Defining Research and Teaching Priorities that Could be Advanced Through a Near-Surface Geophysics Center

A Community Report Facilitated by the American Geophysical Union
Draft 2 August 2022

1) Executive Summary

The National Science Foundation provided support to the American Geophysical Union (AGU) to engage its relevant community and help clarify the need for a Near-Surface Geophysics (NSG) Center and identify how it could advance key science questions, provide benefits for society, and develop the geophysical workforce of the future. This effort was lead by a unique steering committee composed of 11 people from 11 institutions (including a federal agency and a national lab) and several AGU staff. Workshops were facilitated by Knowinnovation (a consulting firm specialized on accelerating scientific innovation). This report synthesizes the broad input from the community through a survey around these questions and a total of three workshops (between March-April 2022) designed via weekly meetings of the steering committee initiated in May 2021. The major conclusions are:

- The capability and importance of NSG is expanding rapidly, and NSG is providing key science and knowledge to many specific scientific challenges in diverse disciplines–from ecology and anthropology to hydrology, oceanography, cryosphere science, soil and critical zone science, and more.
- This has been thanks to diverse new instruments and approaches, expanded monitoring, improved resolution, interoperable data sets, and new computing power and approaches, among other developments.
- As a result, advancing NSG is critical to addressing many societal challenges at local to global scales. Human society depends on and interacts with the NSG environment in deep and diverse ways at all scales.
- Despite these developments, integration of NSG approaches and awareness of these across related disciplines are not nearly robust enough for these needs.

- Major challenges include providing equipment and training around its use, developing and deploying new equipment and sensors, developing interoperable data, and developing computation techniques.
- In particular, educating both current researchers and developing an NSG-enabled workforce is a major challenge.
- Integrating education with societal and scientific challenges provides a great opportunity and means to expand inclusivity and diversity in the Earth sciences and to address climate justice and equity challenges.
- Thus there was a strong consensus for support of an NSG Center designed to address these challenges and needs and to foster convergent science, provide broad and hands-on educational training, and engage communities and the public meaningfully.
- We were not charged with envisioning the specific model for a Center—and indeed emphasized that the term "Center" was generic and did not necessarily imply that these efforts were envisioned to be in one location--but note that NSF is supporting important complementary facilities include the new EarthScope Consortium combining IRIS and UNAVCO, NCALM, and CTEMPS.
- In sum, we strongly encourage the NSF to take the next step in considering the best implementation model for a NSG Center that addresses these needs, enables these opportunities, and leverages and complements existing efforts.

2) Introduction

Earth's near-surface environment extends from the ground to depths of several kilometers–including the region that is accessible by humans or directly affects and includes accessible resources, processes, and dynamics. A better understanding of Earth's near-surface environment is critical to many first-order research questions and also many major issues and challenges facing society in the 21st century. Research into the dynamics of surface water and groundwater, the behavior of the changing cryosphere, the retreat of fragile coastal habitats including many highly populated areas, the full depth and properties of the critical zone, managing water supplies and ensuring clean water, discovery and management of mineral resources, the dynamics of natural and intentional carbon storage, and assessing hazards from earthquakes to volcanoes to floods to landslides and sinkholes all depend on a deep understanding of Earth's near-surface. In turn, these topics are central to helping ensure sustainability and food, energy, and water for a growing population, mitigating and addressing climate change and natural hazards and their effects, storing captured carbon and accounting for it, improving health, and conservation of habitats critical for human and wildlife. Much as remote sensing methods have transformed our views of Earth's surface and the shifting patterns of its resources and features, commensurate advances in geophysical methods are needed to extend our view into the subsurface and the key elements that sustain and constrain life.

The understanding of Earth's shallow subsurface environment using a variety of techniques and across all scales is embodied within the discipline of Near-Surface Geophysics (NSG). NSG data, knowledge, and results need to be integrated with data and expertise from economics, social science, land use planning, and other disciplines to address a wide range of related societal challenges. Many advances in instrumentation, computational methods, and interdisciplinary approaches related to NSG have been developed or improved greatly over recent years. However, for the most part, these advances have not risen to fully meet the huge scientific and societal needs faced today. Recognizing these recent developments, the broad importance of NSG for science and society, and the lack of broader awareness and integration, the U.S. National Academy of Sciences (NAS) recommended in its report "*Earth in Time*" that the National Science Foundation (NSF) should develop an NSG Center for two specific reasons: 1) the fact that surveying of the near-surface has become an essential tool for many Earth science fields; and 2) the certainty that an NSG Center would enable novel observations and new insights for several science priority questions highlighted in the report (**Figure 1**). The report also recommended that NSF Earth's Science Directorate should encourage the scientific community to explore a Continental Critical Zone initiative to construct and deploy a major mapping campaign to characterize the subsurface critical zone over large areas. This initiative would complement and interact strongly with an NSG Center in many ways.

In light of these recommendations, NSF asked AGU to collect and organize community input and recommendations to help explore and clarify the needs and opportunities within NSG, including how a center might enable this important integration. Throughout this effort, the idea of a "Center" was kept as generic and undefined as possible to focus on the overall needs and opportunities; we use the term "Center" following the *Earth in Time* recommendation. This effort was led by a diverse steering committee spanning career stage, expertise in NSG and also related disciplines as well as in Earth science education, and representing government agencies and small to large institutions. These were:

Steering Committee
Sarah Kruse (co-lead), University of South Florida
Xavier Comas (co-lead), Florida Atlantic University
Kennedy Doro, University of Toledo
Tiffani Holmes, Fort Valley State University
Rosemary Knight, Stanford University
John McDaris, Carleton University
Burke Minsley, USGS and AGU NSG Section President
Isabel Morris, New Mexico Tech
Verónica Rodriguez Tribaldos, Lawrence Berkeley National Lab
Lee Slater, Rutgers University
Victor Tsai, Brown University
Chi Zhang, University of Vienna and AGU NSG Section President-elect

AGU Staff
Brooks Hanson
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Malachi Greaves

Community input started with a broad survey that asked about key research questions; needs, barriers, and opportunities to address these; and ways to improve education, safety, and inclusivity across NSG. A total of 769 researchers and educators responded, representing most of the allied disciplines studying Earth's near surface. An overview of the results from the survey was presented to the community in a Town Hall at the 2021 Fall Meeting of the AGU, and was followed by three workshops that discussed these topics in greater depth and provided the basis for the community recommendations below. **Figure 2** summarizes the main objective of this effort and its initiatives including specific outputs. This report provides an overview of this input and community recommendations around the importance of NSG, the critical need for increased attention and integration, and how a Center can play a critical role in addressing challenges. The appendix includes the full survey results and outputs from the workshops. Every effort was made to ensure that the report reflects broad community input: the underlying content of this report was generated through breakout group discussions in the three workshops. The Project Steering Committee's primary role was to organize discussion topics, ensure breadth of participant expertise, and synthesize common threads in discussion. The initial synthesis was conducted by AGU staff. The Steering Committee, led by

Sarah Kruse and Xavier Comas, and AGU staff leads are responsible for most of the editing and connective writing.

The major recommendation is that such an integrated effort, embodied in a "Center," is indeed essential to enable NSG to accelerate the science and societal responses to the needs of present and future times. This report focuses on elaborating examples of high-priority science that could be advanced through an NSG Center, envisioning a center's desired capabilities, and providing recommendations on how it may facilitate overcoming barriers in current science infrastructure while lowering impediments to and enabling recruitment and retention of students into geophysics. Although recommending a specific model for a Center is beyond the scope of this effort and report, the information in this report helps provide framing on how such a Center can be envisioned, developed, implemented, and supported. For that reason, we recommended that NSF follow these recommendation with a similar effort that emphasizes community engagement to best plan for a NSG Center.

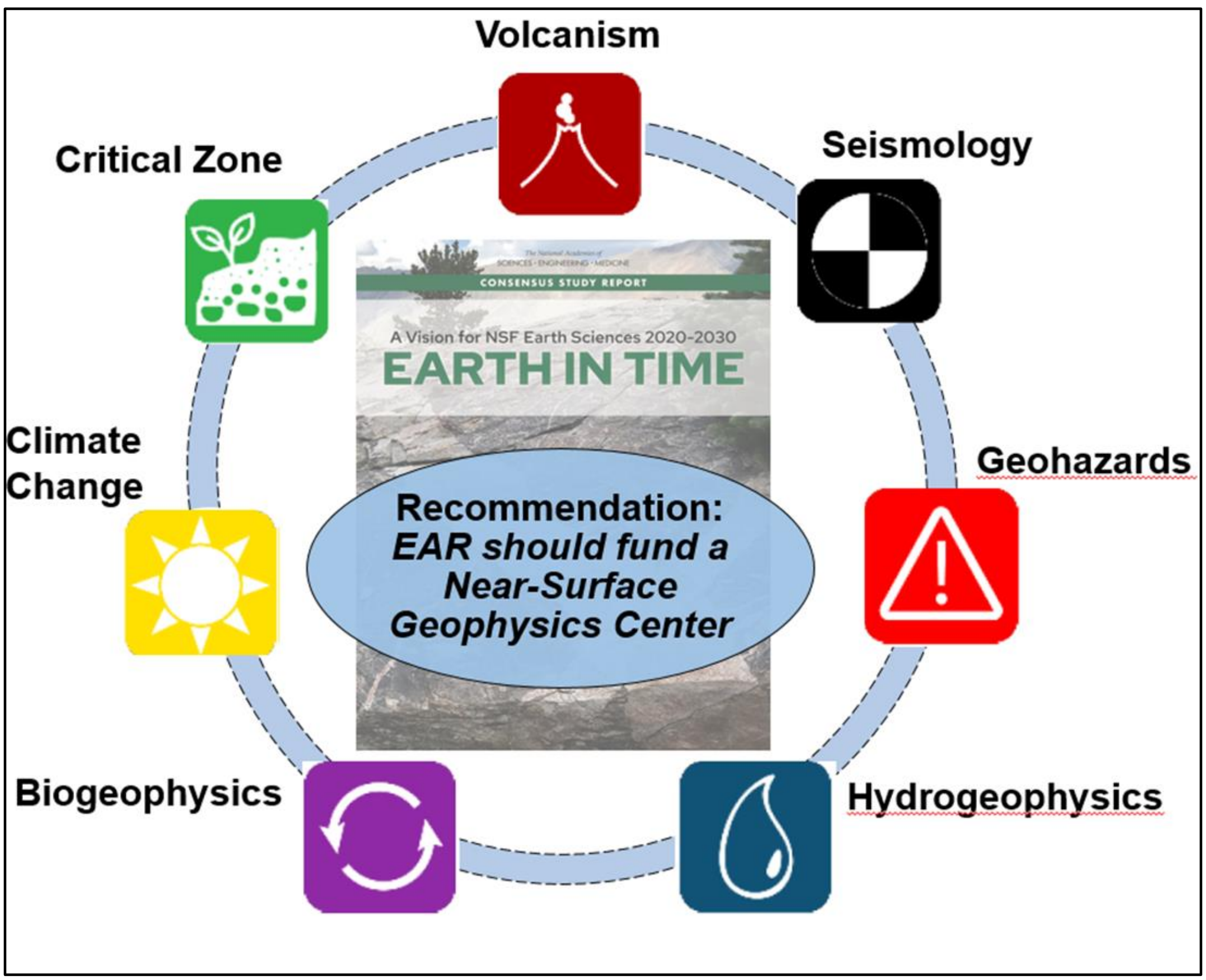

Figure 1: Conceptual diagram highlighting the recommendation found in the "Earth in Time" report for EAR to fund a Near-Surface Geophysics Center, and its direct relevance to seven science priority questions as highlighted in the report.

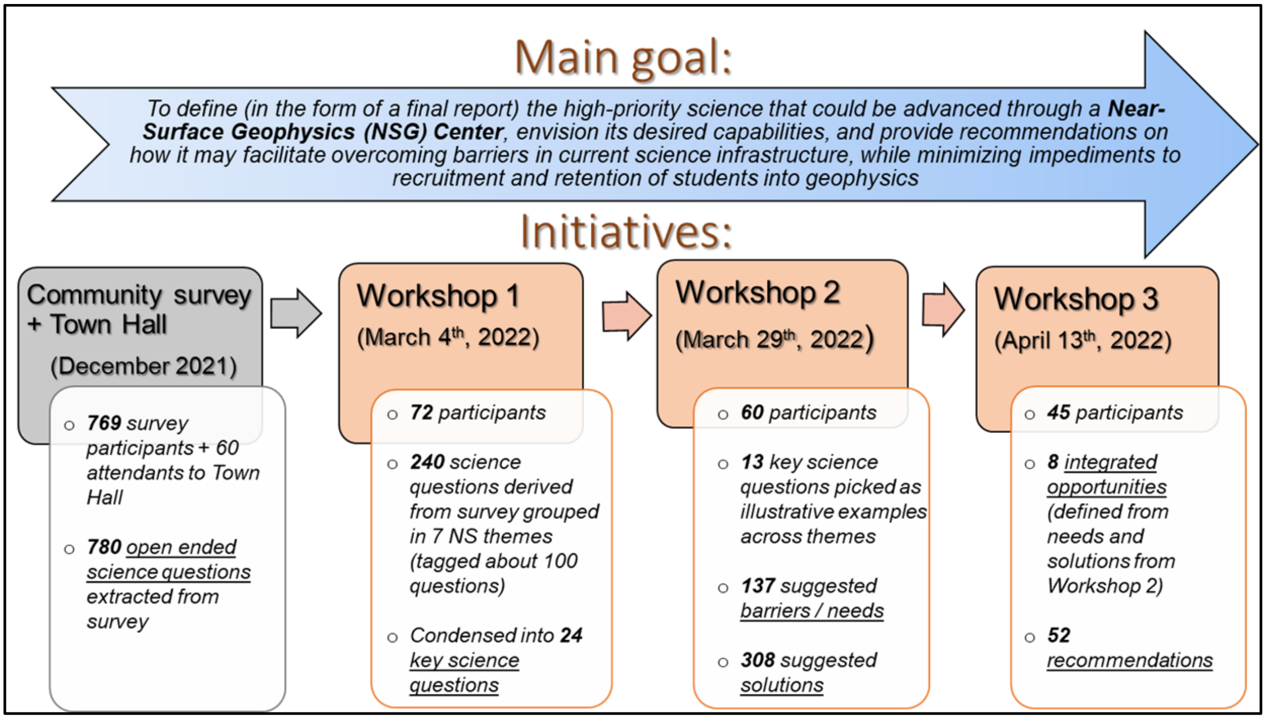

Figure 2: Main goal and initiatives (including participants and specific outputs) used to develop the recommendations in this report.

3) Previous and Current efforts Related to an NSG Center

Although our mandate was not to propose a specific model for an NSG Center (neither in terms of design or implementation), the landscape of other related complementary NSF funded centers has evolved during the time of the development of this work and report, and we feel that it is critical to consider these in the context of our recommendations. There are currently two NSF supported geophysics centers: IRIS/UNAVCO (EarthScope) and NCALM, and other related centers.

3a) IRIS/UNAVCO (EarthScope Consortium)

The Incorporated Research Institutions for Seismology (IRIS) and the University NAVSTAR Consortium (UNAVCO will merge into the "EarthScope Consortium" in December 2022. IRIS operates SAGE (Seismological Facilities for the Advancement of Geoscience) and UNAVCO operates GAGE (Geodetic Facility for the Advancement of Geoscience). IRIS has proposed NSG-related efforts and supports the NSG IGUaNA (Introductory Geophysics for Urban and Near-Surface Applications) modules. UNAVCO's GETSI (GEodesy Tools for Societal Issues) materials support teaching of methods often used alongside NSG. The EarthScope Consortium mission is "dedicated to transforming global geophysical research and education", with a vision for "an engaged society, resilient to geohazards, informed by geophysical discovery and global collaboration".

IRIS and UNAVCO provide instrument access, science and education and outreach support, global network operations, and data archiving, quality assessment, and management in their respective subdisciplines of seismology and geodesy, with cooperative arrangements and support with the USGS and other organizations. Funding comes principally but not exclusively from the NSF. Both are governed with strong community input.

3b) NCALM

Separately, the National Center for Airborne Laser Mapping (NCALM) is a stand-alone center that similarly emphasizes service to researchers, instrumentation advancement, software development, and training, for airborne lidar. NCALM does offer terrestrial lidar equipment support, but otherwise users don't have direct experience of aerial acquisitions (which now includes drone-based surveys). NCALM is based at the University of Houston and is operated in partnership with the University of California, Berkeley.

PI's obtain a specific cost of obtaining lidar surveys from NCALM, add that to their proposal to NSF, and if supported, the funds go to NCALM to provide the products requested. NCALM is not involved in funding decisions. NCALM has consistently relied on separate funds to do instrument upgrades. Only about one-half of the annual operating costs of NCALM comes from NSF, the rest comes from other requestors for lidar surveys (e.g. DOE, USFS and so on). In essence, this NSF support reduces the cost of lidar surveys, enables close interactions with PIs (if requested), and enables reaching the stated mission goals (cited above).

3c) Other efforts

In addition, there are several related NSF-funded efforts that would be considered in relationship to an NSG Center, including the former Critical Zone Observatories Research Program (2007-2020) and its continuation phase, the Critical Zone Collaborative Network (CZNet) (2020-2025). Other well established networks for ecological research include the Long Term Ecological Research (LTER) Network (1980-present) and the National Ecological Observatory Network (NEON) (2006-present), where the presence of NSG methods have increased in recent years, and the Center for Transformative Environmental Monitoring Programs (CTEMPS), which provides "field-deployable high-precision fiber optic temperature measurement systems, wireless self-organizing multi-parameter sensor stations, and Unmanned Aircraft Systems (UAS). User fees are very low, and experiment design, installation, and data analysis is supported by a staff of scientists."

Although out of scope for this work, leveraging these existing programs and their experience and complementary efforts could be very valuable, from a scientific community standpoint, but particularly to leverage scientific inputs and collaborative efforts within the NS community at large. The *Earth in Time* report also proposes that NSF considers expanding quantification of the critical zone by supporting a Continental Critical Zone Initiative that combines theory, modeling, and field knowledge and experience to design a program focused on major mapping campaigns to characterize the subsurface critical zone over large areas. Given the importance on field campaign design (both in terms of methodology and implementation over large areas), an NSG Center can play a central role in such a multi-disciplinary, multi-scale, and multi-method effort.

Indeed, an NSG Center as part of these efforts (whether integrated directly or indirectly) would in many ways provide missing capacity and complete scientific opportunities needed for addressing many of the challenges above. As this report emphasizes, one of the challenges across NSG is the need to integrate and coordinate efforts, and indeed approaches, measurements and data, together to solve major challenges and provide specific societal benefits. The merging of UNAVCO and IRIS help address this but only partly, and an NSG Center will need to work across this facility landscape and beyond. Greater coordination is essential.

4) The Current State and Future Potential of NSG

The importance and potential of NSG have grown significantly over the past decades. A history of innovation and methods development has resulted in a plethora of techniques now available for studying Earth's near surface over a range of scales and with accuracy not previously achievable (**Figure 3**). The resolution and availability of traditional ground-based NSG techniques such as gravity, seismic imaging, electrical and electromagnetic methods, magnetics, and nuclear magnetic resonance have increased to the point where they can be realistically combined together, and with other data, to provide new views of the near surface at nearly all useful scales, traditionally from plot to catchment scales and expanded to watershed and basin scales via airborne methods in recent years. These can be combined further with complementary remote sensing approaches that include a variety of near-continuous geodetic and satellite observations of Earth's surface and subsurface. These and a wide variety of in situ data sets are growing and starting also to provide longitudinal records of near-surface dynamics, including as part of several intensely studied areas including in other NSF-funded "observatories." A variety of now mature or maturing computational approaches, from machine learning, artificial intelligence, inversion approaches, and modeling, can help the integration, interpretation, and understanding of these data. When these resources can be brought together, the results can now provide planners and resource managers information at the scale and resolution to realistically guide critical society decisions. Such information and integration of NSG and researchers with community leaders will be essential going forward.

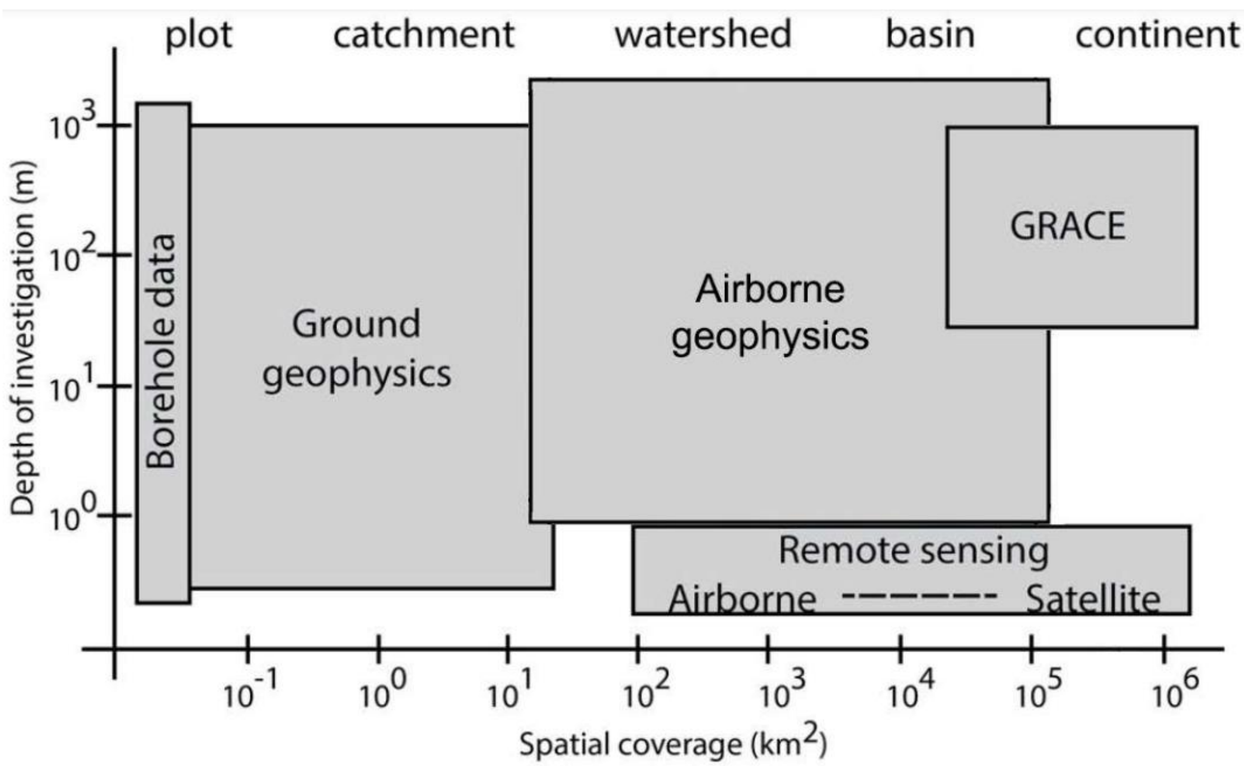

Figure 3: NS geophysical methods for characterization of subsurface properties at multiple scales (from plot to continental). Modified from Minsley *et al.*., 2021.

Realizing the great potential for NSG to help advance discovery-driven and solution-based science requires developing NSG as a truly cross-disciplinary and convergent science. For the most part, many of these approaches, techniques and data sets have been developed for specific disciplines or individual studies. As a consequence, awareness of these multiple approaches, even that they are possible, let alone how to best bring them together, is patchy. Many scientific studies are missing opportunities for geophysical integration that would accelerate advances in knowledge or understanding in other fields. This challenge, and the need for interdisciplinary awareness and connections, were raised repeatedly in the survey results and workshop discussions (see survey results in appendix).

Several studies over the last two decades have been able to pull knowledge and resources together to serve as examples of the potential for leveraging diverse NSG data and tools (e.g. Robinson *et al.*, 2008; van Dam, 2012; Parsekian *et al.*, 2015; Minsley *et al.*, 2021). However, they also highlight the need for a much more robust, inclusive, scalable, and deliberate process of directing this integration. In most cases researchers and research teams had to spend considerable time and energy overcoming disciplinary barriers and other challenges to achieve success. Many of these have been "one-off" advances that, because of barriers, have not been scalable or able to have broader impacts. In many instances larger opportunities for education and awareness of NSG and expanding diversity broadly were not realized, or in fact lost. Empowering and scaling NSG for the future thus requires including NSG in all levels of education, promoting NSG careers, and expanding inclusivity in NSG to foster diversity of the science workforce (e.g. Johnson and Okoro, 2016; McDaris et al., 2019). It also includes consistently connecting NSG consistently with society leaders.

Some examples of the types of successful integrations and that challenges that had to be overcome include:

4a) High resolution mapping of coastal zones and the seafloor near coasts with sonar, radar, and lidar provided key data to understand sediment dynamics, coastal erosion, effects of storms, and benthic habitats (e.g. Goff et al., 2015 and articles within; Wright *et al.*., 2018). This required obtaining small vessels, new technology, and having access to the coastal regions along with considerable data integration and modeling. Major challenges to realizing this effort included providing access to newest technology to smaller institutions, the expense of renting equipment; and accessibility of software to analyze 3D data.

4b) Discovery of firn aquifers and drainage networks under the ice in Greenland and Antarctica, providing critical information for predicting the stability of ice sheets. This was ultimately enabled by ice-penetrating radar (e.g., Forster *et al.*, 2013) but integrated complementary information on detecting and monitoring subglacial fluid pathways using seismic instrumentation (Montgomery *et al.* 2017) and Electrical Resistivity Tomography (ERT) of the subsurface of the ice sheets. GPS, radar, and seismic instrumentation also help measure motions of ice sheets and infer stick-slip motion at the bed of ice streams (e.g., Winberry *et al.*, 2011). Together these data fundamentally changed how we understand ice sheet motion to occur and the importance of sediment deformation and water pressure. This was in some ways easier to achieve in Antarctica where there was (and is) and well supported research infrastructure.

4c) Understanding and mapping water-rock interactions in the subsurface including mapping chemical weathering (Brantley and Lebedeva, 2011; St. Clair *et al.*, 2015; Holbrook *et al.*, 2019), subsurface water flow (Robinson *et al.*, 2008; Crook *et al.*, 2008; Binley *et al.*, 2015; Knight *et al.*, 2018), bedrock fractures (Day-Lewis *et al.*, 2017; Comas *et al.*, 2018; Chandra *et al.*, 2019); porosity (Bradford *et al.*, 2009; Mount *et al.*, 2014, Uhlemann *et al.*, 2022); and the extent of biological processes (Atekwana and Slater, 2009; Slater and Atekwana, 2013). This work has involved developing broad communication across communities (e.g. civil engineering, earth science, chemistry, physics, biology, etc.); and application of multiple NSG techniques including neutron probe, NMR, MRI, in combination with remote sensing tools to look at hydrologic distribution from depth to shallow, and over time (Robinson *et al.*, 2008; Parsekian *et al.*, 2015). Key challenges to overcome have included handling use restrictions, applying tools used at depth to the near surface environment (NMR) (Behroozmand *et al.*, 2015), using and interpreting seismic refraction (Miller *et al.*, 2010), extending numerical modeling and data assimilation to provide 2D to 3D to 4D results to infer temporal and spatial distributions of near surface critical zone architecture and dynamics (Li *et al.*, 2017; Hermans *et al.*, 2022). A challenge in extending these results further is the lack of field and observation data limitation at 1) local, regional, to continental spatial scales and 2) geologic to human timescales.

4d) Discovering, mapping, and characterizing sites and dynamics related to anthropogenic activity. Examples include finding ordnance (Bhuiyan and Nath, 2006; Davis and Nabighian, 2010; Wang *et al.*. 2022), waste sites (Benson and Mustoe, 1998; Taylor *et al.*, 2019), radioactive areas (Xie *et al.*., 2019), and other hazards (Parsons, 2021); finding archaeological sites (e.g. Aziz *et al.*., 2016; Conyers, 2016; Damiata *et al.*., 2017) including abandoned wells (Saribudak *et al.*., 2020); identifying salinization of land (Hendrix *et al.*, 1992; Farifteh *et al.*., 2006; Adam *et al.*., 2012; Wagner *et al.*., 2013); and induced seismicity (Schoenball and Ellsworth, 2017; Shah and Crain, 2018; Haaf and Schill, 2022). Many of these discoveries were enabled by airborne (magnetics, EM, radiometric, gravity, etc.) data in complement with ground- based information (e.g. Paasche and Eberle, 2009; Lawley *et al.*., 2021; Martelet *et al.*., 2021). Related, radiometric data have also been used to trace pathways of minerals in sediments to assess mineral resources (Baratoux *et al.*., 2016; Shah *et al.*., 2021). Key challenges included obtaining funding, managing the collection of large datasets and making them accessible (Fremand *et al.*., 2022, EMRI: https://ngmdb.usgs.gov/emri/#3/40/-96); developing methods, for example, around airborne gravity and unmanned aerial vehicles (UAVs) (Day *et al.*., 2019; Martelet *et al.*., 2021); and getting ground truth data such as hydrology, geochemistry, and mineralogy (Lawley *et al.*., 2021).

4e) Mapping regional-to-basin scale aquifer structure and groundwater salinity. This has been enabled thanks to airborne EM data integrated through tomography but also required merging borehole geophysical logs and other data to 'connect the dots' and link scales through time and space (e.g. Knight *et al.*., 2018; Minsley *et al.*., 2021). It required development of both instrumentation that can measure accurate signals (and overcome noise) related to aquifer structure and that was robust enough to be deployed from helicopters/airplanes, together with software to be able to process and interpret these large volumes of data (Foged *et al.*., 2014; Auken *et al.*., 2017; Marker *et al.*., 2017, National Academies, 2019, Ball *et al.*., 2020, Ley-Cooper *et al.*., 2020, Korus *et al.*., 2021).

Many of the barriers indicated in the survey had to be addressed in these examples, including building diverse teams, obtaining funding, integrating diverse data sets, and developing new equipment and models. In many cases the teams existed for the duration of a grant cycle, and sustaining such work was challenging and made leveraging the experiences of others difficult.

5) Selected Major Questions that Require Robust Near Surface Geophysics

The *Earth in Time* report highlighted several key science questions that should be a focus for NSF's Geoscience Directorates in the next decade (**Figure 1**). NSG is central to advancing many of these, and its remit is also relevant to other Directorates including Engineering, Education, and the new Technology effort. The survey and first workshop gathered and explored pressing major challenges and questions related to NSG—in all more than 100 major questions spanning all the disciplines that NSG covers were provided, most directly connected to and part of the major challenges in the Earth in Time report. These cover all parts of Earth's terrestrial near-surface environment and are of strong importance to society. The full list is in the appendix.

We highlighted 13 research questions that illustrate broadly how an integrated approach to NSG and with other disciplines can advance science (**Figure 4**). These questions also illustrate the range of contributions that NSG can bring to address important questions across disciplines and the significant impact this knowledge can have on addressing societal challenges. They also collectively illustrate several common major challenges and needs required to enable further progress.

5a. How will the acquisition of spatially rich datasets improve understanding of the vulnerability of coastal zones to salinization due to increased storminess and due to rising sea levels?

Modern coastal groundwater systems, from onshore to offshore, are critical resources for an area experiencing rapid population growth and increased vulnerability. Real-time monitoring is needed to understand the flow of groundwater and surface water and biological processes as coastlines are inundated with saltwater more frequently. Being able to measure more frequently and with high spatial resolution to capture subsurface heterogeneity as storm surge occurs will give an accurate picture of where the vulnerable zones are, and when current models prove inaccurate. Scales spanning from the shelf to rock porosity are important but challenging to integrate.

5b. How can NSG better characterize changing permafrost conditions and advance monitoring to limit impacts to critical infrastructure and vulnerable communities?

Earth's cold regions are experiencing rapid and widespread changes in climate leading to changing environmental conditions--both above and below ground--such as gradual and abrupt permafrost thaw, redistribution of water (some areas are getting wetter, others drier), and ecosystem transformation (forests to wetlands). Permafrost thaw triggers ground subsidence, which can cause significant infrastructural damage (also affecting energy and resources lifelines) to vulnerable Arctic communities and beyond. Additionally, carbon previously frozen in permafrost soils is released upon thaw, potentially contributing atmospheric greenhouse gas and propagating further thaw.

Near surface geophysical measurements offer an opportunity to image permafrost continuously and rapidly and at much less cost than direct borehole measurements, and in ways that are minimally invasive or non-invasive. NSG approaches can measure parameters (e.g, permittivity, conductivity) that are directly related to permafrost parameters of interest (e.g., water content, salinity, subsurface geometries).

The arctic is warming twice as fast as temperate latitudes and the impacts of change to feedbacks and equilibria in arctic systems remains largely unknown. Communities in arctic regions are at high risk for disruption including damage to transportation and energy infrastructure, loss of habitable land, and reduced access to water sources.

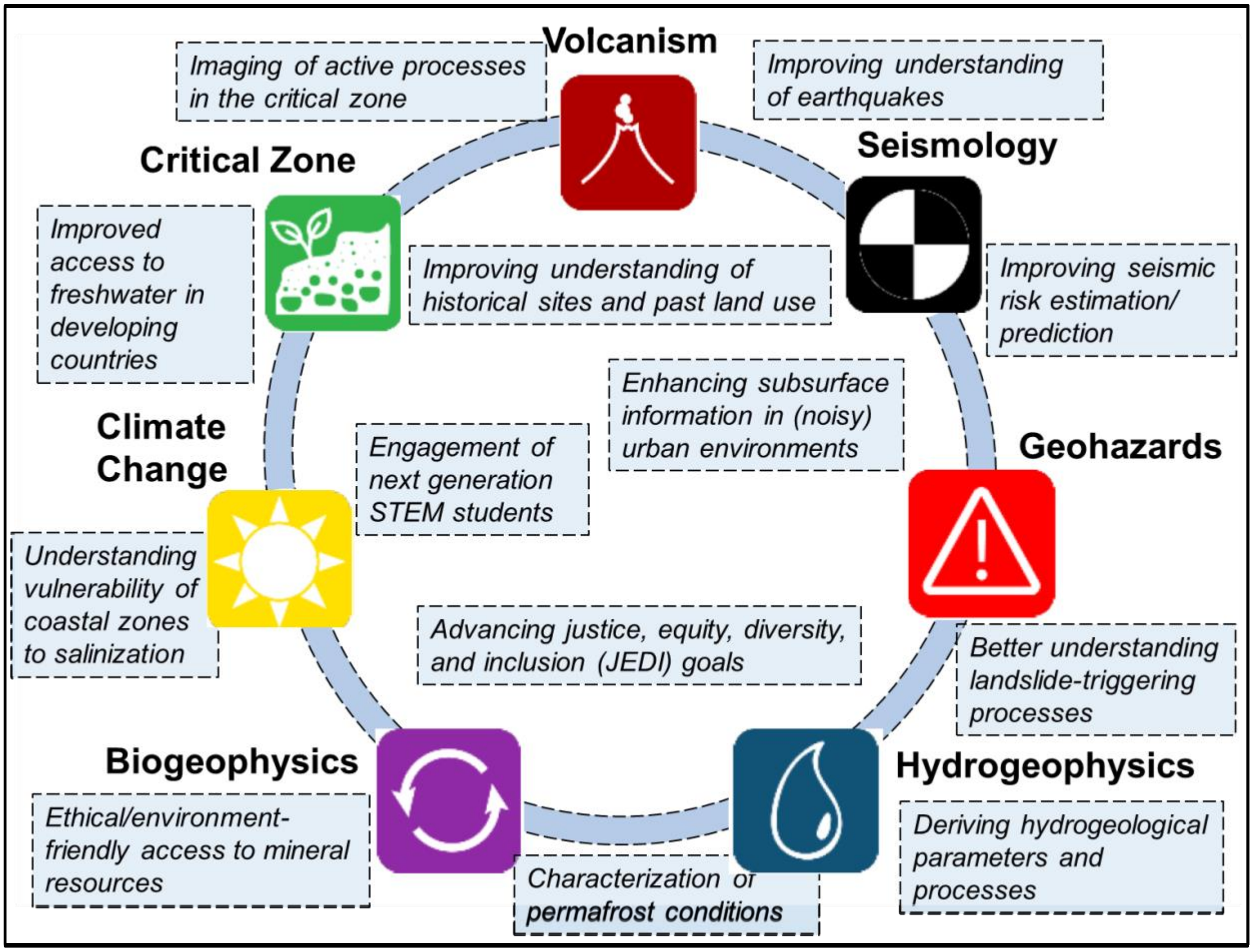

Figure 4: Examples of major NS questions in the context of the conceptual diagram in Figure 1 showing the broad range of topics that NSG can bring to address important questions across disciplines and its relevance to societal issues and engagement of students.

5c. How can NSG engage the next generation of students in STEM by showing them the relevance of geoscience to their lives, communities, and environments, particularly in communities affected by climate change?

NSG can be useful in raising awareness among students about links between their lives, communities, and the environment. Several prospective areas include climate change broadly, as well as sea level rise, groundwater depletion, rising fire hazards, salt water intrusion, changing weather patterns, and the effect of warming in cities. Many of these topics have an environmental or climate justice component, for example, around expanding disparities between rich and poor communities related to power-consumption or in differential impacts of these events.

Incorporating NSG science and resources would help in both sides of this: helping to improve knowledge about the impacts of climate change and to communicate those impacts on communities to all levels of STEM students from K-12 to higher. By linking local activities to global outcomes, students can see that by engaging in the geosciences, they can affect/understand future environments.

5d. How can NSG advance real-time imaging of active processes in the critical zone (such as salt-water intrusion or water withdrawal) over relevant scales?

NSG has the potential to image active processes but we lack the technology and community infrastructure to acquire/utilize the best data and methods to inform processes in different critical zone environments. We could (with funding available) develop sensors and methods that can provide critical understanding across a wide range of temporal and spatial scales (sampling rates, extent, duration, etc); community discussions are needed to decide on the appropriate scales. Making these observations at low latency offers the opportunity to respond quickly to signals and tailor sensor deployment to enable further discovery.

5e. How can NSG reveal and monitor processes in the critical zone to advance justice, equity, diversity, and inclusion (JEDI) goals?

Critical zone science is relevant to every terrestrial environment on Earth, and all layers of society and cultural natural resources. Impacts are tangible in daily lives (i.e. contamination, biogeochemical reactions, nutrient runoff etc). Because personal participation in the science process supports retention, hands-on geophysical measurements are an opportunity for increasing excitement, engagement, and training for people/public/students while simultaneously monitoring important CZ processes relevant and important to specific areas that may lack the resources for these measurements. One specific challenge is that important biogeochemical cycles need to be monitored including to understand differential impacts on marginalized communities.

To advance justice equity diversity and inclusion (JEDI) goals, it is critical to promote the funding, collection, standardization and archiving of global large scale and continuous data that can be made available through database repositories to communities. One possible mechanism whereby the NSG community can support some of this effort, and provide useful examples, could be through a dedicated field-research team that collects a standardized set of geophysical data and shows how these can be made interoperable. Expeditions should be guided by a diverse community. The data they generate will add value and develop interest in training in order to sustain long-term (i.e. generational) datasets, similar to the Long Term Ecological Research (LTER) sites. Expanding NSG efforts globally will play a key role for advancing JEDI goals by promoting international collaboration and showcasing NSG applications to the non-NSG community, with emphasis on local and indigenous communities, and particularly under-served communities that may have limited access and/or resources. The NSG community can also build on the examples of "Geoscientists Without Borders" and "AGU's Thriving Earth Exchange".

5f. How can we improve NSG surveys, data processing, and data analysis to obtain reliable and high-quality subsurface information in (noisy) urban environments?

Most land-based geophysical methods are designed for and tested in natural environments and may not be appropriate in other settings. However, hazard reduction and mitigation and climate resilience, are particularly needed in growing cities, especially along coastal regions. Urban environments are intrinsically noisy, with factors ranging from wind effects through buildings, construction, traffic, to their infrastructure and lifelines (sewage, water supply, etc.). This 'baseline' noise, and the lack of appropriate calibration (possibly beyond instrumentation's sensitivity) can be challenging; on the other hand, understanding noise structure and patterns or leveraging it may provide useful insight. Collectively, these data would help to understand the geophysical footprint of cities, and help planners and policy makers to improve resilience and sustainability. Besides, urban noise may provide an opportunity for partially "free of charge" data if, for instance, acquired in cooperation with urban maintenance works.

Geophysics in urban environments can be greatly enhanced by adding new technologies and analysis methods including passive high resolution data (DAS and electrical methods) over long enough periods to recognize patterns and identify noise sources. These studies are still in nascent stages—community facilities, expertise, and software tools are required to optimally acquire and interpret these data. Ancillary data (cameras, metadata) may help with noise identification. New filtering techniques and machine learning can assist with separating signal from noise.

5g. How can we use NSG to identify, quantify, and access critical mineral resources ethically and with minimal environmental impact?

Throughout the 21st century, energy and other technologies are going to increasingly depend on critical mineral resources. Consequently, enhanced knowledge of the availability such resources is essential. Detailed information on the geometry of ores will help economic geologists, land use planners, and companies minimize environmental and ethical impacts of mining. This can include avoiding drilling in areas where critical minerals are unlikely to occur (or be economically attainable), preparing analyses of environmental conditions and suitability for development, and minimizing harm from mine waste.

NSG holds potential for assessing both negative (environmental hazard, groundwater, stability changes) and positive impacts (resource extraction, economic turnout) of mine waste. There is value in aggregating spatial data and metadata on topics such as acid mine drainage, underground heating, heavy metal pollution, and other challenges. Industry is less likely than government agencies to tackle questions related to waste, remediation, and environmental impacts, including at several superfund sites involving abandoned mines and tailings. Standards for working with proprietary data are needed and will be helpful in dealing with industry and risk assessment that could have impacts on the community welfare.

5h. How can NSG contribute to understanding historical sites and past land use that will enhance the response to societal, environmental, and climate justice issues for today and tomorrow?

NSG techniques are increasingly important in identifying and further describing historical and archeological sites and in managing access to them by researchers and the public. There is an increased and rapidly evolving need to consider the societal, environmental, and climate justice issues of these findings, including the living lessons they cast concerning the persistence and resilience of human siting and communities. For example, urban developments may expose or encroach upon important cultural sites. These sites must then be evaluated, assessed, and incorporated into the relevant cultural resource management frameworks. In response to re-evaluation, growing understanding, and awareness about the nature or extent of different sites, NSG can contribute to updating the records and management of these sites by providing the essential spatial and temporal information to cultural resource and land managers and to stakeholders.

5i. How can characterizing the near-surface environment improve our resolution and understanding of earthquakes?

Exploitation of the NSG capabilities is critical to mitigating seismic hazard and for contributing to reducing seismic risk. By characterizing the near subsurface, NSG can locate faults that might pose seismic hazards, understand pathways of fluids that can influence seismicity, help to characterize ground amplifications that may locally affect intensity of shaking, predict and estimate ground motion and severity of shaking, and improve the interpretation of deeper geophysical measurements by accounting for the near-surface environment. Paleoseismic and other data can help infer earthquake recurrence times; geodetic and SAR data can monitor ongoing ground deformation related to earthquakes. NSG data can provide high-resolution mapping of surface rupture and deformation (to fully understand the rupture process) and illuminate vulnerabilities inherent in the built environment (to concur in enhanced seismic risk modeling). Integration of multiple imaging methods can reduce ambiguities in interpretation of high-resolution data.

5j. How can NSG, combined with seismic and ground motion observations and modeling, improve seismic risk estimation/prediction?

The near-surface environment is highly heterogeneous and we do not currently have data to capture the short spatial scales of the geotechnical layer and study how the built-environment interacts with ground motions. Additionally, we currently do not account for the shallow hydrology in the time-dependence of seismic risk prediction or their variations. We use simulations to overcome the lack of data and combine them with sparse observations to make ground motion predictions at higher resolution. Higher NSG data density will permit better assessment of the simulations and processes in the built environment.

5k. How can we integrate NSG with other methods to better understand landslide-triggering processes at high spatial and temporal resolution?

Due to their frequent spatial and time patterns of occurrence, geohazards and landslides in particular have tangible, often recurring impact on communities. They have the potential to cause loss of life or isolate communities by destroying critical infrastructure (from roads to lifelines). NSG can close the resolution gap between currently existing global and site-specific methods; however, key data, including in situ monitoring, is largely lacking. By linking surface deformation obtained from global measurements (GPS, InSAR) with subsurface properties and processes, we can understand the triggering processes (at the intersection between the hydrosphere and the subsurface conditions), to possibly upscale the criteria and predict where and when landslides are likely to occur. Currently, there is decentralization of NSG in various groups leading to many distinct studies that are difficult to exploit on a global scale.

5l. How can NSG help improve knowledge of and access to freshwater in developing countries?

Freshwater (both surface and groundwater) is a critical resource, and there is a profound lack of it in certain areas around the globe. Equitable access to freshwater is a key UN development goal to maintain healthy populations, agriculture, and industrial activities. This is complicated by climate change, wasteful use, relic and current pollution. Lack of clean or available water risks can lead to health impacts and crop failures and trigger water conflicts and/or mass migration.

Many developing countries don't have ready access to historical or current data and/or lack coverage. Furthermore, they often don't have the technical capacity or knowledge to find and make use of data/information where it is needed. We need solutions that can be deployed at a local scale within the limits of funding and technical capabilities available that also build local capacity.

NSG can provide insight into where freshwater used to be and is currently as well as helping to predict future availability. Specifically, remote sensing combined with detailed resource measurement and data on usage, quality, storage, precipitation, runoff, are needed to be actionable by communities. Remote sensing ranges from satellite-scale (e.g. LIDAR) to airborne scale (e.g. AEM) to ground-scale (e.g. GPR) to point-scale (e.g. distributed temp sensors). NSG is an attractive option for developing countries as it can rapidly and efficiently map resources across broad spatiotemporal scales within the funding constraints of the communities.

5m. How can NSG data be used to derive hydrogeological parameters (such as porosity and permeability) and groundwater flow processes to solve hydrogeologic and societal problems?

Subsurface hydrogeologic properties and processes are largely invisible, but understanding groundwater flow and storage is essential for both basic hydrogeology questions and also for many societal issues around water availability and quality—much water pollution is in or moves through the subsurface. Predicting storage and flow is especially critical in the face of climate change. Subsurface flow is also important in triggering earthquakes and landslides. Direct information on subsurface hydrology has been limited to mostly well data and tracer studies. A growing number of geophysics techniques are providing increasingly detailed and complementary three-dimensional views of hydrological systems, and repeated measurements reveal the dynamics of these systems, thus also allowing inferences of basic hydrologic processes and parameters. Together, this information can address questions such as: How fast can or will seawater intrusion occur; how much recharge is occurring in key groundwater resources and where; how are contaminants moving and how can pollutants best be removed or contained; how does groundwater link to surface water baseflow; and many others, including related to any future subsurface carbon storage.

6) Major barriers and bottlenecks and gaps in achieving this future that involve NSG

The examples above clearly reveal that there are many common major barriers to enabling NSG widely and effectively. These same barriers and needs were also expressed in the survey responses and are illustrated in past examples of success. Addressing these needs collectively can have a huge cumulative impact, versus continuing to tackle them separately in each project and for each challenge. Many are also interconnected (**Figure 5**). These main barriers and needs, including specific challenges are:

6a. Connecting diverse research communities including process modelers, geophysicists, geochemists, and data scientists

Science challenges that benefit from NSG are inherently interdisciplinary. They require integrating and engaging disparate groups deeply around a science theme or question, and developing and supporting research teams. This is currently a large challenge, in part because other barriers limit the deeper knowledge and awareness of the state of the art in NSG. Significant advances hinge on integrating modelers and data scientists within projects. Similarly, there exists a common need for collaboration with other disciplines to improve interpretations of geophysical data going forward, including in the social sciences. Thus there are needs for both broad awareness that can lead to engagement and supporting work, and also enabling deep collaborations within research teams. Some specific needs are:

- Developing interdisciplinary workshops and conferences aimed at specific challenges
- Enabling cross-disciplinary training, with funding and logistics support (see Education and Training Challenge below)
- Providing access to and education about tools that cross disciplinary boundaries
- Leveraging sites and case-studies that are already highly instrumented to conduct multi-method, multi-scale geophysical deployments, so as to complement point measurements for cross-disciplinary understanding, also enabling AI/ML tools.
- Developing a data infrastructure with data standards that enables modelers, data scientists and geophysicists to easily transfer their data.
- Funding that requires collaboration between different disciplines and near-surface geophysicists
- Connecting method experts to problem/place experts (leveraging communities); an NSG center could serve as a clearinghouse to connect industry and academic experts to nearby place-based challenges
- Bringing together geophysicists/practitioners from different disciplines in land use/heritage
- Bringing together geophysicists with electrical, mechanical, and software engineers
- Engaging relevant professional societies (which are largely disciplinary) to work together to support convergent science including around NSG.

6b. Expertly managed/facilitated deployment of geophysical instruments for research and education

All of the challenges described in section 5 require integrating multiple techniques to reveal the hidden world beneath our feet. There is a great need for interdisciplinary access to a wide range of geophysical instrumentation, software, archived data and the ability to curate new data, dedicated experts, and educational tools and training to make the most of the data and equipment. Specific needs include:

- Providing and maintaining a broad-based instrument pool to support the geophysics and allied communities
- Opening access to existing equipment that is unused or underused that could be repurposed or rented/shared in creative ways (e.g. Salman *et al.*., 2022)
- Establishing policies for equipment usage to ensure fair access and self-consistent and calibrated results and data
- Training on instrument usage and best practices
- Supporting field usage, ranging from zero support (other than shipment) to full experiment design and deployment
- Enabling community science through co-design and execution
- Designing monitoring campaigns, including linking sensor, survey and interpretation design,. For example, linking hydraulic properties to survey design and interpretation to site-specific goals, with an emphasis on the scaling of hydraulic properties and flow.
- Establish new or provide access to existing field test-sites instrumented with a variety of geophysical and geodetic instrumentation, so investigators can test different approaches and derive relationships between different types of datasets.
- Considering existing models for NSF-supported research for high-cost surveys, such as airborne EM (AEM). the economic advantages of purchasing vs renting equipment. For example, it may make more sense to rent airborne EM or to purchase other items locally

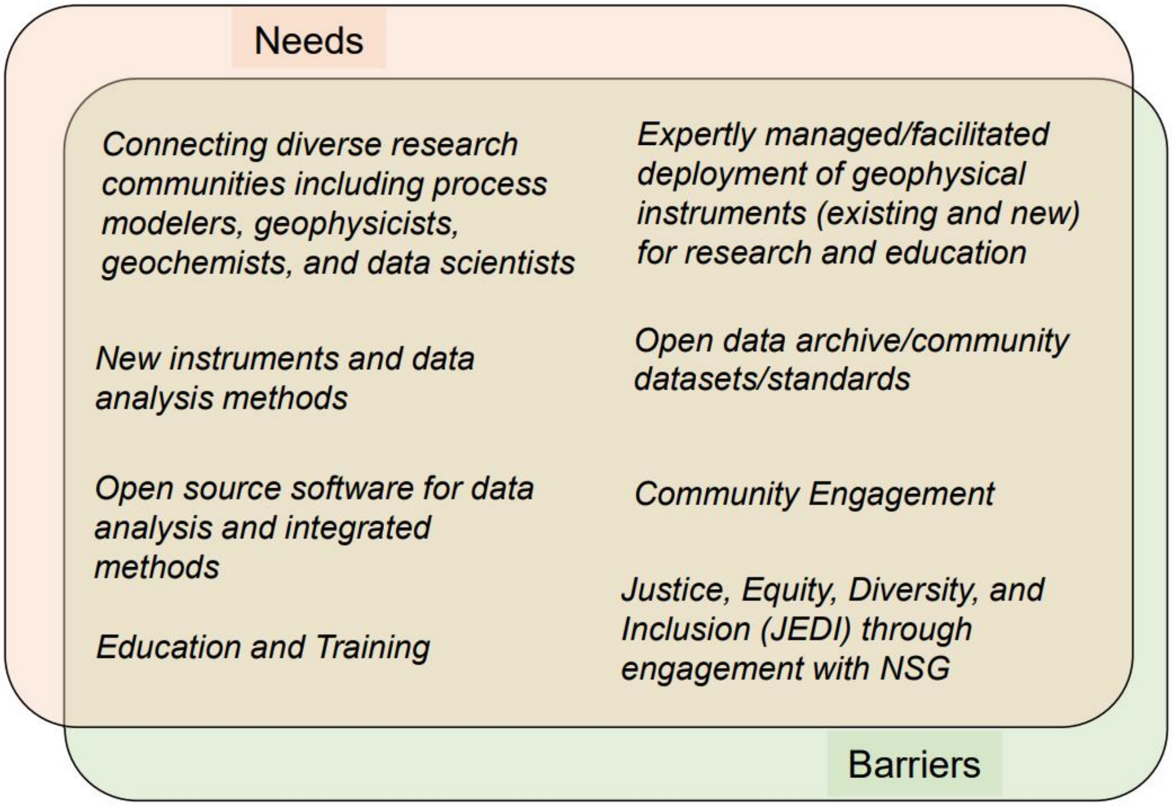

Figure 5: Overlap between barriers and needs as identified during the workshops and survey to enabling NSG widely and effectively.

6c. Education and Training

The diversity of methods, tools, and applications of geophysics support many societal needs. However, this diversity itself and the lack of an umbrella organization or organizing resources means that geophysics expertise at many institutions is quite limited. There is a clearly expressed need for centralized educational support that would enable diverse communities and user groups to participate in geophysics at an equitable level. This gap could be efficiently addressed by providing strong centralized support for educational infrastructure, pedagogies, and expertise, combined with regional-scale structures that facilitate collaborative networks to incorporate local problems and knowledge.

In addition, related training in specific approaches and integrating data and with modeling is needed. Beyond training in state-of-the-art science practice, training opportunities should include how to develop collaborative and interdisciplinary teams in local settings and best practices in community science. Overall there is great need to increase and improve both the NSG workforce and NSG knowledge in practitioners of benefitting disciplines; addressing this requires both broad and deep education.

Education generally

Some ideas to address this need include:

- Sustained programs in pre-K through 12 curricula and broader outreach activities to expand awareness of near-surface features and issues, near-surface imaging, and NSG careers
- Videos highlighting the usefulness of NSG in solving real-world problems, day in the field using NSG equipment, careers in NSG, etc.
- Education-focused workshops on NSG for 'past/present land-use' at (inter)national conferences (e.g, AGU, EGU, ...)
- Educational grant opportunities for students, teachers, and educational researchers
- Funding for K-12 teachers to attend training opportunities and field work opportunities
- Funding for higher ed faculty to attend training opportunities and field work opportunities
- Funding/collaboration with NAGT/SERC to provide funding for alternative pathways for students to enter NSG and the earth sciences
- Travel grants for students/K-12 teachers/faculty with need to present at conferences
- Sessions focused on best practices in teaching NSG
- Collaboration with SERC on the development of more NSG focused educational materials, such as modules similar to the IGUaNA project as well as those that are more general and can be used in K-12 and lower division classrooms.

Training

Training is needed with a focus on using NSG instruments and data, enabling NGS research, and other professional and career development related to NSG. Some specific ideas include:

- Consolidation, organization, and new training for equipment and software in various ways (in-person, virtual, self-paced YouTube videos, and courses/modules).

Training designed for researchers and others for enabling broader impacts and community science should include the following:

- Enabling collaboration, networking, cross-cutting training: education/training for different or specific audiences.
- Engaging local community members in this network development, so that researchers have awareness of local problems, cultures, customs and challenges and actual needs of communities
- More direct engagement with heritage stakeholders and associations (e.g., SAA, National Park Service, …) to increase awareness/utility of geophysics as a means for non-invasive investigation of sensitive sites.
- Involving existing stakeholders, such as local communities, NGOs and companies working in developing countries in education.
- Coordinating multiple communities, e.g. multiple geoscience societies and centers, volcano monitoring groups, landslide monitoring groups, earthquake monitoring groups, groundwater monitoring groups, and more. Mechanisms for coordination include web-based platforms, workshops tied to national meetings (or independent), and very targeted listservs and co-sponsored and developed workshops and meetings. Engaging and providing pathways for students and early-career input in these organizations is critical.
- Seed funding for researchers to include opportunities for students to leverage research projects at universities, research centers, federal agencies (e.g. USGS), National Laboratories with communities. To promote cross-disciplinary collaboration and community engagement, we might create a research network which could include: working groups that meet regularly to discuss common needs, workshops, virtual courses/training series, etc.
- A platform for developing community-based processing and data analysis approaches for data integration and incorporation to ground-motion forecasting and simulations.
- Recognition that equipment or technique training must be accessible, inclusive, safe, and relevant by design

6d. Justice, Equity, Diversity, and Inclusion (JEDI) in NSG

Bringing a variety of voices into conversation brings a diversity of ideas to bear on many different issues and helps foster both the future NSG workforce and applications to diverse communities. NSG has the tools and approaches to address problems faced by many marginalized communities, including key challenges above and around sustainability, land and water use, mitigation of hazards, and developing resilience to climate change. For the most part, these needs are unmet and are not a sufficient focus. They are closely tied to many of the education and community building barriers and needs above. Specific challenges include:

- Engaging, educating, and empowering stakeholders in academia, government and industry to act to increase equity and diversity and remove barriers.
- Leverage partnerships with industry and agencies.
- Establish networks for mentorships and training to increase diversity in NSG.
- Develop a framework for addressing critical research questions through the engagement of stakeholders, community, researchers, etc., emphasizing relevance.
- Promoting JEDI for new innovation such as software, computation, and modeling and ensuring that there are not unintended harmful consequences.
- Democratize access to data and sensors.
- Promoting international collaboration and showcasing NSG applications to the non-NSG community, with emphasis on local and indigenous communities, and particularly under-served communities that may have limited access and/or resources.
- Enable access to equipment for low or no cost to 2-year colleges (2YCs), predominantly undergraduate institutions (PUIs), minority serving institutions (MSIs), etc. via rental or loan programs
- Access to course modules that highlight NSG and their applicability to regional and local issues (place-based learning for rural and urban environments)
- Internship programs, networking opportunities, and job placement for students with private companies/government/etc.
- Bridging the cultural gap (i.e. language, etc) between scientists and the broad local communities to translate scientific knowledge and solutions into action. (For example, changing permafrost.)
- There is no common path for young students to be exposed to the value of NSG in addressing relevant and meaningful societal issues.

6e. New instruments and data analysis methods

Most of the major challenges above and across NSG will require development and deployment of new instruments and methods. In particular, sensors and instruments are needed that can monitor key processes across NSG, and new computational and visualization approaches are needed that integrate geophysical data with geochemical, hydrological and environmental data. This will allow us to generate unique multi-scale information that is not obtainable with available technologies and provide hitherto unrealized opportunities for monitoring a wide range of subsurface processes over process-relevant scales. Key challenges are:

- Balancing operational deployment to enable discovery science and development of new instrument/software technologies needed to answer remaining science gaps
- Clearly defining what most needs to be measured and at what spatial and temporal scales. There is a glaring need for the development of new technology, but a funding gap currently exists for both an organizational structure to give weight to recommendations, and for technology development itself.

- Defining functional requirements of instruments in terms of performance, cost/unit and minimum volume needed.
- Developing and distributing cheap geophysical survey instrumentation, capitalizing on open-source and maker communities to aid in development, both for researcher and “citizen scientists”
- Overcoming that lack of instrumentation that can be deployed in remote and urban settings that currently limits the observational network.
- Enabling standards, QC, training, for the data consumers from various fields.
- Providing and maintaining instrumentation for long-term observations – development of robust enclosures and communication modes for NSG instruments lags behind geodetic and seismic monitoring methods.
- Developing resilient remote observatories, which requires linking mechanical/electrical engineers/etc. to scientists

6f. Open data archive/community datasets/standards

Nearly all of the challenges in NSG require interoperable data, supported by the FAIR guidelines for findability, accessibility, interoperability, and reuse. Indeed, enabling the field requires interdisciplinary approaches combining diverse data sets. For the most part, and for most data and data types, this goal is not realized. While there are some well established repositories, notably for seismic and geodetic data, the data infrastructure needed to enable widespread FAIR data is not supported or funded. In addition, standards and leading practices are not well developed or shared across all of the NSG data types and instruments (e.g. Salman *et al.*., 2022).

The imperative of FAIR data across the Earth and space sciences has been emphasized in two other recent reports to the NSF (Hanson *et al.*, 2022a; Hanson *et al.*, 2022b) and in several NAS guidance reports (e.g., *Open Science by Design*, 2019). Several specific ideas are covered in these, as well. Key challenges include:

- Standardizing user education, training, and outreach of leading practices across the community, so that data and open science are thought of early in the research life cycle. Use of diverse datasets will require user education/training in order to be successful.
- Developing a metarepository, common archive, or an interactive geographic tool to search and discover relevant datasets. NSG questions increasingly require combining diverse data sets and their discoverability and quality are paramount.
- NSG needs leading practices around data led by communities for each type of data but built around a common template(s) for interdisciplinary communication. (Best practices and standards for data archiving and sharing)
- Incentivizing best practices in grants (elevating the data management plan).
- Breaking down barriers between subdisciplines by pushing for common data formats and/or facilitating conversions between formats to enable multidisciplinary analyses
- Open data in an accessible and transferable format can improve stakeholder engagement and JEDI by giving the public and scientists (such as young students) the opportunity to work with data and get involved.
- Diverse repositories that can collect and curate data to encourage submissions from a variety of researchers–not just those funded by NSF.
- Access to proprietary data- for example, related to mining and resource exploration.

6g. Open source software for data analysis and integrated methods

Related to the need for diverse data sets is the need for closely integrated computational approaches including modeling and approaches for data analysis, integration, and visualization. Increasingly these are being combined in research notebooks. We recommend open-source platforms (github, Jupyter notebooks) for all research and teaching software development and open sharing of software following leading practices (with citation, for example). Synthesis, integration, and comparison of existing software are needed. There are both gaps and overlaps in useful software development. Thoughtful assessment and filling of gaps would make all related science studies more efficient. Gaps are especially pronounced in time-lapse analysis, multi-method interpretation and inversion, and simple software for teaching and training. Some specific needs include:

- Software for noise characterization in urban environments
- Software for joint inversion and interpretation of multiple methods that are open source and easy to use
- Visualizations of measurements of salinity (and other) distributions through time and space in coastal zones combined with point verification. Focus on translating results for public ingestion.
- For a nationwide program of site characterization with JEDI education and environmental justice goals, software would be needed both to examine data at a basic level for local learning and to upload data to a comprehensive database
- Software for performing simulations at high spatial and temporal resolution
- software that is accessible to scientists as well as some levels to K-12 to get them into science and analyses early
- Need to review other models for open-source software development and community sharing
- Funds for software development
- Software for utilizing teaching modules and for remote field work teaching
- Web-based software for teaching that doesn't require specific computer/OS/installation to work
- Fraining in open source software best practices
- Improving frameworks for NSG data for land use by developing geophysical data processing/integration protocols

6h. Community Engagement

Nearly all of these NSG challenges are directly related to large societal challenges related to resilience against hazards and climate change, managing water, food, and energy; improving health; and supporting sustainability. Engagement with communities at all levels is essential and has been broadly neglected. New efforts are starting and being developed in societies and several NGO's but they are not yet well connected with broad disciplines like NSG. Such engagement. Because NSG measurements are made locally, any comprehensive NSG efforts should include community engagement issues from the start. This ensures that NSG efforts will critically advance JEDI goals as well and engender public trust in and understanding of science.

Here there are needs to:

- Help researchers across disciplines engage with community and local and regional government leaders
- Develop a framework and infrastructure involving various methods (and coupling of methods and models) for answering specific question and community needs.
- Develop and support regular programs for co-creation of science (community science) locally, regionally, nationally, and internationally.
- Collaborate with state and national agricultural extension services to help them show how broadly (and possibly gravely) communities will be impacted by processes occurring in the CZ, and to help build resilience and mitigation programs.
- Strengthen coordination between government, industry, and local community stakeholders to find solutions where responsible development can be achieved, with support from local communities.

- Grow local knowledge and capacity. Successful grants would include community engagement.

7) Recommendations

The analysis above shows that fundamental questions in NSG related to the larger challenges as described in the *Earth in Time* report share numerous common barriers or needs. For example, they require the formation of interdisciplinary teams, a robust FAIR data infrastructure, and open software. They also require awareness of, and education and training on, approaches, techniques, data sources, and use of software. Identification of priority applications and impact require engaging with communities, especially disadvantaged ones. Collectively, these needs require a broad education effort.

These needs demand new ways of approaching NSG as a bridging discipline that enables discovery science in the 21st Century and then effectively engages society and communities using that science. Addressing each of these needs separately for each challenge is highly inefficient and in the longer term will diverge rather than converge to the needed solutions, for example, around truly integrated data. It will slow progress on broad awareness of approaches and on needed education. Given that many of the needs overlap, as do many of the types of approaches, models, and data needed to address the range of NSG questions, it seems more efficient to have an integrative effort that leverages expertise, training, access, and development of NSG capacity broadly in order to maximize its impact.

The detailed work presented in this report on a high level thus strongly reinforces the recommendation in the *Earth in Time* report that NSF should fund an NSG Center. The additional recommendation in *Earth in Time* that NSF should encourage the community to explore a Continental Critical Zone also follows many of the points stressed in this report, particularly by further illustrating the type of community-scale integration that is needed in order to promote “a systematic and focused effort to generate maps of surface properties over large areas”. As suggested in the *Earth in Time* report, such an ambitious field mapping program could act as essential training program to the NSG Center. For that reason, both initiatives can be considered complementary and implemented synchronously.

The work from the survey and workshops provides some overarching attributes and values of such an NSG Center. The most important ideas and approaches are developed below and are the focus of our recommendations in this report. These include integrating work across disciplinary lines and addressing each of the main barriers above.

7a. An NSG Center Should Create a Vibrant Community of Practice in NSG

One of the main challenges facing NSG is the diversity of approaches and connections and thus the integration needed for robust 21st century science. An “NSG Center” is critically needed to create and develop a “community of practice” around NSG that would provide and foster a state-of-the-art set of resources and expertise not just for the NSG community but for all adjacent disciplines. In this way, the whole is much greater than a sum of the parts. An NSG Center, by bringing together this diverse community could build on best practices from other centers and lead in fostering interoperable data, developing partnerships with industry, fostering educational and training approaches, manage key equipment, and thus provide a broad set of available resources. Several of these specific ideas and needs are outlined further below, but all require the larger collaboration and integration provided by an NSG Center to be really effective.

This need for integration and a community of practice came through repeatedly in the workshops. NSG helps many specific disciplines in some common ways. For example, the need for sharable “best practices” in the use of NSG were mentioned with regards to nearly all specific problems above (and more). More broadly, an NSG Center and community of practice therein could explore deeper needs and connections across NSG and further address the individual challenges below. For example, geohazard research is often detached from the affected communities. An NSG Center could facilitate deeper community engagement and have a mandate to do so, that spans across funding cycles of individual grants. This would help create “permanent” field support and networks for such communities.

A key focus would be to foster interdisciplinary connections. On data, for example, this could involve combining traditional geophysical data, at high resolution, with non-traditional information (cameras, long-term monitoring, etc.) to maximize effectiveness and societal relevance. An NSG Center could serve as a hub for such efforts and data archiving. An NSG-devoted Center can also leverage sites and case-studies that are already highly instrumented to conduct multi-method, multi-scale geophysical deployments, so as to complement point measurements for cross-disciplinary understanding, also resorting to AI/ML tools.

An NSG Center should also aim at capacity building from solid earth geophysicists and data modelers toward earth systems scientists, multi-sector dynamicists, and environmental geophysicists. This should include addressing challenges that NSG encounters, so as to nurture the understanding of intrinsic limitations in techniques and tools, as well as developing and enhancing the capability of process-based models to utilize geophysical data. Such a transparent approach would also engage societies into why such an NSG initiative is needed at all, accruing its societal educational outreach.

An NSG Center would thus require collaboration between different disciplines and near surface geophysicists, that could, or should, serve as a central network to coordinate multiple communities. Other groups include Seismological Society of American, AGU, GSA, USGS, IRIS, UNAVCO, SCEC, CERI, CUSEP, CISN, volcano monitoring groups, landslide monitoring groups, and more. Indeed, the main challenge is that, for historical reasons, much of the key science is supported separately and at least partially siloed; the advantage of an NSG Center is that it can be created and empowered to cross these groups and disciplines.

Such a community of practice should include up-to-date expertise, guidance and leadership for providing low-cost instrumentation, both for researcher and “citizen scientists” and should help consolidate and share this information and provide overall standards guidance to help interoperable data.

Most importantly, this Community of Practice would be available for the community–for education; for training in equipment, software, data; for outreach and coordinating meetings and workshops; and more. These opportunities are outlined below but all depend on a vibrant Community of Practice developed through an NSG Center.

7b. An NSG Center Should Provide a Needed JEDI Focus

An NSG Center should also have a mandate for and help broadly in expanding justice equity diversity and inclusivity in geophysics and in broadening community engagement to address equity and justice challenges. A mandate would be to enable NSG to engage with communities and any NSG Center should be designed with this goal in mind, with dedicated funding to develop expertise and initiatives around JEDI issues. From the context of an integrated center, affiliates could better apply for funding for JEDI initiatives from sources outside NSF.

Suggested ways that an NSG Center could contribute to societal, environmental, and climate justice issues include:

- Managing and providing grants for shipping of equipment to institutions or communities with needs but lacking access to either expertise or equipment.

- Enhancing and leading engagement with heritage stakeholders and associations (e.g., SAA, National Park Service, …) to increase awareness/utility of geophysics as a means for non-invasive investigation of sensitive sites.
- Providing training to NGOs or the Peace Corps, allowing us to leverage their existing connections and expertise in developing countries.
- Focusing on community science via a certain amount of dedicated funding supporting a diverse set of experts and broad awareness of best practices, including reducing mistrust/misinformation.
- Developing workshops with attendees from all sectors, followed by joint research projects that deepen relationships, build local capacity, and provide pathways for follow on work. Multiple workshops (including virtual) will be needed to build local capacity but not too siloed so that best practices are shared.
- Exploring and developing various citizen science projects.
- Working with local communities to understand their actual needs, for example, in terms of freshwater and information, or geohazard resilience, and then involving those communities in national cooperative funding programs and projects designed to directly meet those needs. Successful grants would include continuation of this community engagement. The program must be developed to be a national program working locally so that the results of these individual monitoring and modeling efforts are made available to all, rather than remaining isolated fragments of information. A center could help consolidate and share this information and provide overall standards guidance to help interoperable data.
- Providing a repository of best practices, lessons learned and a professional staff to facilitate experiments in urban, tribal, and rural areas and develop site access practices and field safety plans, as well as ethical environmental practices.
- Last but not least, a NSG center could set the example to reach out to diverse talents not just across demographic or ethnicity groups but also throughout different career stages, to build capacities and confidence in early-career researchers.

7c. An NSG Center Should Enable Widespread and State-of-the-Art NSG Education and Training

NSG needs an integrated education model with two-fold purpose: 1) building capacities and feedback into academic and training curricula to nurture the cross-disciplinarity and sensitivities in next generation's geophysicists; and 2) educating peers on tools and data, so as to accelerate science, and reconcile scientific issues and data meaningfulness. These resources would be available for the broader community worldwide and thus have international impact. (We note there is considerable overlap in recommendations for education and training and JEDI activities.) The NSG Center model, and a community of practice, should address this need and provide additional advantages. Ideas include:

- Developing a mentoring program aimed at students with an interest in NSG
- Funding for K-12 teachers to attend training opportunities and field work opportunities, and to create discoverable content for formal and informal education settings
- Funding/collaboration with NAGT/SERC to provide funding for geoscience education research into math/physics support, pathways for NSG students, etc.
- Sponsorship of educational sessions at AGU/GSA/AAPG/etc.
- Organization of sessions focused on best practices in teaching NSG, including field, modeling, and data analytics training for workforce development
- Collaboration with SERC on the development of societally-relevant NSG focused educational materials, leveraging training opportunities with partners to develop materials.
- Maintaining an NSG-focused YouTube channel and learning management system (e.g., on openedx) with training videos as well as videos highlighting the usefulness of NSG in solving real-world problems. One example is a "day-in-the-field" using NSG equipment.Bringing

hydrologists and geophysicists together to test and develop relevant educational material that would be available for a broad community
- Providing seed funding for researchers to include opportunities (internships) for students to participate in research projects at universities, research centers, federal agencies (e.g. USGS), National Laboratories.
- Leading the creation of or supporting attendance at NSG fieldcamps.
- Organizing annual workshops by experts in the field to teach field, data acquisition, data processing, modeling skills in ways that will make content available virtually also.
- Coordinating research projects focused on data assimilation, data fusion, and multi-physics modeling.
- Training with a focus on the potential barriers in linking geophysical modeling to actual data.
- Training on open science and FAIR data.
- Developing models that provide researchers with NSG expertise through a central dedicated research team where principle investigators can "buy ship time" or through a network of nodes, where dedicated full time personnel are supported by NSF and embedded at a university with an "expert" in some element of NSG.

7d. An NSG Center Should Enable Access to Needed NSG Equipment and Optimize Equipment Development

Access to equipment is limiting much NSG science. An NSG Center should provide a model for making equipment available, providing training around that equipment (see above), and showcasing the value of integrated studies. The greatest needs are foundational instrument access, funding to link practitioners with geophysicists, engineers, and software developers, and innovation for sensors, survey design and interpretation. An NSG Center should enable discovery through investment in the expert operation and maintenance of geophysical instruments and methods, as well as identification of research gaps where new instruments or computational methods are needed to solve challenging questions.

Lack of instrumentation that can be deployed in remote settings is currently limiting the observational network. An NSG Center should mitigate this by developing, providing and maintaining robust instrumentation accommodating for long-term observations. Efficiencies would arise from enclosure and communication designs that are adaptable to multiple methods.

Overall, workshop participants see strong analogies between the NSG Center and ocean sciences with research ships that enable ocean observation to answer fundamental science questions, or astronomy where telescopes are deployed for new discoveries. In both fields, there is a balance between operational deployment to enable discovery science and development of new instrument/software technologies to answer remaining science gaps.

Because useful instrumentation exists at many universities at present, there are various models that might expand access to equipment. Many institutions may be willing to loan, rent, or donate equipment, and an NSG Center could coordinate this effort nationally or even internationally.

7e. An NSG Center Should Empower NSG Data

There are great needs for coordinating data across NSG, collecting new data, organizing systematic monitoring, and enabling interoperability broadly. An NSG center should have a mandate to stay at the forefront of technological developments and data collection, ensure broad dissemination, set standards for data collection methods and data formatting, and provide an overall lead in enabling NSG data interoperability. For example, an NSG Center should work with existing repositories and others to create and disseminate a standard template and workflow for how to share and present NSG data and create standards to describe when this is appropriate/necessary, including on proprietary data. An NSG Center would help elevate data standards and interoperability by elevating leading practices for data management plans.

Specific suggestions for an NSG center include:

- Staff joining and/or training virtual Earth science data help desks that are expanding.
- Serving as a data aggregator or indexer from a wide variety of problems and types of field sites.
- Providing guidance to combine (1) traditional geophysical data, at high resolution, with (2) non-traditional information (cameras, long-term monitoring, etc.) to maximize effectiveness and societal relevance.
- Organizing peer review of data models and/or data sets.
- Providing strategic input into the needs for new repositories.
- Coordinating efforts for term data repository for near-surface geophysics datasets that are not in other existing repositories (i.e. orphan datasets)
- Linking to existing NSG data repositories (such as IRIS DMC, UNAVCO, or the USGS Geolog locator). Providing an interactive geographic tool to disseminate existing data at sites to avoid duplication.
- Helping researchers convert their proprietary datasets to an open format for archival, following a community standard

7f. An NSG Center Should Develop and Share Diverse NSG Software

As for data, integrated efforts are needed to develop and share a wide variety of NSG software, related to modeling, visualization, data assimilation and processing, and more. This is best done when users and developers are able to work together, and an NSG Center should catalyze this collaboration. The community needs leadership and coordination in open code, common grids, testing, ethics around use, training and training sets, and more. In sum, an NSG Center without software would be profoundly incomplete.

Needs that could be filled by an NSG center include:

- Developing visualization techniques to help researchers translate collected data to the public. For coastal systems, for example, water managers would benefit from data integration and visualization.
- Providing workflows and open-source software (Jupyter notebooks etc) for data processing, particularly for noise characterization.
- Creating a database of modeling results
- Supporting access to computing resources to scientists to perform simulations at high spatial and temporal resolution
- Partnering with companies to provide low-cost discounts on software for institutions with need and with software companies to offer low or no cost training on software.
- Maintaining a cache of commercial software for rental for academic use.

7g. An NSG Center Should Elevate NSG Job Opportunities

Career development is needed to expand and diversify the NSG workforce. A key role of an NSG Center would be to develop partnerships across industry (environmental consultants, cloud providers, geotechnical engineering firms), NGO's, communities, and academia to develop and foster careers. Any program should include internships, networking opportunities, and job placement for students. Partnerships should be leveraged with new NSF facilities and initiatives (CloudBank, Earthscope Inc - instrumentation+cyberinfrastructure, Pangeo, future geohazard centers), NASA (new satellite mission and new data, their new cloud infrastructure), USGS and DOE (database and field sites). An NSG Center could coordinate these opportunities across higher education institutions and industry. It could also help sponsor job placement sessions at conferences and provide career workshops for students. Having a critical mass and community of practice of an NSG Center would help foster the needed partnerships as there would be a stronger set of reasons for key stakeholders, like industry, to engage.

7h. An NSG Center Should Also Lead in Outreach and Public Engagement

An NSG Center also provides an important means to engage beyond the scientific community. The community of practice created in an NSG Center would allow development and maintenance of a professionals speakers program, including also for schools. It could coordinate and enable classroom visits, field visits, public talks, and provide speakers and field trip leaders for events, virtually and in person. It could also develop grants specifically aimed to support community engagement time, so this work is not done just "on the side."

An NSG Center would also build connections with broader disciplines and efforts, including on education and communication and outreach. There is a need for coordination between existing groups doing outreach and education so they can leverage respective efforts. A center could bring together geophysicists/practitioners from different disciplines in land use/heritage/ecosystem application on a regular basis in dedicated meetings. While NSG conferences are important, there is a need for problem-oriented meetings where multi-disciplinary perspectives are shared to optimize interpretative frameworks for NSG. More efforts are needed showcasing and promoting integrated sampling schemes and ground-truthing methods to evaluate the full complexity of past/present human land use (e.g., taking advantage of co-locating geophysical measurements with other sampling-based, in-situ or time-lapse measurements to relate geophysical parameters to physical and bio-chemical parameters). Mechanisms for coordination include web-based platforms, workshops tied to national meetings (or independent), and targeted listservs. It is important to engage and provide pathways for student and early-career input into outreach and public engagement.

Related to landslides, an NSG Center could serve as a hub to link the many researchers and civil servants working on landslide problems. It could provide a platform for developing community-based processing and data analysis approaches for data integration and incorporation to ground-motion forecasting and simulations.

8) Envisioning what an NSG Center should look like (a primer)

This report does not intend to propose a specific model or budget for such an NSG Center. It is our recommendation that this should be evaluated carefully on a separate effort, considering the size and scope of such an NSG Center in the context of already existing centers (see Section 3 above). Regardless of the specific model developed, NSF should consider how to best leverage a close collaboration between NSG and the EarthScope Consortium and other efforts such as NCALM, also explained in section 3. Some suggested needs overlap with the capabilities of these facilities or are analogous, such as airborne lidar and needs for airborne electromagnetics (AEM). Other NSG needs around cross-communication between scientists and engineers from various disciplines, training, JEDI, and community engagement, in particular, would be a significant expansion. Some NSG tools, such as distributed acoustic sensing (DAS), are currently in rapid stages of development without a clear national US facility or data management structure; others, such as resistivity or nuclear magnetic resonance (NMR), currently lack any formalized mechanisms for wider access or data distribution. There are also various funding models currently within NSF that could be adopted depending on the NSG Center model that a follow-up evaluation may be able to recommend.

Although it was not a mandate or expectation for this effort, several of the workshop outcomes included ideas around envisioning how an NSG Center could be developed. These are summarized below:

One operation of an NSG Center could be like an operational unit inspired by the NSF ‘fleet’ of research vessels – except this ship comes to you. A unit that is 1) is led by a full time operational director with broad authority, deep experience, and leadership skills, 2) employs multiple experienced field technicians who can train and lead teams deployed in the field, and computational technicians who can assist with inversion and interpretation of data, and geophysicists who have a strong understanding of hydrologic objectives, 3) has exclusive access to a dedicated suite of equipment, and a budget to maintain and grow it as new technologies emerge, 4) has all necessary vehicles and ancillary equipment to transport the equipment and personnel to study sites anywhere in the continental US, 5) can employ a team of short-term field assistants as needed, 6) is dedicated to hands-on training of graduate students who can join the ship for a period of time, 7) actively works to ensure that field teams are diverse and provide opportunities for underrepresented groups to participate. The operational unit could be available to the community through a dedicated NSF program that requires NSG and non-NSG PIs to collaborate. This program might solicit both larger ‘cruise’ proposals (4-8 months projects) that allow this team to focus on longer term sites to construct time-lapse data, and smaller pilot and focused structural surveys (1-2 week expeditions).

A way to leverage strength to an NSG Center would be to develop partnership "nodes" in different countries. An NSG Center could provide a small subset of instrumentation and staff on site to learn local problems, cultures, customs and challenges. This node would serve as a way to make international NSG (for example, water) problems more accessible to researchers in the US and incorporate more expensive or less available instruments. An NSG Center could also coordinate a pilot program to test this before scaling. Local scientists and leaders would have to be involved in acquisition and interpretation.

Consideration should be given, as described in section 7c above, to effective modes of leveraging both existing equipment and expertise scattered among universities across the US. Planning must recognize that the knowledge base for effective integration of NSG methods is very diffuse, and the applications and benefits are quite widespread – beyond EAR to engineering, anthropology, etc.

Finally, the NSF should consider whether, and how, an NSG Center could join, or complement the new EarthScope Consortium and other related geophysical, geochemical, and biogeochemical efforts as such coordination is increasingly required.

9) Conclusions

This report is the culmination of a year-long community based effort to define the high-priority science that could be advanced through a Near-Surface Geophysics (NSG) Center, envision its desired capabilities, and provide recommendations on how it may facilitate overcoming barriers in current science infrastructure, while minimizing impediments to recruitment and retention of students into geophysics. While our focus has been on a NSG Center, such a Center is only part of the needed solution to many of the challenges; yet, it can be a key catalyst and help foster the awareness and broader effort, including internationally, that the science and societal needs demand. Indeed, it seems difficult to envision significant advancement in addressing these challenges in the absence of such a NSG Center. We thus hope that this report is useful not just to the NSF in considering its programs but also for other agencies, societies, and funders worldwide and for communities and the public in engaging with the scientific community.

In many ways, this report, and the needs and opportunities described herein, argue for some new ways of supporting and funding convergent science for today's and tomorrows challenges. The integration needed of education, training, equipment, data, software, and more across disciplines, is broader than many earlier programs and it is hard to find an ideal analogy. At the same time, the approach goes beyond NSG and could be implemented in other efforts. For that reason, in addition to developing a model for similar "Centers", NSF and other funders, as well as institutions, should consider how to incentivize such convergence and integration in their funding models, organization, and programs. In that respect an NSG Center could provide a leading example.

10) Acknowledgments

This report represents tremendous community input provided through survey responses, a townhall, workshop outcomes, and separate correspondence, as well as weekly meetings from the steering committee between May 2021-April 2022. The broad community engagement (input from over 1,000 participants from all activities combined) is further evidence for the timeliness and importance of these recommendations, which is also reflected in the overall output, including a list of 780 open ended science questions (later summarized into 240 science questions); a list of 137 barriers and needs, and a list of 308 solutions (more details in Figure 2). Although the steering committee, led by Sarah Kruse and Xavier Comas, and the AGU staff Brooks Hanson and Laura Lyon are listed as authors on the public version, this input was invaluable in preparing the report, and many of the examples and recommendations were provided by the group work from the workshops—this is in many ways a community document. In some cases a diversity of perspectives are presented to reflect this broad input. Special thanks goes to the key volunteers in the steering committee for their time and effort. In particular John McDaris prepared the workshop presentation on *What Does the Research Say About Recruitment, Retention, and DEI* (Appendix 4), targeting one of the project's specific goals. This effort and report was supported by NSF grant EAR-2139353 to the American Geophysical Union.

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12. Appendices (see separate documents)

Appendix 1. Workshop participant
Appendix 2. Survey Results
Appendix 3. Additional research Topics (from workshop)
Appendix 4. Presentation