LBNL FORGE Project 3-2535 Report for Milestone 4.1

Building of the 3D Resistivity Model for Simulation and Survey Design of EM Measurements at the Utah FORGE Site

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1. Introduction

In FORGE project 3-2535, Lawrence Berkeley National Lab (LBNL) is planning to deploy a specialized downhole magnetic field measurement tool (the VEMP tool) in observation wells at the Utah FORGE site. The proposed measurements will involve electrically energizing the injection and / or production wells (Wells 16A and 16B respectively) and making the borehole measurements in wells 58-32 and 78-32 prior to and after stimulation with the goal of delineating properties (i.e. dimensions and stimulated zone porosity) of the stimulated zone. In parallel to reconditioning the VEMP tool for deployment at FORGE under Task 2 of the project, Task 4 involves electromagnetic simulation using a numerical resistivity model representation of the FORGE site. This will involve using two different resistivity models and then comparing the computed electromagnetic (EM) responses to determine how large a magnetic and/or electric field anomaly will be generated by resistivity changes within the stimulated reservoir volume. Two different versions of the model will be employed in this modeling effort: a baseline model and a 'stimulated' reservoir model. In addition, two different versions of the stimulated reservoir model will be employed; one in which the fractures are aligned in a direction perpendicular to the borehole to produce an electrically anisotropic reservoir, and a second one that uses the fracture orientation statistics as used by the discreet fracture network modeling team that produces a more electrically isotropic reservoir. This milestone report briefly outlines the creation of these two models for approval by Utah FORGE with Section 2 below covering the creation of the baseline model, and Section 3 the inclusion of a stimulated reservoir zone within the baseline model.

2. The Utah FORGE Baseline Resistivity Model

The baseline model uses the 3D magnetotelluric (MT) inversion results of Kordy et al.(2016), Wannamaker et al. (2020), and Wannamaker and Maris (2020). This involved the inversion of 122 processed MT sites that were collected over Utah FORGE and the surrounding area. The inversion was accomplished via a finite element code that employs deformed hexahedral meshes in order to properly account for the rugged Basin and Range topography that is in the region. Figure 1 shows a cross section from Wannamaker et al. (2020) that runs through the 3D model as well as the FORGE site to 25km depth. This 3D resistivity model is available on the Geothermal Data Repository (GDR) and thus the first step in constructing the baseline model was to download it from GDR. Figure 2 shows the map view of the Utah FORGE site with locations of the injection wells and adjacent observation wells.

In terms of the modeling, LBNL's EM numerical modeling algorithms (Um et al., 2020) involve the use of a structured rectangular or unstructured tetrahedral rather than a deformable mesh such as used to produce the 3D MT inversions. Due to the difference, we have mapped and interpolated 3D results of Wannamaker et al (2020) from deformed hexahedral meshes to regular rectangular meshes. This resulted in the models shown in Figure 3 where the structured mesh consists of 80 cells in both the X and Y directions, and 240 cells in the Z direction. Note that the central part of the mesh where the fields are to be calculated extends from -2000 to 2000 in X and Y, and from -350 to 3600m in Z where Z is positive downward. Cell sizes in X and Y are 50m within this region, and start at 10m in Z at the surface to better account for topography and slowly increase to 50m at depth.

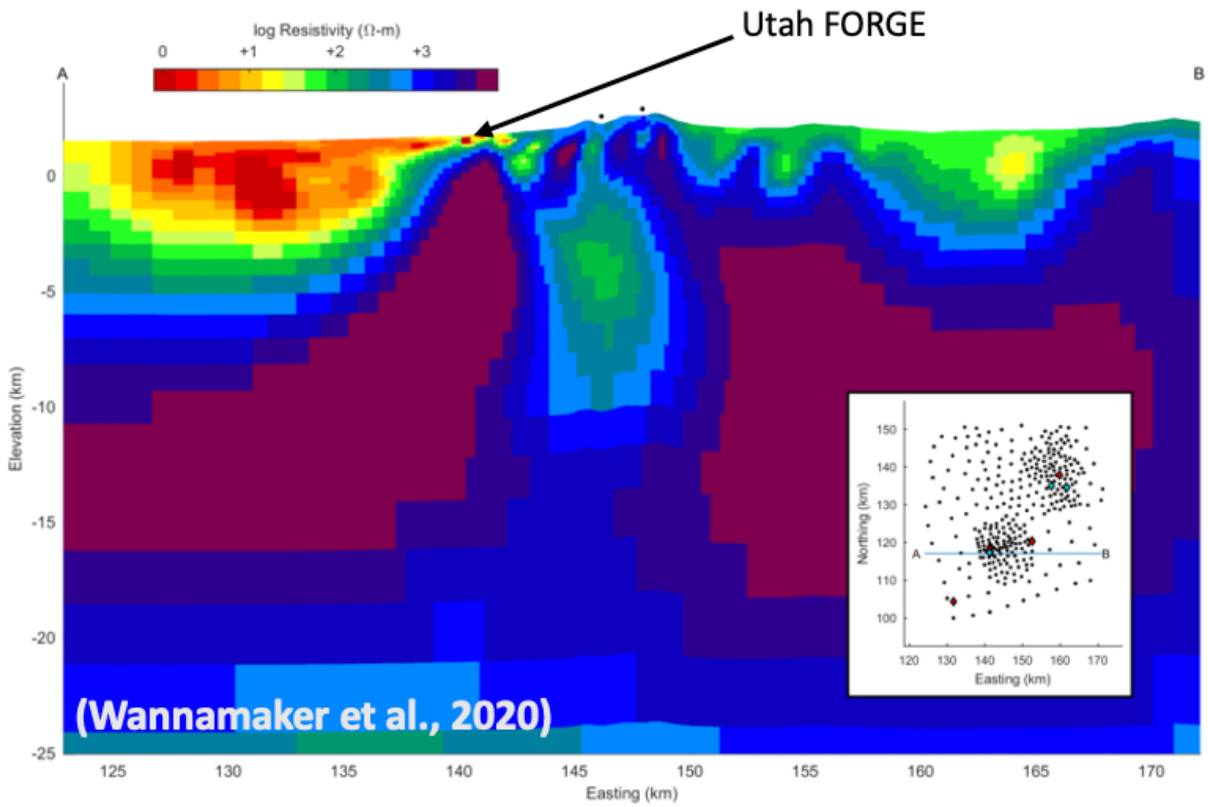

Figure 1. East-West cross section through the 3D resistivity volume resulting from the inversion of MT data collected at 122 sites as reported in Kordy et al. (2016) and Wannamaker et al. (2020). The inset shows the location of the cross section relative to the MT sites.

3. Inclusion of a Hypothetical Stimulated Reservoir for Sensitivity Modeling

In order to simulate the EM response of the hypothetical reservoir after stimulation, we incorporated various features discrete fracture network (DFN) models that are currently being developed and simulated as part of the FORGE project, along with results found in Finnila (2021). Figure 4 is compiled from figures in Podgorny (2022) and shows both the microearthquake hypocenter locations for the first stimulation that has been used to define the dimensions of the reservoir, as well as a visual representation of a DFN model (Finnila, 2020) at the toe of the well that has been used in the stimulation modeling. Using the results of the microseismic hypocenter locations, we estimated the size of the reservoir to be 400m perpendicular to and centered on the well, 300m along the well trajectory, and 600m in the z direction as shown in Figure 5. Table 1 (Aleta Finnila, 2021 and personnel communication) provides the statistics of the 4 sets of naturally occurring fractures that have been used in the modeling.

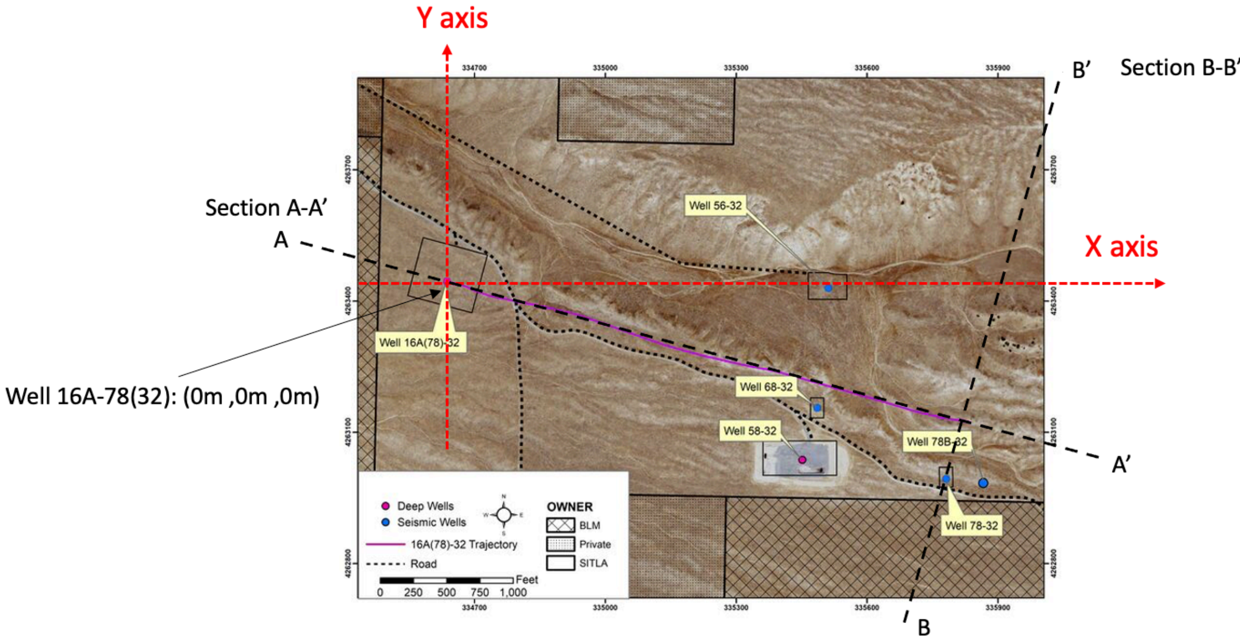

Figure 2. Map view of the Utah FORGE site showing the trajectory of the deviated section of Well 16A.

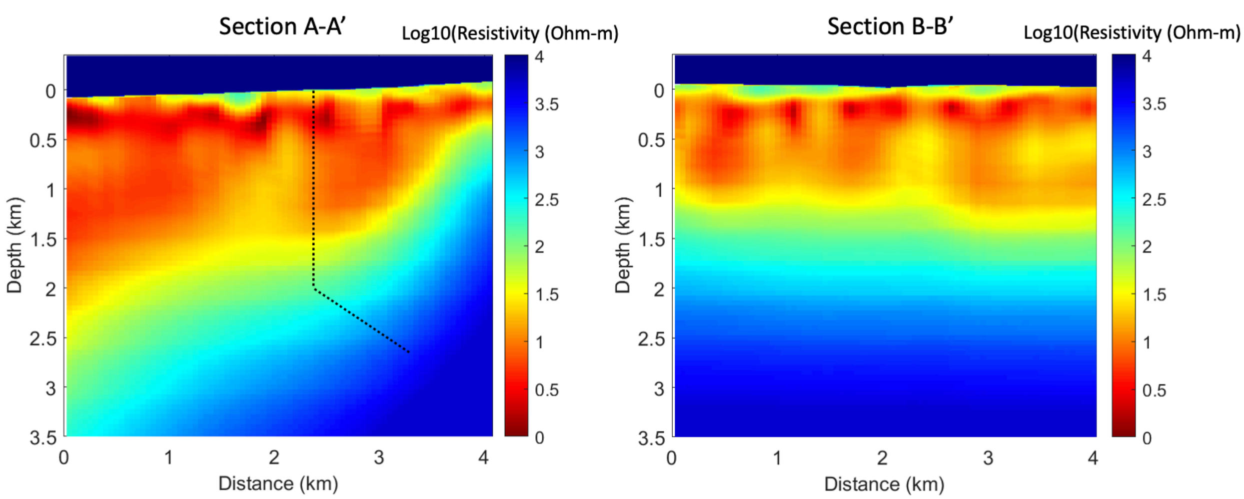

Figure 3. Cross-sections through the 3D resistivity model used for simulating EM responses with the LBNL modeling algorithms. The locations of Section A-A' and B-B' relative to the Utah FORGE site are shown in Figure 2. Note that the dotted line in section A-A' represents the approximate trajectory of the 16A well.

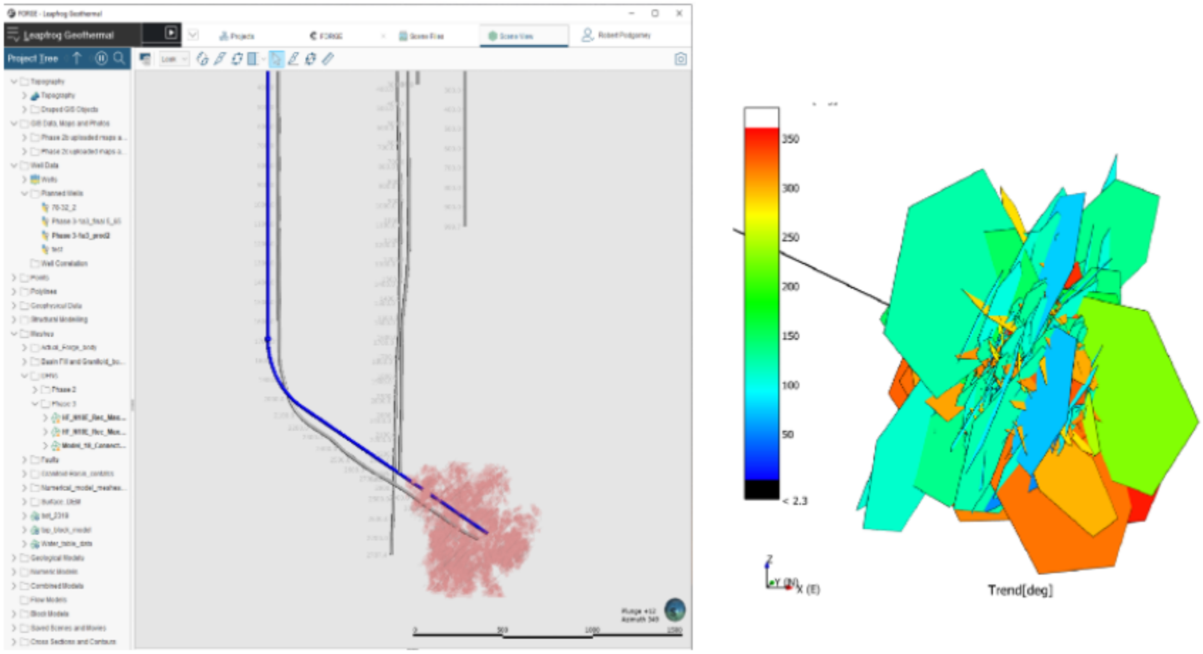

Figure 4. The left-hand side shows the micro-seismic hypocenter locations determined from seismic data collected during the test (Podgorney, 2022). The right side shows the DFN model located at the toe of the well from Finnila (2020).

In order to calculate the resistivity of the hypothetical stimulated zone generated by a fractured granite, we used the effective medium theory algorithm of Berryman and Hoversten (2013) that assumes a series of penny shaped cracks filled with electrically conductive fluid relative to the host medium are embedded in on otherwise homogenous medium with resistivity of 3000 Ωm. The radius of the cracks was assumed to be 10m which falls with the distribution assumed for the DFN modeling (2022, personal communication with A. Finnila), and the width was assumed to be 2 mm. We also assume a crack-density that provides for 1% porosity. The water filling the pore space was assumed to have a salinity of 400ppm which is consistent with the culinary water in the area that will be used during the stimulation, and a temperature of 425^{o}F which is a measured temperature at that depth was used to determine the resistivity of the fracture-filling fluid. Combining these parameters yields a water resistivity of 2 Ωm.

The Berryman and Hoversten (2013) formulation allow the user to orient cracks in the X (i.e. the well axis), Y, and /or Z direction. In the first case we assumed all fractures that were filled with the electrically conductive fluid were oriented only perpendicular to the well bore (i.e., the YZ plane). This yields an electrically anisotropic reservoir with a resistivity in the X direction of 2970Ωm, and in the Y and Z directions the computed resistivity is 190Ωm. In the second case we used the statistics shown in Table 1 for four different sets of fractures as employed in the DFN modeling to determine that 28% of the fracture have a component with a XY orientation, 32% an orientation with an X-Z alignment, and 40% with a YZ orientation. Using these statistics yielded a more isotropic resistivity with values of 302Ωm in the X direction, 270Ωm in the Y direction, and 256Ωm in the Z direction. We created two different reservoir models using these two sets of anisotropic resistivities in order to determine if there will be sensitivity within the EM measurements to whether the stimulated reservoir is isotropic or anisotropic. The resulting resistivities were then used to fill a zone with the reservoir dimensions given above to produce the model shown in Figure 5.

Set Description	Orientation: Mean Trend/Plunge [deg]	Orientation: Mean Strike/Dip [deg]	Intensity: P_{32} [1/m]	Intensity: [%]
South striking moderately dipping west	88.5/46	178.5/44	0.42	36.1%
East striking steeply dipping south	1.5/13.5	91.5/76.5	0.35	30.1%
North striking steeply dipping east	260/17	350/73	0.20	17.2%
SSW striking vertical	131/5	221/85	0.19	16.6%
			1.15	**100.0%**

Table 1. Statistics for four-sets of fractures used for the DFN modeling (Finnila, 2021)

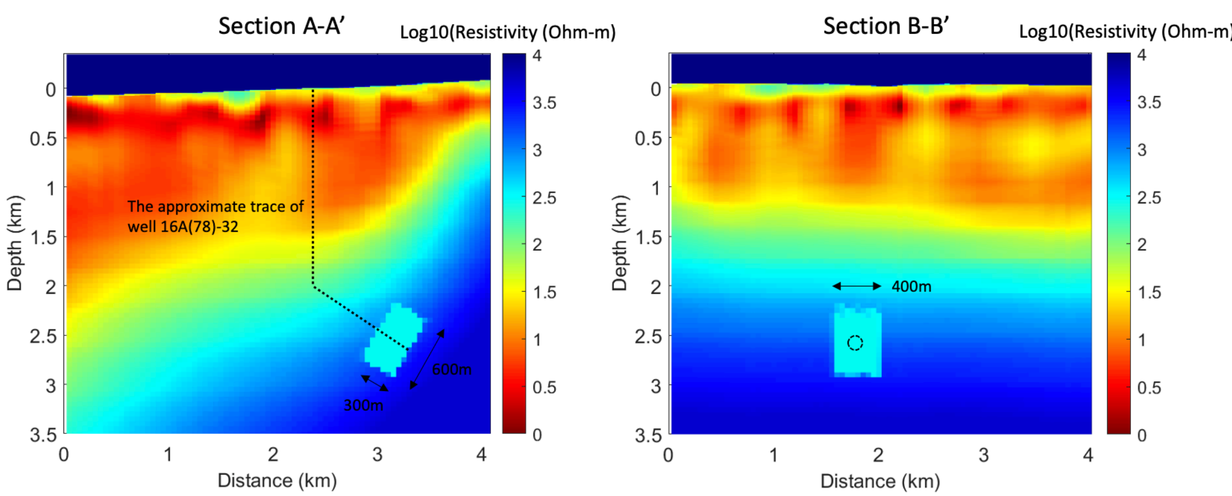

Figure 5. Cross-sections through the 3D resistivity model used for simulating EM responses with the LBNL modeling algorithms. The locations of Section A-A' and B-B' relative to the Utah FORGE site are shown in Figure 2. Note that the dotted line in section A-A' represents the approximate trajectory of the 16A well.

4. Conclusions and Future Work

One baseline and two different stimulated reservoir models have been created to test the sensitivity of borehole electromagnetic measurements to increases in fracture-porosity that will be generated during reservoir EGS stimulation at the Utah FORGE site. The baseline model in Figure 3 has been created by mapping and interpolating 3D results of Wannamaker et al (2020) from deformed hexahedral meshes to regular rectangular meshes. The reservoir models depicted in Figure 5 have used microseismic hypocenter locations to estimate the size of the reservoir, and the effective medium theory code of Berryman and Hoversten (2013) to estimate two different stimulated reservoir resistivities. The modeling will assume that steel well casings installed during the completion of wells 16A and 16B are energized with an electric current, and measurements of magnetic and electric fields made at the bottom of adjacent monitoring wells. The approximation of the energized well casings with a series of electric dipoles will be addressed in Milestone 4.2, while the full 3D sensitivity modeling will be part of the survey design deliverable that will be addressed in Milestone 4.3.

5. References

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