PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2019
SGP-TR-214

A Framework for Modeling and Simulation of the Utah FORGE Site

Robert K. Podgorney[1], Aleta Finnila[2], John McLennan[3], Ahmad Ghassemi[4], Hai Huang[1], Bryan Forbes[3] and Janina Elliott[5]

[1]Idaho National Laboratory, Energy and Environment, PO Box 1625, Idaho Falls, ID, USA 83415

[2]Golder Associates Inc.,18300 NE Union Hill Road, Suite 200, Redmond, WA, USA 98052

[3]Energy & Geoscience Institute, University of Utah, 423 Wakara Way, Salt Lake City, UT USA 84108

[4]University of Oklahoma, Sarkeys Energy Center, 100 East Boyd Street, Norman, OK, USA 73069

[5]Seequent, #506-1168 Hamilton Street, Vancouver, BC, Canada, V6B 2S2

robert.podgorney@inl.gov

Keywords: FORGE, earth model, numerical modeling, data

ABSTRACT

The Frontier Observatory for Research in Geothermal Energy (FORGE) site in Milford, Utah, is being designed as an Enhanced Geothermal System (EGS) laboratory with funding provided for the next five years to allow investigators to interactively develop and optimize EGS methodology. In preparation for this process, it is necessary to develop baseline models using earth modeling, continuum modeling and discrete modeling methods. Reservoir development activities conducted at the FORGE site will require detailed earth and numerical models. Modeling and simulation activities will be undertaken by the site operations team using a variety of numerical methods, and also are envisioned to be conducted by the research community. In order to ensure quantitative comparability of simulation results, and consistent initial and boundary conditions, a framework has been developed to provide reference earth and numerical models with version control. This paper will describe the methodology of how the data will be shared and distributed.

1. INTRODUCTION

FORGE is a multi-year initiative funded by the US Department of Energy (DOE) for testing targeted EGS research and development. Located inside the southeast margin of the Great Basin near the town of Milford, Utah (Figure 1), the initial site characterization is described in detail in the FORGE Phase 2B Report (EGI, 2018). The current Phase 2C work includes the development of baseline models using Earth modeling, continuum modeling and discrete modeling methods.

The work through Phase 2B of the FORGE program has resulted in the compilation of a large amount of new and legacy data within and surrounding the Utah FORGE site, incorporating information for Roosevelt Hot Springs, the central segment of the Mineral Mountains, and most of the north Milford valley. Results from the deep subsurface characterization were used to further improve the geologic understanding of the site in Phase 2B. Based on the compiled data, a three-dimensional geologic model describing the structure, composition, permeability, and temperature at the Utah FORGE site was developed (Podgorney et al., 2018). The exploratory well (Well 58-32) and numerous tests conducted therein were used to confirm that the site met all of the DOE prescribed conditions of reservoir rock type, temperature, and permeability. Additionally, preliminary geomechanical models were developed that were constrained by rock strength measurements, fractures measured in boreholes, and regional stress orientations.

Modeling and simulation will play a critical role at FORGE and needs to be considered as a general scientific discovery tool to elucidate behavior of EGS systems and also as a deterministic or stochastic tool to plan and predict specific activities. Critical to this process is quantitative comparison of modeling and simulation results obtained from different codes and numerical methods. Developing a framework to ensure these comparisons can take place, and be tracked over time, will be a critical outcome.

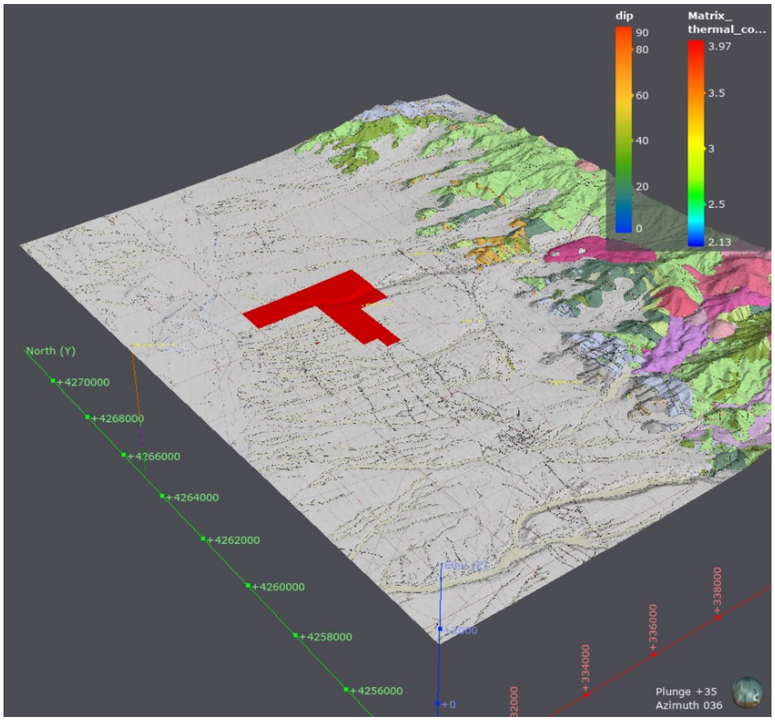

Figure 1. Location map of the Utah FORGE site (red highlighted area) near Milford Utah, overlain on an oblique view showing the topography and the updated geologic map (Kirby, 2018).

2. EARTH MODELING AND DATA COMPILATION

Earth Modeling activities will function as the central hub for FORGE geologic characterization, subsurface testing, and modeling activities. The earth model will be designed to accept, process, and visualize data from many sources, and output these data in formats usable by any numerical simulator. The earth model will also act as a communication tool, presenting FORGE data and analysis results in three-dimensions via numerous formats and primarily delivered through a web interface. Graphical, on-line tools will be implemented to share and distribute geologic data, and the protocols outlined in this paper will be used for distributing data from the geologic model to numerical modeling platforms (in alignment with COLLAB experience, see Kneafsey et al., 2019). For the Utah FORGE project team, we are using Seequent's 3D data modeling software and data management system, LeapFrog Geothermal and Central (Elliott, 2019), as they allow remote collaboration and version control/comparison of changes in the earth model, and also allow for quantitative comparison of numerical model simulation results.

The key outcome from the earth modeling, in addition to incorporating the geologic, geophysical, geochemical data, etc, was the establishment of a "reference" earth model for use by numerical modelers as a means to ensure consistent geologic structural features and reservoir parameters in numerical simulations. As part of the Phase 2B activities, the Utah FORGE team developed a comprehensive earth model of the Milford Site and surrounding area. A video overview of the earth model, and access to the individual datasets used, are available on the Utah FORGE website (https://utahforge.com/project/earth-model/). Note that the current version of the earth model from Phase 2B was locked as the current reference model on March 5th, 2018. It is currently (and continuously) being updated as data are analyzed, and more data are collected. All the data used to create the reference earth model are also available on the National Geothermal Data System (INL, 2018). Note that all earth modeling data uses SI units in UTM, Zone 12N, NAD83, NAVD88 referenced coordinates. Figure 2 shows an example of the earth model version control interface in LeapFrog Central and the earth model web page where the Phase 2B reference data can be obtained.

Results from the characterization activities completed in the current phase of the project (Phase 2C) will be used to improve the geologic model. The data collection will be used to increase resolution of geologic contacts provide greater detail about permeability and temperature at depth, and increase our understanding of the existing fracture population, as well as the in-situ stress orientation and magnitude. An updated geologic model will be developed incorporating newly acquired geologic, geophysical, geochemical, groundwater, thermal and seismic data. In order to support planning for new wells and stimulation activities, specific attention and focus will be paid to incorporating the newly collected data, where appropriate, and developing 3-dimensional distributions of critical reservoir parameters within the planned FORGE drilling and stimulation area.

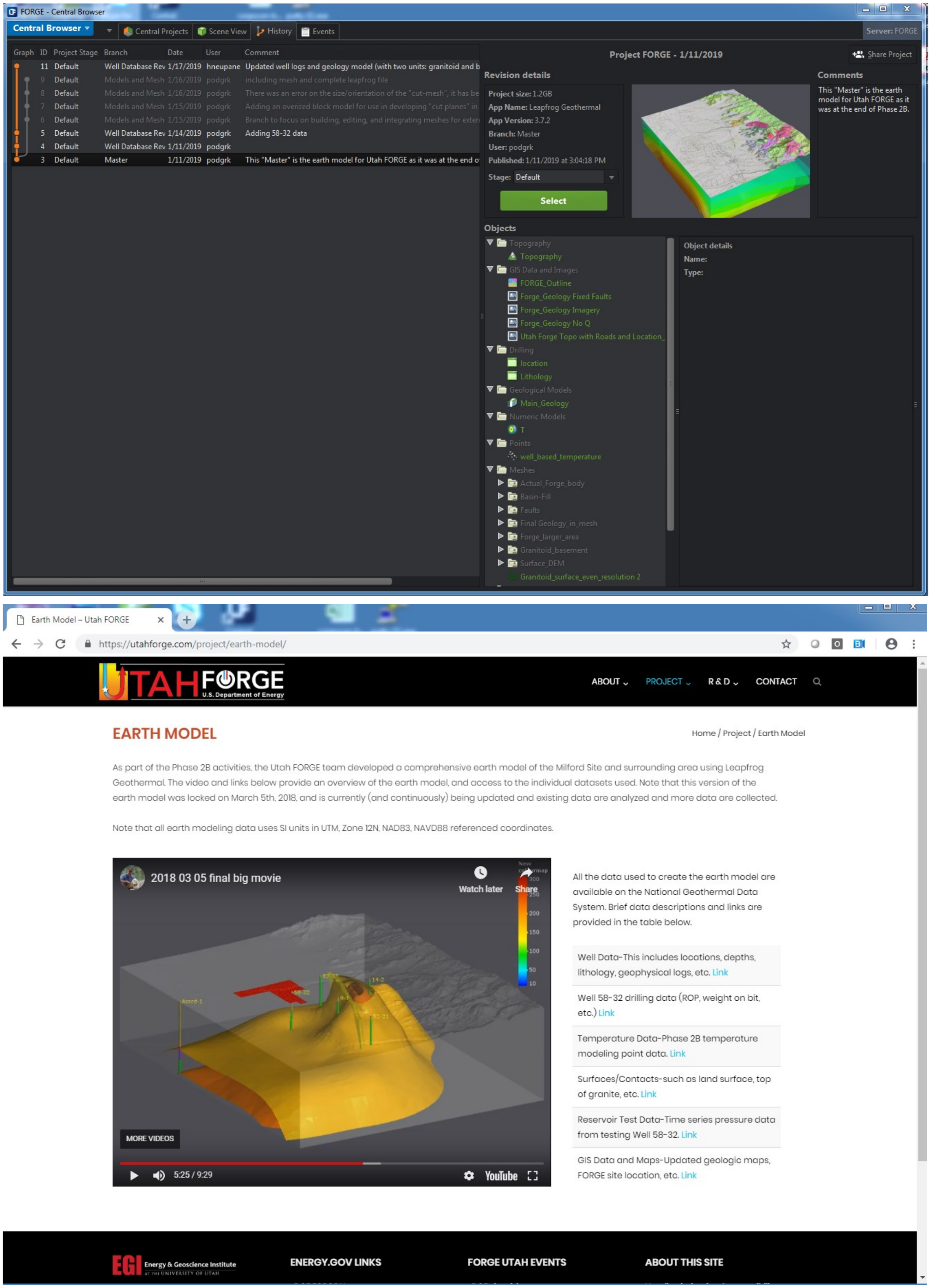

Figure 2. Top: The version control and data management interface in use for the FORGE site showing the current state of the earth model, starting from the Phase 2B reference case (from LeapFrog Central). Bottom: Screen shot of the earth model web page where the Phase 2B reference data can be obtained.

3. NUMERICAL MODELING AND SIMULATION MESH PREPARATION

Multi-physics reservoir models will be developed to simulate the coupled thermo-hydro-mechanical responses of the subsurface to FORGE reservoir creation and operation. Modeling, in conjunction with monitoring, will play an important role in evaluating proposed experiments to ensure that experiments do not interfere with each other, facilitating optimal use of the field laboratory. The reservoir models will be based on the reference geologic model discussed above and will be used as a tool to better understand the physics of the reservoir-creation process and to elucidate the behavior of the system. We will create models at several scales, with specific simulations focused on near-field fracturing processes and larger-scale simulations using continuum methods. Numerical implementation of the conceptual model will be made in commercial software packages and in open-source numerical packages to enable greater collaboration and understanding of the system. We will use these models to determine the optimal drilling directions and injection pressures to both stimulate existing fractures and generate new fractures.

The initial model region is sized to accommodate the geothermal reservoir intersected by well 58-32 and future injection and production wells along with their predicted stimulation volumes created during FORGE Phase 3. This results in a region box 2.5 km x 2.5 km x 2.75 km, located approximately between depths of 400 m to 3200 m below the surface aligned with the calculated principle stress direction (N25E) (Figure 3). The lithology is divided into two broadly defined units, comprising granitic basement rocks (granitoid) and the overlying basin fill sedimentary deposits (Figure 4).

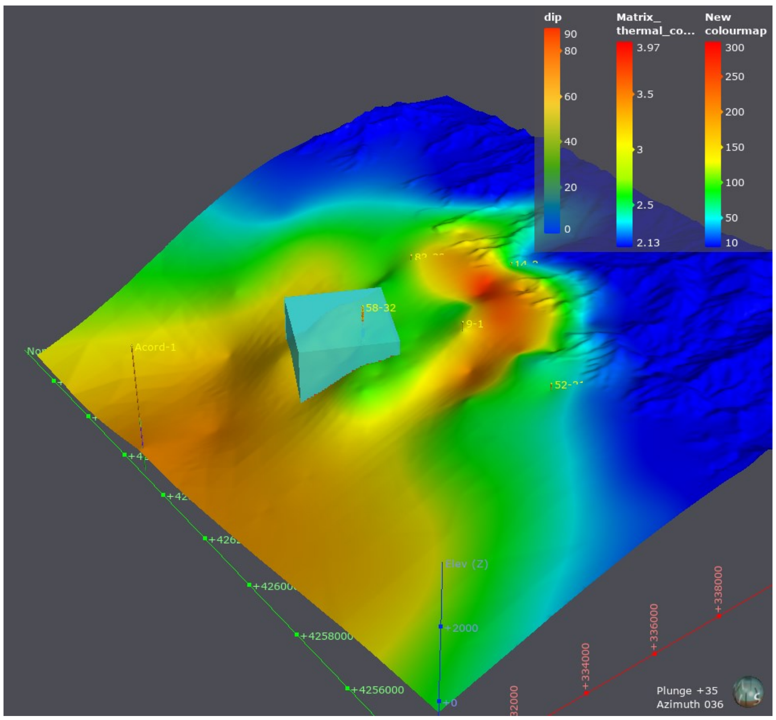

Figure 3. Initial model region (cyan box) shown in relation to the full extents of the earth model domain. Surface shown in the Phase 2B reference top of granitoid, with the predicted temperature draped over the surface. The "dip" and "matrix thermal conductivity" legend boxes relate to well logs for Well 58-32, while the "new colormap" is for the temperature data.

Continuum based modeling codes are by far the most prevalent in geothermal reservoir engineering. Solution schemes based on finite-difference, finite-element, or finite-volume methods all represent the subsurface as a generalized representative elementary volume, at various grid scales, to simulate and predict behavior. In densely fractured formations, it is common to use a DFN as a starting point to develop upscaling relationships in the development of continuum models. For Utah FORGE, the project team will establish reference mesh using the earth model and a reference continuum simulation using the FALCON code (Podgorney at al., 2010, Xia et al., 2017).

The Discrete Fracture Network (DFN) approach allows for a more explicit representation of rock mass fabric than is possible with a more conventional, continuum analysis. The DFN analysis takes borehole and fracture mapping data and defines the geometric and spatial properties of the rock mass fracture system, allowing the construction of a validated three-dimensional network of fracture elements using a stochastic approach. In the Discrete Element Model (DEM) method, rock is represented by a network of discrete elements connected by mechanical bonds. A network flow model using a lattice conjugate to the DEM network is used to model fluid flow. A volume of rock is represented by a network of discrete elements connected by various types of mechanical bonds such as springs, elastic beams, or bonds that have complex properties (such as stress-dependent elastic constants). The strength of the DEM method is in simulating crack initiation, propagation, coalescence, and eventual macroscopic failure, which is critically important to understand the coupled processes that occur during hydraulic stimulation of EGS reservoirs. A Reference DFN (Finnila et al., 2019) using the simulation code FracMan (Golder Associates, 2019) has been constructed that contains fracture trajectory, density, aperture, length, and qualitative strength for major systems, with the data available to be incorporated into DEM and continuum models.

The choice of continuum mesh type and configuration is as much a part of an individual modeling practitioner's preference as the numerical simulation code's formulation. As such, it is impossible to provide the community with every conceivable possibility for computational meshes. Our approach to sharing meshes (and eventually reservoir property distributions—a Phase 2C task) is based on sharing scatter data sets of mesh points/nodes at reasonable spacings in both structured and structured configurations and allow the community to construct their own meshes should they like to perform simulations of the Utah FORGE site. Figure 4 shows two meshes for the initial simulation domain, with the structured mesh using a uniform 50 meter spacing while the unstructured mesh uses a finer spacing to define the granitoid-sediment contact at the site. For the reference DFN, fracture information will be shared in a similar manner, with each fracture being identified using a set of vertices that outline the extent of the fracture plane.

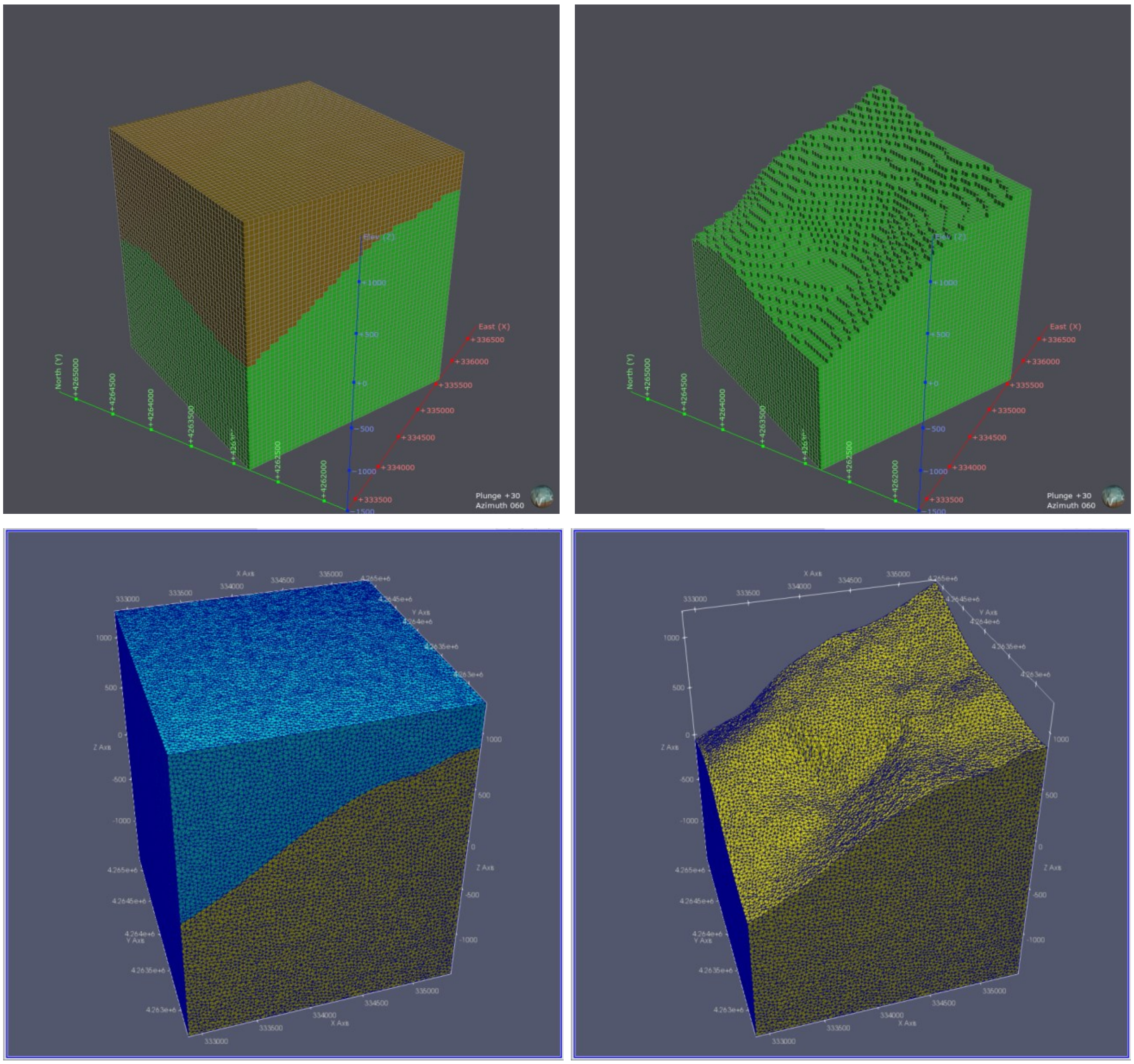

Figure 4. Top: Two views of the uniform 50-meter structured mesh, with the top left image showing the full simulation domain (the brown color represents sediments and green is granitoid) and the top right only the granitoid. Bottom: Unstructured mesh representing the same domain as above. While color scheme changed between the top and bottom images on the figure, the geologic units for both are sediments on the upper and granitoid on the lower.

4. WORKFLOW STEPS FOR EARTH AND NUMERICAL MODELING FRAMEWORK

Using the tools and methods outlined above, the general workflow for earth model updates and numerical model structure/input revisions can be summarized in the following steps:

1. Initial/Baseline Characterization Activities—which included input from geology, geophysics, geochemistry, reservoir engineering, etc. team members—collected, processed, and iterated on the subsurface structure and properties at the FORGE site. In Phase 2B, these activities culminated in a reference earth model that all future changes will be compared against. The data from this reference earth model are publicly available on the GDR from links on the Utah FORGE website (https://utahforge.com/project/earth-model/)
2. Continued Characterization Activities—As new data are collected over the lifetime of FORGE; periodic updates of the reference earth model will be published. Individual characterization activities and hypothesis testing will utilize specific "branches" of the earth model so that potential changes can be evaluated without modifying the reference model. Version control will be maintained over all branches of the earth model, thereby maintaining a record of the through processes and data involved. The next planned revision to the earth model will occur at the end of Phase 2c of FORGE, scheduled for July 2019.
3. Development of Structural Mesh Data for Numerical Simulators—based on the current reference earth model, structural data for constructing numerical meshes broadly on identified rock types will be developed. Currently, based on the Phase 2B reference earth model, a binary system consisting of sediments overlying granitoid rocks has been constructed. These data are shared/stored as ASCII text files based on the spatial coordinates of mesh vertices or nodes.
4. Development of Reservoir/Rock Property Data for Numerical Simulators—based on the current reference earth model and characterization efforts, reservoir and rock properties (including fracture networks) will be shared/stored as ASCII text files based on the spatial coordinates of mesh vertices or nodes. For the current reference earth model from Phase 2B, uniform/ representative values were used. A planned revision will occur at the end of Phase 2c of FORGE, scheduled for July 2019, where heterogeneous property distributions will be developed.
5. Incorporation of Numerical Model Results into the Earth Model—separate branches of the earth model have been created to house results from numerical simulators, allowing for quantitative comparison of results from various simulations. Detailed numerical modeling of the site, developing native state models, DFNs, stimulation models, and long-term performance/sustainability. These modeling efforts are currently underway as part of the tasks for Phase 2C of FORGE. Data will be externally published in approximately July, 2019.

The steps above will be repeated at least annually during Phase 3 of FORGE, and likely more often during periods of intense activity such as potential field experimental campaigns.

5. CONCLUSIONS

There are many issues with integrated subsurface geothermal studies; different disciplines are involved (geophysics, geochemistry, geology, reservoir engineering), alternative models and scenarios need to be investigated, new (sometimes conflicting) data are collected and interpreted to update the models, multiple organizations and people working in different locations and time zones may also be involved. The FORGE project, sponsored by the US Department of Energy's Geothermal Technology Office, encompasses all of these issues. This highlights the challenge of how a multi-disciplinary distributed team can work together in a coherent way on a day to day basis and at the same time be able to present their work to inform a wider audience.

In this paper we presented a framework and workflow that supports multiple users and disciplines, model management, audit trails, visualization and collaboration.

ACKNOWLEDGEMENTS

Funding for this work was provided by the U.S. DOE under grant DE-EE0007080 "Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site". We thank the many stakeholders who are supporting this project, including U.S. DOE Geothermal Technologies Office, Smithfield (Murphy Brown LLC), Utah School and Institutional Trust Lands Administration, and Beaver County as well as the Utah Governor's Office of Energy Development.

REFERENCES

Elliott, J., 2019, LeapFrog website, accessed Feb. 1. 2019. https://www.leapfrog3d.com/products/leapfrog-geothermal

Energy and Geoscience Institute at the University of Utah. 2018. Roosevelt Hot Springs, Utah FORGE Final Topical Report 2018 [data set]. Retrieved from http://gdr.openei.org/submissions/1038.

Finnila, A., B. Forbes, and R.K. Podgorney, 2019, Building and Utilizing a Discrete Fracture Network Model of the FORGE Utah Site, *in* PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019, SGP-TR-214

Golder Associates, 2019, FracMan® Reservoir Edition, version 7.7 Discrete Fracture Network Simulator.

Idaho National Laboratory. 2018. Utah FORGE Roosevelt Hot Springs Earth Model Mesh Data for Selected Surfaces [data set]. Retrieved from http://gdr.openei.org/submissions/1107.

Kirby, S. 2018, Revised geologic mapping of the central mineral mountains adjoining the Utah FORGE Site, Millard and Beaver Counties, Utah, Appendix to the Utah FORGE Phase 2B Final Topical Report.

Kneafsey, T., D. Blankenship, H. Knox, T. Johnson, J. Ajo-Franklin, P Schwering, P. Dobson, J. Morris, M. White, P. Fu, R. Podgorney, W. Roggenthen, T. Doe, E. Mattson, A. Ghassemi, C. Valladao, and the EGS Collab team, 2019, EGS Collab Project: Status and Progress *in* PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019, SGP-TR-214

Podgorney, R.K., Janis, M. Simmons, s., Allis, R., Moore, J., 2018, Earth Modeling of the Utah FORGE Site, Geothermal Resources Council 42nd Annual Meeting, Reno, NV, October 14-17, 2018

Podgorney, R.K., H. Huang, and D. Gaston, 2010, FALCON: A Hybrid Finite Element-Discrete Element Physics Based Model for Simultaneously Solving Fully Coupled Multiphase Fluid Flow, Heat Transport, Rock Deformation, and Fracturing, Geothermal Resources Council 34th Annual Meeting, Sacramento, CA, October 24-27, 2010

Xia, Y., R.K. Podgorney, and H. Huang, 2017, Rock Mech Rock Eng., 50: 719. https://doi.org/10.1007/s00603-016-0951-y