Testimony of

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Unearthing Innovation: The Future of Subsurface Science

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Chairman Williams, Ranking Member Bowman, Chairman Lucas, Ranking Member Lofgren, and members of the committee,

Thank you for this opportunity to testify today on the importance of the Department of Energy's subsurface science programs.

As a researcher at MIT, and previously at the Lawrence Berkeley National Laboratory and University of California, Berkeley, I have been involved in DOE's subsurface science-related programs for 15 years. My research has been focused on developing and applying statistical methods and artificial intelligence (AI) technologies to improve the characterization, monitoring and prediction of dynamic subsurface processes for various applications. I have worked on many interdisciplinary projects, on such topics as water resources, soil and groundwater remediation, carbon dioxide storage, permafrost science, and nuclear waste disposal.

The subsurface provides much of our energy, as well as critical minerals needed for many parts of our economy. Groundwater is an important source of water for drinking and for industrial and agricultural use. The subsurface also provides spaces for isolated storage of nuclear waste, carbon dioxide and other waste products.

DOE's Scientific Computing and Observation Capabilities

The DOE Office of Science (OS) has a long history of supporting the development of subsurface modeling and simulation capabilities. By taking advantage of the latest generation of high-performance computing (HPC) systems and software libraries developed through the Advanced Scientific Computing Research (ASCR) program, we can now simulate coupled thermal, hydrological, mechanical, chemical, and biological processes that interact within complex three-dimensional environments, and their responses to various perturbations. Two new geoscience codes have been developed to utilize the exascale Frontier supercomputer recently installed at Oak Ridge National Laboratory -- one for simulating coupled thermal-hydrological-mechanical-chemical (THMC) processes in the subsurface, and the other for predicting large-scale earthquakes from the initiation of fault rupture to surface ground motions (www.exascaleproject.org). Computational tools like these are a valuable and unique resource DOE provides to subsurface scientists.

The Office of Science's user facilities and observational sites are also essential resources for subsurface research. The OS facilities have been used to study vast and novel microbial communities in the subsurface, and to visualize flow processes and chemical reactions in rock pore structures. DOE's Joint Genome Institute, for example, provides high-throughput genomic sequencing to research communities, which enabled DOE funded researchers to discover the subsurface microbial communities and their functions and significantly expand the tree of life (Hug et al., 2016). In parallel, DOE observation sites have enabled us to quantify subsurface properties and dynamics at site and regional scales, and to rapidly develop and test new subsurface sensors and imaging technologies. In LBNL's Watershed Science Focus Area project (watershed.lbl.gov), for example, a machine learning technique was applied to integrate remote sensing and airborne geophysics data for mapping rock properties over an entire watershed and improving groundwater flow simulations (Uhlemann et al. 2022; Wainwright et al., 2022). In addition, fiber optic sensor technologies have advanced rapidly under the DOE programs. They can be used to monitor various properties such as seismic signals, temperature and pressure changes, making it possible to rapidly detect subsurface anomalies in an extended area (e.g., Daley et al., 2013).

Applications to Offices of Environmental Management and Nuclear Energy

The capabilities developed by DOE's basic research programs in subsurface science are proving their value across the agency. The Office of Environmental Management is using the subsurface sensor, imaging and simulation tools to improve long-term groundwater monitoring for supporting the DOE's stewardship responsibility at legacy sites. The Advanced Long-term Environmental Monitoring (ALTEMIS) project (altemis.lbl.gov), led by Savannah River National Laboratory and MIT, aims to establish a new paradigm for groundwater contamination monitoring through the integration of these tools. The integrated system can be used to continuously confirm the stability and effectiveness of remediation systems and to detect any anomalies that occur in real-time, while reducing the overall costs (Schmidt et al., 2018; Denham et al., 2022). ALTEMIS heavily leverages groundwater flow and transport simulation capabilities and sensor technologies developed under the Biological and Environmental Research program.

Long-term subsurface simulation capabilities also support the spent nuclear fuel disposal program under the Office of Nuclear Energy, which requires that nuclear waste remains isolated for much longer than 10,000 years. The THMC models and simulations developed by ASCR are particularly important for assessing the performance of disposal systems, and for quantifying the long-term integrity of the engineered barrier system (EBS) surrounding the emplaced waste (e.g., Zheng et al., 2017) as well as the thermal impact on host rock, such as potential fracture generations (e.g., Sasaki and Rutqvist, 2022). Recent research in this domain often utilizes AI techniques; for example, surrogate modeling approaches enable us to accelerate complex simulations (e.g., Mariner et al., 2017; Lu et al., 2021). They are also used to synthesize community datasets (such as geochemical experiments) from multiple literature sources and institutions for improving uncertainty quantifications (e.g., Zavarin et al., 2022).

New Opportunities for Subsurface Research

The Office of Science is increasing its investment in the uses of artificial intelligence in subsurface research. This rapidly evolving field has already improved modeling and observation research by making it possible to find patterns in very large datasets and accelerate simulations. In 2021, I co-organized the *Artificial Intelligence for Earth Systems Prediction* workshop, which explored how AI should be incorporated across DOE's earth systems modeling program (www.ai4esp.org). The workshop identified a range of opportunities as well as significant challenges that can be tackled using AI, such as scaling and heterogeneity, AI-guided data acquisition, and the representation of extreme events.

The integration of AI and simulations within scientific computing – often called *simulation intelligence* – is a particularly exciting area where many new developments are happening to synthesize large datasets and physically-based numerical models (Lavin et al., 2021). I believe that DOE can make a unique contribution in this topic, with its strength in both computing and observational science. In particular, an iterative model-experiment (ModEx) approach, developed by the Biological and Environmental Research (BER) program, is an effective framework to rapidly integrate data into predictive models, and then to use modeling results to inform future observations and experiments. Tight integration of modeling and measurements is critical to address difficult but important challenges such as quantifying flow dynamics and reactions in fractured rocks (Viswanathan et al., 2022)

The use of AI to inform data acquisition and observation is an emerging field as well. ASCR's Center for Advanced Mathematics for Energy Research Applications (CAMERA) has been developing autonomous data acquisition and experimentation frameworks for various science domains (Noack et al., 2021). Along with advances in high-resolution subsurface sensors and imaging technologies, this approach has the potential to transform subsurface observation protocols, such as sensor optimization, autonomous data acquisitions and self-driving field labs (Wu et al., 2018). Dedicated observational facilities and sites are critical for integrating interdisciplinary components effectively, and rapid prototyping and testing.

Another promising new area of research is the use of low-cost subsurface sensors to improve environmental monitoring in rural regions far from scientific centers, where mining, waste disposal or storage, and other commercial subsurface activities are underway or seeking approval (e.g., Schmidt et al., 2018; Wielandt et al., 2023). Coupled with innovative STEM education approaches such as the Teaching Through Technology program (t3alliance.org), community science programs could be built around these sensor datasets, empowering local communities to monitor and protect their own environment.

Next-generation Workforce Development

Access to DOE's leading-edge resources has been essential to my career and research. During my PhD research, for example, I ran thousands of groundwater flow simulations for assessing soil and groundwater remediation strategies at the DOE's Hanford Site. This would not have been possible without access to HPCs at the National Energy Research Scientific Computing Center (NERSC). In addition, I have also benefited tremendously from the team science approach that the National Labs have pioneered. I have seen firsthand how new discoveries and innovations happen at the interface between different fields, as well as how effectively modelers and experimentalists can work together to develop new ideas and technologies. Now as a member of an academic institution, I believe it is important that we train more students and scientists to work in interdisciplinary teams. In particular, the AI4ESP workshop identified the need for developing next-generation researchers who know both Earth science and AI well. Strong continuing collaboration between the National Labs and academia is extremely important in developing that kind of workforce.

Closing Remarks

In summary, DOE programs support work at the national labs and in academia that plays an essential role in advancing subsurface science and technologies for various applications. The tools and understanding from these programs improve our ability to take advantage of subsurface resources, and to minimize and remediate any environmental impacts.

Thank you for this opportunity to share my thoughts with the subcommittee. I welcome any questions you may have.

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