FORECASTING VOLCANIC UNREST AND ERUPTION POTENTIAL USING STATISTICAL DATA ASSIMILATION

Allocation: Illinois/85 Knh
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EXECUTIVE SUMMARY

A primary motivation for investigating volcanic systems is developing the ability to predict eruptions and mitigate disaster for vulnerable populations. Over the past three years, the Gregg Lab has been developing approaches for forecasting the evolution of volcanic systems in collaboration with the National Center for Supercomputing Applications (NCSA). The research team has implemented a high-performance computing (HPC) workflow using COMSOL Multiphysics finite-element software that links multiphysics model outputs with geophysical monitoring data for volcano forecasting. This project focuses on conducting large system-scale numerical experiments to investigate eruption potential and triggering mechanisms for three volcano targets utilizing the unique computational configuration of Blue Waters. In addition to the scientific outcomes of this effort, the experiments mark the largest distributed implementations of COMSOL Multiphysics. This achievement is of great practical importance for finite-element applications and provides benchmarking for future efforts in other fields, such as engineering, in addition to earth sciences.

RESEARCH CHALLENGE

Currently, 500 million people worldwide live on or near active volcanoes. The team's current efforts on Blue Waters are focused on developing strategies for rapid assimilation of volcano monitoring data sets into evolving geodynamic models to provide near real-time forecasts and assessment of volcanic unrest. To that end, the group is adapting data assimilation strategies developed in other fields to combine observations of volcanoes experiencing unrest with thermomechanical finite-element models to calculate volcano evolution. By combining multiphysics finite-element models with volcano monitoring data the team is able to track the stress evolution of a magmatic system and provide probability forecasts of volcanic stability during periods of unrest. Utilizing ensemble-based methods, hundreds to thousands of models are run simultaneously to track the evolution of volcanic systems. This method allows the team to evaluate stress accumulation and failure in the lead-up to volcanic eruption and to test for potential eruption-triggering mechanisms to provide a framework for early warning probability forecasts for monitoring agencies. The ultimate goal of this work is to provide a transferable data assimilation approach that can be utilized by volcano monitors worldwide.

Three volcano targets were chosen for this study owing to their excellent, real-time geophysical monitoring data sets and past eruption records: (1) Sierra Negra Volcano, Galápagos, Ecuador; (2) Laguna del Maule Volcano, Chile; and (3) Axial Volcano, Juan de Fuca Ridge—a submarine volcano located off the coast of Oregon, U.S.A. Each volcano application provides unique computational and data challenges to allow the team to evaluate potential roadblocks in transferability of the data assimilation approach.

METHODS & CODES

The research team has developed an HPC workflow using Python to efficiently distribute COMSOL Multiphysics models across Blue Waters' compute nodes and compile model outputs for Ensemble Kalman Filter (EnKF) data assimilation at each timestep. The main computational task is evaluating hundreds of large multiphysics, mechanical finite-element models at each timestep and compiling the model data to provide a probabilistic forecast of volcanic unrest.

RESULTS & IMPACT

The team has applied its Blue Waters allocation to investigate three active volcanic systems. In 2018, the researchers had the opportunity to track the unrest of Sierra Negra Volcano, Galápagos, Ecuador, during an extensive period of unrest (Fig. 1). The EnKF approach provided a forecast that indicated an eruption window that coincided with the timing and location of the 2018 eruption almost six months in advance of the event. Subsequent hindcasting on Blue Waters of the eruption further indicates that it was likely triggered by an earthquake that struck the southern portion of the Sierra Negra caldera 10 hours preceding the eruption (Fig. 2). The successful forecast of the 2018 eruption of Sierra Negra is a critical proof of concept for the volcano data assimilation HPC approach.

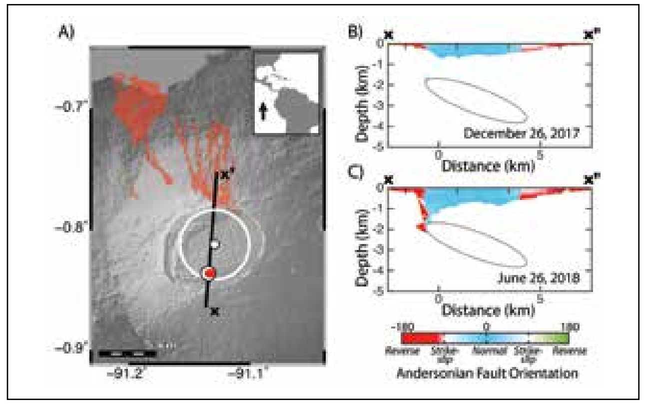

Figure 1: Sierra Negra's June 26, 2018 Mw 5.4 earthquake (beachball) and eruption (red shaded region). White circle indicates the center of the hindcast source, with its extent outlined by the white line. B) Mean model calculated Mohr-Coulomb failure for December 26, 2017. C) Mean model failure for June 26, 2018.

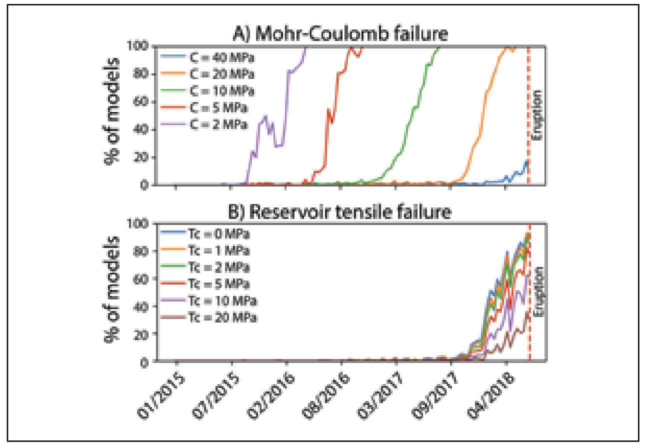

Figure 2: EnKF hindcast of the 2018 eruption of Sierra Negra.A) The percentage of finite element models in the EnKF ensemble experiencing Mohr-Coulomb failure as a function of cohesion, C. B) The percentage of modelsexhibiting Mode-I, tensile failure along the magma reservoir boundary as a function of tensile strength, Tc.

In addition to Sierra Negra, Ph.D. candidate and NASA Fellow Yan Zhan has been investigating the unrest and eruption potential of the Laguna del Maule volcano in Chile. Laguna del Maule has experienced significant inflation over the past decade indicating the potential for a large-scale eruptive event. However, current HPC forecasts reveal that the magmatic system appears to be on a stable trajectory currently. Future efforts will continue to monitor real-time data from Laguna del Maule to provide updated model forecasts as the system evolves.

The volcano EnKF approach was applied to a submarine volcanic system. Axial Volcano is an active underwater caldera volcano located off the Pacific Northwest coast of Oregon and Washington. Three eruptions have been recorded by bottom pressure recorders (1998, 2011, 2015) and ocean bottom seismometers (2011, 2015). Axial Caldera is currently monitored in real time via the Ocean Observatory Initiative (OOI). New hindcasts, conducted on Blue Waters as part of NSF-funded Ph.D. candidate Haley Cabaniss's dissertation, indicate that while the current OOI data stream provides unique insights into this underwater system, the sparse spacing of the bottom pressure recorders does not provide adequate data coverage for the EnKF approach. Cabaniss is utilizing these outcomes to develop new data targets for the OOI and to investigate the incorporation of new data streams.

Finally, the large-scale distributed implementation of COMSOL Multiphysics was tested on Blue Waters. The research group determined a key bottleneck when distributing COMSOL across hundreds of nodes. COMSOL begins to slow down exponentially owing to the inherent overhead of distributing and then compiling the model data. Unfortunately, this issue limits the scalability of the current version of COMSOL Multiphysics 5.4. Ph.D. candidate and NSF Fellow John Albright has been working with undergraduate NCSA SPIN (Students Pushing Innovation) Fellow Keon Park to test open source finite-element modeling approaches to replace COMSOL to provide better scalability. This effort will continue in the coming years.

WHY BLUE WATERS

EnKF is an ensemble-based sequential data assimilation method that requires calculating hundreds to thousands of finite-element models at each timestep. As such, the EnKF implementation utilizes high-throughput computing with hundreds to thousands of independent concurrent runs that require many nodes. While the EnKF analysis step has been optimized to run very swiftly, the computational expense of running and storing hundred to thousands of finite-element models for each timestep in the EnKF analysis is cost prohibitive for even the large XSEDE clusters. Blue Waters is uniquely positioned to handle the computational needs of this project and has allowed the research group to make rapid progress and to think ambitiously without being hampered by computational limitations.

PUBLICATIONS & DATA SETS

P. M. Gregg *et al.*, "Forecasting the June 26, 2018, eruption of Sierra Negra volcano, Galápagos, Ecuador," in preparation, 2019.

Y. Zhan, P. M. Gregg, H. Le Mével, C. A. Miller, and C. Cardona, "Integrating reservoir dynamics, crustal stress, and geophysical observations of the Laguna del Maule magmatic system by FEM models and data assimilation," in preparation, 2019.

H. E. Cabaniss, P. M. Gregg, S. L. Nooner, and W. W. Chadwick, "Triggering the eruption of Axial Seamount, Juan de Fuca Ridge," in preparation, 2019.

P. M. Gregg, Y. Zhan, H. Le Mével, J. A. Albright, and H. E. Cabaniss, "Linking thermomechanical models with geodetic observations to assess magma reservoir evolution and stability," presented at the 27th IUGG General Assembly, Montréal, Québec, Canada, Jul. 8–18, 2019.

P. M. Gregg *et al.*, "Forecasting the June 26, 2018, eruption of Sierra Negra, Galápagos," presented at the 27th IUGG General Assembly, Montréal, Québec, Canada, Jul. 8–18, 2019.

P. M. Gregg, Y. Zhan, F. Amelung, D. Geist, and P. Mothes, "Model forecasts of the 26 June 2018 Eruption of Sierra Negra Volcano, Galápagos," presented at the AGU Fall 2018 Meeting; Washington, D.C., U.S.A., Dec. 10–14, 2018.

P. M. Gregg, Y. Zhan, J. A. Albright, Z. Lu, J. Freymueller, and F. Amelung, "Imaging volcano deformation sources through geodetic data assimilation," presented at the 2018 UNAVCO Science Workshop, Broomfield, CO, U.S.A., Mar. 27–29, 2018.