecasting.

   In addition to seismic sensors, hydrophones are essential for the recording of acoustic signals, which are often generated along with seismic signals by undersea earthquakes. As noted for other geohazards, a variety of instrumentation (seismic, acoustic, pressure) is required to accurately characterize how systems change and evolve as a result of a geohazard. As on land, the duration of aftershock sequences following a large earthquake will vary with the size of the mainshock. Large undersea aftershock sequences can last a year or more, requiring power systems capable of recording for at least that long. While including telemetry can significantly increase the power needs of undersea stations, real-time telemetry is required if the data are used for hazard monitoring and event forecasting.

   Because of the increased difficulty and expense associated with rapidly responding to an offshore event, the thresholds for response are likely to be somewhat higher than those for events on land, but proximity to shore and/or major population centers can increase the need to rapidly respond to even moderate events. In all cases, deploying as rapidly as possible is important.

4. **Additional geophysical instrumentation**
   In addition to seismic, infrasound, meteorological, and geodetic instrumentation, the community would like to see additional instrumentation incorporated into a rapid response pool. Gas measurements at volcanoes, and strainmeters and pore pressure measurements to study induced seismicity. DAS systems should eventually allow for

revolutionary and important observations for aftershock and other hazard scenarios. To characterize changing magnetic fields, co-located fluxgate magnetometers are essential. Because magnetic fields can also generate signals on broadband seismometers, having fluxgate magnetometers co-located with seismometers allows for identifying and removing these signals from seismic data as well. Hydrophones provide great benefits when integrated with OBS packages. Many signals seen on OBS originate and travel within the water column, and hydrophones can be both more sensitive to these signals, and can assist with discriminating those signals from tectonic signals in the seismic data.

5. Response Time

A defining characteristic of a rapid response capability is to be able to get instruments to the location of event and recording in a timely manner. Generally, this is constrained by the availability of instrumentation, the effort required to transport and install the equipment (logistics), and the availability of funding. Current capabilities for responding post event generally takes weeks. For many geohazards, the response time needs to be shortened to days to capture critical signals and observations available only immediately after the event.

Having equipment on the shelf and ready to deploy is essential to ensure a timely response. Instruments for these studies need to be small, light, low-power, and easy to transport and deploy quickly and efficiently. Several instrument manufacturers have responded to these needs in recent years with new systems that are excellent candidates for a rapid response pool. Beyond sensors, quick-deploy boxes that include pre-cut slots for digitizers, batteries and ancillary control systems can minimize installation time. Power systems can seriously impact both deployment time and logistics (i.e. lithium battery power is small and light, but are considered “dangerous goods” in shipping, requiring special handling).

Project funding is required, either through the NSF RAPID program, or other funding mechanisms and organizations, before shipping and deployment can take place. This, alone, can cause considerable and detrimental delays in rapid response efforts. Coordination between facilities (e.g. SAGE and GAGE) as well as between agencies (e.g. NSF, USGS, and international partners) is necessary, and having protocols for these kinds of efforts established in advance is critical.

International responses bring many additional considerations, including the importance of local collaborators and an invitation to deploy in-country. Customs and shipping are highly variable and can be difficult to navigate. Coordination is often required with other international response teams, and contact with and assistance from the local U.S. Embassy is critical.

6. Data Latency

The importance of real-time data telemetry to rapid response capabilities depends on the goals of specific response efforts. Data from deployments for hazard forecasting require real-time data to determine when and how a particular geohazard may be changing, and how those changes impact hazard levels. Real-time data can be useful in adapting station deployments as specific geohazards evolve in time and space over the course of the event.

However, telemetered data adds costs and logistics. Telemetry service must be rapidly available so systems will accrue standby costs paid by the facility and deployment and usage costs paid by the grantee. In addition, telemetry increases station power demands (e.g. larger power systems and enclosures). If rapid integration of temporary stations for event assessment or other near-real-time activities are envisioned, telemetry and data protocols must be compatible with appropriate processing systems.

That said, rapid response deployments can succeed without access to real-time data or can be modified after the initial deployment to add telemetry – if needed. Near real-time telemetry or state-of-health monitoring could also be helpful on some deployments.

VII. Technology Requirements

Implementing the rapid response capabilities outlined by the community will require a range of technology, some familiar and some new, and will require financial resources beyond the limits of the NSF SAGE II award. Below we outline a stepwise approach to enhancing community based rapid response capabilities, beginning with an expansion of the current capabilities within the SAGE facility consistent with the funding available within the SAGE II award. This is followed by additional instrumentation that would add new capabilities to the community through the addition of off-the-shelf equipment not currently part of NSF supported facilities. Including these technologies in a rapid response capability requires resources beyond those available within the SAGE II award. In addition to the instrumentation needs listed below, the community expressed strong interest in enhanced geodetic and offshore (both seismic and geodetic) observing capabilities.

1. Expansion of current capabilities at PASSCAL

The current rapid response capabilities of the SAGE facility consist primarily of simple best effort to supply and ship instrumentation already in the equipment pool as rapidly as possible. The instrumentation supplied is not purpose-built for rapid response deployments, and in the case of broadband seismometers it often consists of observatory-class sensors ill-suited for rapid deployments in hastily-constructed vaults with severe time and resource limitations. In addition, beyond 10 broadband stations, there is no dedicated pool of instruments that is set apart from the larger pool and held in reserve for rapid response applications. Under the current operational model, if a rapid response request came in at a time when the instrument pool was already fully subscribed, the facility might be unable to accommodate the rapid request.

In looking to expand the current SAGE capability to better support rapid response deployments, the most commonly-requested items include:

- *Direct-bury seismometers (nodes, compact broadbands)*
  Seismic instrumentation that can be buried directly in the ground is crucial for rapid response efforts, because of the amount of time and labor saved by not having to construct sensor vaults and secure and transport vault materials. Recent direct-bury seismographs also benefit from reduced size, weight, and power requirements, all of which greatly simplify logistics, and reduce costs associated with rapidly deploying instrumentation. In addition, having a variety of sensors with different frequency responses is essential for adequately sampling the seismic wavefield. By deploying a multi-modal combination of high and low frequency sensors, PIs can maximize field time by deploying fewer low-frequency sensors (compact broadbands) spaced farther apart, along with denser deployments of high-frequency sensors (nodes).
- *Accelerometers*
  In addition to having the right mix of seismometers to adequately sample the weaker seismic wavefield, it is crucial that strong motion sensors also be deployed--particularly in regions likely to experience strong shaking--in order to capture on-scale recordings of near-field accelerations. These near-field on-scale strong motion records are sorely lacking in engineering and scientific databases, and are critically important for modeling expected ground shaking and future seismic hazard.
- *Quick deploy boxes*
  While some all-in-one sensors/seismographs (e.g. nodes) do not require any ancillary instrumentation, most other seismic sensors require an associated digitizer and battery that will need to be housed and protected. PASSCAL has designed and deployed a variety of quick deploy boxes that allow the digitizer, battery, and any associated circuitry to be housed in a single transportable enclosure. The enclosure itself is about the size of a suitcase and contains a foldable solar panel that is mounted to the outside of the case. Quick-deploy boxes like these allow for rapid station installation, and immediate and sufficient power to get stations up and running and to keep them running for up to several months.
- *Telemetry solutions*
  Telemetry is another key component of rapid response--especially for hazard monitoring applications in aftershock zones and active volcanoes. In these environments, having real-time information on the size and location of earthquakes, tremor, and other seismic signals is important for assessing and forecasting future hazards. In areas where cellular service is available, cell modems provide inexpensive, high-bandwidth telemetry back to a central server. Drawbacks for this type of telemetry include the extent of cellular coverage, which can be limited in rugged, remote terrain. Also, cellular networks may be disrupted in the aftermath of a large earthquake, and may not be a reliable method for data telemetry. Where cellular coverage is inadequate or uncertain, satellite telemetry is the best option for providing low to moderate bandwidth

connections to just about anywhere on the planet. The biggest drawback with satellite telemetry is significantly higher cost and power.

2. **Off the shelf technologies not currently part of NSF supported facilities**
The following off the shelf technologies, while beyond the scope of the SAGE II award, would significantly enhance rapid response science:
    - *Telemetry-capable nodal seismometers*
    Nodal seismometers, all-in-one sensor/battery/digitizer devices with on-board GPS timing all in a small, cable-free package that is easy to transport and deploy. Adding telemetry comes with increased power demands decreasing recording time or requiring additional external batteries.
    - *Fiber-optic cable systems*
    Distributed acoustic sensing (DAS) is a new technology that utilizes laser interrogators to measure strain along fiber-optic cables, including those already installed for telecommunications purposes. These interrogators allow scientists to create simulated seismometers at regular intervals along a fiber over distances up to 50 km, potentially yielding thousands of seismograms without any digging required!
    - *Infrasound*
    Infrasound sensors have been deployed alongside some seismic installations within the Global Seismic Network, on the Alaska Transportable Array, and on volcanoes. There are several designs that are compact, low-power, and which can be fed into a digitizer along with seismic data. Adding these sensors to the rapid response pool would be particularly beneficial for volcano rapid response scenarios where near-surface sources are common.
    - *Meteorological*
    Meteorological or “met” packs have also seen some deployments at seismic stations, most notably throughout the EarthScope Alaska Transportable Array. Like infrasound, these sensors come in several compact, low-power designs and lend themselves to easy incorporation with seismic data in the digitizer. Several hydrologic hazards--including floods, hurricanes, and other atmospheric phenomena that also produce seismic signals--require co-located met packs in order to adequately characterize and understand the collected datasets.
    - *Near surface geophysics*
    Near surface geophysics encompasses a wide variety of near-surface instrumentation (e.g. ground penetrating radar, force plates, sediment traps, video or time-lapse imagery) that can enhance, and in some cases are essential to, the observation of geohazard signals. This is particularly true for hydrologic and cryospheric geohazards (e.g. debris flows, lahars, floods, iceberg calving events), which are often recorded seismically, but which require complementary near-surface observations to adequately characterize and study.

VIII. Operational Requirements

Clear protocols for operation and support are critical to successfully field community rapid response efforts. Rapid response capabilities are needed to respond to and/or record data from time-limited geohazard events, and are not intended for long-term monitoring or extended research of geohazards. There must be a clear understanding that instruments in the rapid response pool cannot become part of a permanent or long-term monitoring system for a single event. If there becomes a need for longer-term observations, clear transition plans and additional PI funding will be required to transition these experiments into a more standard PASSCAL deployment and return/replace the rapid instrumentation. A clear and transparent instrument request process needs to be in place that includes a well-defined deployment plan and duration estimate at the start of a rapid response effort. But given the dynamic nature of this type of deployment and geohazard events that evolve over time, a process for managing change requests needs to be in place. Expectations and responsibilities for data delivery and archiving need to be clear and acknowledged as part of instrument use policy. In the case of instrumentation at PASSCAL, the policies governing the use of the rapid response pool will be developed by the IRIS staff in conjunction with the pertinent governance body (the PASSCAL Standing Committee) and then will be further discussed and ultimately approved by the IRIS Board of Directors.

A successful rapid response deployment consists of many moving parts, all of which must function quickly and effectively to ensure that instrumentation can be deployed and data gathered in a very short amount of time. Some of the steps in the process are the responsibility of the PI, some belong to the facility, and others to the funding agency. Accordingly, steps to improve the rapid response process will require input, consultation, and changes from multiple parties. A “Roles and Responsibilities” document that clearly defines the expectations from all involved in the rapid response exercise is essential.

Funding for a rapid response experiment and the speed at which it can be secured is a concern often expressed by community members. For NSF funded responses, the RAPID award is the preferred method for securing funding and PIs who may be interested in rapid response efforts should familiarize themselves with the application process ahead of time. There are also other agencies who may be able to fund rapid response efforts (Federal, State, University, etc.). To improve response time, potential funding sources need to be identified and coordinated in advance of an event. A significant barrier to reducing the time between the event and getting instruments into the field is the spin up time required to coordinate the response effort within the community and to obtain funding. To significantly improve response time, we need a rapid funding mechanism to engage and coordinate the community and funding agencies, and a process to identify stakeholders who are able to respond quickly.

On the facility side, an effective rapid response capability requires expertise in logistics, scheduling, maintenance, training, and in some cases field support. This range of skills will not reside within a single individual; it requires a team of experts. PASSCAL staff can prepare and provide trainings, user guides, and checklists to PIs in advance so that they are ready for immediate usage when needed. Logistics staff handle the many intricacies of scheduling, shipping, and receiving instrumentation and ancillary equipment. To ensure that rapid response instrumentation is always ready and available for the next unforeseen geohazard, a strictly run and well-designed scheduling system is required. Guided by approved usage policies, rapid response scheduling will describe and enforce instrument use parameters that ensure the rapid response capabilities support community needs while remaining responsive to future events. A rapid response pool is of little use to the community if the equipment it contains is not functioning properly. Facility staff will need to assess returning rapid response instrumentation and ancillary equipment to ensure it is operating correctly before being placed back into the active pool. Timely assessment and repair strategies are needed to determine if repairs can be done successfully and economically in-house, or if they require repairs to be conducted by the equipment manufacturer. The goal is to get the equipment ready for reuse as quickly as possible in a sustainable manner. IRIS has funding under the current SAGE-II award from NSF to support facility staff in maintaining, operating, and deploying equipment alongside PIs. Current default policy does not cover staff travel costs to and from the field, so that will remain – as with standard PASSCAL deployments – as a requirement for PI awards or other supplemental funding.

As rapid response capabilities grow and are utilized by the community, overall workload needs to be assessed and an appropriate level of human resources needs to be allocated to assure the rapid response capabilities function well. Coordination and management across logistics, scheduling, field support, training, and maintenance are essential. From a user perspective, a single point of contact within the facility is required.

IX. Recommendations

There is strong community interest in rapid response to geohazards science. There is wide recognition within the community that multidisciplinary data are necessary to support rapid response science and that instrument needs cut across multiple geohazards. In some rapid response efforts, diverse sets of instruments can benefit from co-location. There are benefits to be gained in joint management of an integrated rapid response pool, whether the pool physically resides in a single geographic location, or is distributed.

The current scope for IRIS funding under SAGE-II is limited. Additional funding would be required to implement a comprehensive rapid response system to meet community needs. Below we recommend the highest priority additions to the IRIS PASSCAL facility that are sustainable given funding in hand through the SAGE-II award. We also suggest short- and long-term steps to meet the needs of the community for a more comprehensive solution.

Instrumentation Recommendations

To carry out the IRIS SAGE II award to enhance rapid response capabilities, we recommend PASSCAL invest in new purpose-ready:

- Direct burial 3 component sensors
    - 10 broadbands
    - 30 short period/compact sensors

        - 200 nodes
        - 10 strong motion
    - Dataloggers
        - 40 next-gen, telemetry-capable
    - Other geophysical instrumentation
        - 10 Infrasound
    - Quick-deploy battery/solar-powered boxes
        - 40

The instrumentation listed above is consistent with planned funding in the SAGE II award. In addition to the instrumentation listed above, PASSCAL should develop an appropriate management model, policies and procedures, and assess and allocate the needed staff resources to ensure that the expanded response capability remains ready for immediate deployment on short notice. We note that while the above listed instrumentation is recommended specifically for a rapid response pool, the PASSCAL portable pool also contains instrumentation (nodes, broadbands, etc.) that could be mobilized to augment rapid deployments as available.

Short-term and Long-term Follow-up Recommendations for Continued Work
There is significant community interest in expanded multidisciplinary observations to advance geohazards research. To advance rapid response capabilities more broadly (beyond the scope of the NSF SAGE II award to IRIS), we recommend:

In the short-term:

- Seek funding for development of a robust, easy-to-deploy telemetry solution that includes backend data handling to enable seamless flow of critical real-time data from the field to the data management center.
- Support GAGE in seeking resources to enhance geodetic capabilities that facilitate rapid response science. Geodetic technologies already identified as essential include: GNSS, InSAR, and LiDAR.
- Work with NSF supported ocean science facilities and support USGS efforts to develop rapid response OBS packages and offshore geodetic capabilities.
- Support existing community efforts in support of geohazard science
- Seek funding opportunities and/or partnerships to enhance rapid response capabilities using infrasound, meteorological instrumentation, magnetotelluric instrumentation, and near-surface geophysics.
- Explore opportunities and partnerships to purchase and operate a pool of DAS interrogators and DAS data management resources to inform rapid response efforts.
- Facilitate continued community engagement and organization to prepare in advance to coordinate response efforts, deployments, logistics, and funding.

Longer term, the need for multidisciplinary rapid response capabilities will be an important part of any national facility that supports geophysical instrumentation. It is important for the community to articulate a multi-agency multi-disciplinary strategic vision for rapid response capabilities, so that future funding is incorporated into future facility support and coordinated with other appropriate national facilities.

X. Project Oversight, Implementation, and Timeline for the SAGE-II funded effort

Oversight of the IRIS SAGE II rapid response effort will be provided by the community governance structure within IRIS, the PASSCAL Standing Committee, and the IRIS Board of Directors. Implementation, management, and procurement will be carried out by the staff at IRIS, and the IRIS/PASSCAL Instrument Center. We anticipate the following timeline for instrumentation evaluation and procurement:

- Early 2021
  - Develop functional specifications, RFQs, and evaluation criteria
  - Procure small evaluation sets
  - Evaluation and review by working group and determine final instrumentation procurement plan
- Late 2021 – Early 2022 Procurement process
  - Develop RFPs
  - Acceptance testing
  - Integration with PASSCAL systems, inventory, and logistics
  - Development of policies and procedures
- Late 2022 Implementation of Capability

XI. Bibliography

Aster, R., & Simons, M. (Eds.). (2015). Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences (p. 46). Retrieved from https://www.iris.edu/hq/files/publications/other_workshops/docs/futures_report.pdf

Ebeling, C. W., & Stein, S. (2011). Seismological Identification and Characterization of a Large Hurricane. *Bulletin of the Seismological Society of America*, *101*(1), 399–403. https://doi.org/10.1785/0120100175

Huntington, K. W., and K. A. Klepeis, with 66 community contributors. (2018). *Challenges and opportunities for research in tectonics: Understanding deformation and the processes that link Earth systems, from geologic time to human time.* A community vision document submitted to the U.S. National Science Foundation. University of Washington. 84 pp., https://doi.org/10.6069/H52R3PQ5

McGuire, J. J., Plank, T., Barrientos, S., Becker, T., Brodsky, E., Cottrell, E., et al. (2017). *The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D.* (Vision Document Submitted to the National Science Foundation) (p. 63). The IRIS Consortium. Retrieved from https://www.iris.edu/hq/files/workshops/2016/09/szo_16/sz4d.pdf

National Academies of Science, Engineering, and Medicine. (2017). *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*. Washington, DC: The National Academies Press. Retrieved from https://doi.org/10.17226/24650

National Academies of Sciences, Engineering, and Medicine. (2020). *A Vision for NSF Earth Sciences 2020-2030: Earth in Time*. Washington, DC: The National Academies Press. Retrieved from https://doi.org/10.17226/25761

Schmandt, B., Fischer, T., Coombs, M., Fee, D., Gazel, E., Grapenthin, R., et al. (2018). *Outcomes Report from the Workshop on Advancing Integrative Volcanology with Community Experiments* (Outcomes Report). Albuquerque, NM. Retrieved from https://volcanoresponse.files.wordpress.com/2019/02/cove_workshop_report_final.pdf

Werner, C., Fischer, T. P., Aiuppa, A., Edmonds, M., Cardellini, C., Carn, S., et al. (2019). Carbon Dioxide Emissions from Subaerial Volcanic Regions: Two Decades in Review. In B. N. Orcutt, I. Daniel, & R. Dasgupta (Eds.), *Deep Carbon: Past to Present* (pp. 188–236). Cambridge: Cambridge University Press. Retrieved from https://www.cambridge.org/core/books/deep-carbon/carbon-dioxide-emissions-from-subaerial-volcanic-regions/F8B4EFAE0DAF5306A8D397C23BF3F0D7

Zhan, Z., Li, Z., Shen, Z., Yang, Y., Williams, E. F., Wang, X., et al. (2020, August). *A rapid response Distributed Acoustic Sensing (DAS) array after the 2019 Ridgecrest earthquakes*. Oral Presentation presented at the 2020 SCEC Annual Meeting. Retrieved from https://www.scec.org/publication/10455

XII. Acknowledgements

We thank all the participants of the various SIGs, virtual breakout sessions, and the mini workshop for their interest and input and regret that we have not been able to include everything that was suggested. We especially thank the individuals below for their contributions to the Rapid Response to Geohazards effort, which culminated in this white paper.
Funding for this project is provided by the NSF as an award to IRIS for the operations of the Seismological Facilities for the Advancement of Geoscience (SAGE – EAR-1851048)

Wes Thelen – Volcanic Breakout Group Chair
Susan Beck – Large Earthquakes Breakout Group Chair
Heather DeShon – Induced Seismicity Breakout Group Chair
Victor Tsai – Hydrologic/Cryologic Breakout Group Chair and Invited Speaker
Anna Kelbert – Geomagnetic Breakout Group Chair
Nathan Miller – Rapid OBS Breakout Group Chair
Ninfa Bennington – Rapid Response Workshop Invited Speaker
Jenny Nakai – Rapid Response Workshop Invited Speaker
Emily Wolin – Rapid Response Workshop Invited Speaker