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Bringing Fenton Hill into the Digital Age: Data Conversion in Support of the Geothermal Technologies Office Code Comparison Study Challenge Problems

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ABSTRACT

The Geothermal Technologies Office Code Comparison Study (GTO-CCS) was established by the U.S. Department of Energy to facilitate collaboration among members of the geothermal modeling community and to evaluate and improve upon the ability of existing codes to simulate thermal, hydrological, mechanical, and chemical processes associated with complex enhanced geothermal systems (EGS). The first stage of the project, which has been completed, involved comparing simulations for seven benchmark problems that were primarily designed using well-prescribed, simplified data sets. In the second stage, the participating teams are tackling two challenge problems based on the EGS research conducted in hot dry rock (HDR) at Fenton Hill, near Los Alamos, New Mexico. The Fenton Hill project, conducted by Los Alamos National Laboratory (LANL) from 1970 to 1995, was the world's first HDR demonstration project. One of the criteria for selecting this experiment as the basis for the challenge problems was the amount and availability of data for generating model inputs. The Fenton Hill HDR system consisted of two reservoirs – an earlier Phase I reservoir tested from 1974 to 1981 and a deeper Phase II reservoir tested from 1980 to 1995. Detailed accounts of both phases of the HDR project have been presented in a number of books and reports, including a recently published summary of the lessons learned and a final report with a chronological description of the Fenton Hill project, prepared by LANL. Project documents and records have been archived and made public through the National Geothermal Data System (NGDS). Some of the data acquired from Phase II are available in electronic format readable on modern computers. These include the microseismic data from some of the important experiments (e.g. the massive hydraulic fracturing test conducted in 1983) and the injection/production wellhead data from the circulation tests conducted between 1992-1995. However, much of the data collected during the project, while publicly available, currently only exist in the form of tables or graphs within scanned documents. Therefore, in support of the GTO-CCS, the data needed for developing simulation inputs are being compiled and converted to platform independent, open readable formats so that all participating teams will have access to the same electronic data set. In some cases this requires conversion using optical character recognition, digitizing existing images, and generating the appropriate metadata from project documents. The GTO-Velo knowledge management framework, developed by Pacific Northwest National Laboratory (PNNL), was used for the benchmark problem stage of the comparison study and will also be used as the data repository for the challenge problem data sets. It is staggering and impractical to convert all published data for the Fenton Hill site, so the focus is on data that supports simulations for the three topical areas defined by the study for the challenge problems: 1) reservoir creation/stimulation, 2) reactive and passive transport, and 3) thermal recovery. Conversion of these data provide value not only to GTO-CCS participants, but also to members of the geothermal community at large who may be interested in revisiting the Fenton Hill experiment in the future.

1. INTRODUCTION

Pacific Northwest National Laboratory (PNNL) is supporting the Department of Energy (DOE) Geothermal Technologies Office (GTO) in organizing and executing a geothermal code comparison study (CCS). The Geothermal Code Comparison Study (GTO-CCS) was established to facilitate collaboration among members of the geothermal modeling community, and to evaluate and improve upon the ability of existing codes to simulate thermal, hydrological, mechanical, and chemical processes associated with complex enhanced geothermal systems (EGS). The study comprises two stages: 1) benchmark problems and 2) challenge problems with teams of participants developing solutions to the problems using a collection of numerical simulators. The first stage of the study has been completed, and involved comparison of seven benchmark-scale problems that were chosen by the participants. The benchmark-scale problems were specifically designed to investigate specific coupled processes typical of enhanced geothermal systems and were based on simple, well-defined datasets. In the second stage, the two challenge problems were selected with the purpose to investigate the ability of participating teams and numerical simulators to recreate experimental observations. The challenge problems are based on the research activities conducted at the Fenton Hill Hot Dry Rock (HDR) Test Site. The Fenton Hill HDR system consisted of two reservoirs – an earlier Phase I reservoir tested from 1974 to 1981 and a deeper Phase II reservoir tested from 1980 to 1995. Challenge problems have been defined for both the Phase I and Phase II reservoirs, and they are described in detail in White et al. (2016).

One of the main criteria for selecting Fenton Hill as the basis for the challenge problems was the amount and availability of data for generating model inputs. The Fenton Hill HDR Test site is unique in that it is very data-rich with a long history of research activities, yet there are still many unanswered questions related to designing and understanding EGS. The details of the various experiments conducted over the 20-year research project are well documented in the recent book by Brown et al. (2012), yet the book also poses challenges for further investigation of the complex coupled processes occurring at the site that are still not well understood. Having a large amount of data available along with technical challenges that can lead to increasing our understanding of EGS provides this code comparison study with a unique opportunity to make a valuable contribution to the scientific community by advancing the state of EGS modeling. Reservoir modeling is a critical aspect in every phase of an EGS development, from initial well stimulation to reservoir development and production optimization. Having the best tools to help make informed decisions regarding EGS requires good data sets against which to validate reservoir scale models. Fenton Hill provides an extensive, rich, data set for this purpose.

2. BACKGROUND AND HISTORY OF THE FENTON HILL DATA

In March 1971, the Los Alamos National Laboratory (LANL) launched the Hot Dry Rock Geothermal Energy Development Project to investigate the feasibility of man-made geothermal energy systems. Some early hydraulic fracturing tests were done that provided credibility to the Laboratory's concept for an HDR energy system. Based on the experience gained there, the Fenton Hill area on the western flank of the Valles Caldera in the Jemez Mountains of New Mexico was selected to be the long term HDR test site. In late 1973 the US Department of Energy (DOE) approved funding for drilling an exploratory hole at the Fenton Hill HDR Test Site and research and development continued at the site for over 20 years (Brown et al. 2012). Over the life of the project, 8 major wells were drilled and nearly 100 experiments were conducted related to hydraulic fracturing, acoustic wave propagation, flow testing, and tracer testing. This resulted in a large amount of data generated by the project. However, much of these data were either recorded on paper, or in digital forms that are no longer readable by today's computer software. And although key project staff at LANL retained Fenton Hill records, the number of staff with first-hand knowledge has diminished significantly, and some records have been lost. Nonetheless, a significant amount of records have remained at LANL stored in boxes, filing cabinets, old compact disks, and a hard drive. The DOE Geothermal Technologies Office (DOE-GTO) recognized the value of the Fenton Hill data set and supported LANL to sort through the records of the Fenton Hill project, scan and index the important documents, and archive them, helping to preserve the decades long investment made by DOE in studying EGS at Fenton Hill.

Prior to the beginning of Phase I of Fenton Hill, LANL drilled an exploratory borehole (Granite Test Hole 1, or GT-1) to a depth of 2575 ft in Barley Canyon just west of the Valles Caldera in the Jemez Mountains or New Mexico. Borehole GT-2, at first drilled with the intent of being a second exploratory well, penetrated deep into the hot Precambrian basement rock. Programmatic decisions declared that GT-2 would be used as the injection well for the first-ever HDR Test. At that point GT-2 was deepened to 9619 ft (2932 m), and a favorably oriented joint was opened by hydraulic pressurization near the bottom of GT-2, to form the initial reservoir heat-exchange system. Next, well EE-1 (Energy Extraction Well 1) was drilled directly under the bottom of GT-2, to intersect the lower portion of the joint, and the roles of the wells were reversed with EE-1 becoming the injection well and GT-2 the production well. Between July 17 and August 4, 1974 about 16 drill-stem tests were conducted in GT-2 in the 2600- to 2900-ft (792- to 884-m) and 4700- to 6200-ft (1433- to 1890-m) depth intervals (Brown et al. 2012). However, none of the 16 drill-stem hydrology tests yielded any definitive results, and hence these data have not been compiled for use in the GTO-CCS.

To date, the Fenton Hill project at LANL remains one of the most successful EGS projects in the world. LANL has prepared a final report (Kelkar et al. 2015a) and a summary of the lessons learned (Kelkar et al. 2015b). In addition, project documents and records have been archived and made public through the National Geothermal Data System (NGDS). And the detailed information in Brown et al. (2012) is instrumental to a successful outcome for the code comparison study challenge problem stage. This study is also very fortunate to have the support and insight provided by retired LANL staff who were instrumental in the 20-year project. Scientists such as Don Brown, Dave Duchane, Dan Swenson, Sharad Kelkar, and Leigh House have participated in the study's online weekly meetings, presented their work and insights, and provided data interpretations. One outcome of the GTO-CCS will be to provide an archive of raw and interpreted data to complement the documents currently available in the National Geothermal Data System (NGDS).

3. DATA SOURCES FOR CHALLENGE PROBLEMS

The Fenton Hill HDR system consisted of two reservoirs – an earlier Phase I reservoir tested from 1974 to 1981 and a deeper Phase II reservoir tested from 1980 to 1995. The Phase I Reservoir occurred over the approximate depth interval from 3,000 to 10,000 ft (871 to 3064 m) at temperatures between 105˚C. and 205˚C. The deeper, hotter, Phase II Reservoir occurred over the approximate depth interval from 12,000 to 14,000 ft at temperatures between 260˚C and 317˚C. The GTO-CCS challenge problems address the experiments conducted in these two reservoirs. Challenge problem 1 is based on the Phase II reservoir, and challenge problem 2 concerns the Phase I reservoir. While it may be desirable to convert all of the published data for the Fenton Hill site to digital form, that is an impractical task. However, there is value in translating the data that is pertinent to supporting simulations for the GTO-CCS. Therefore, the challenge problem champions have identified the data needed for conducting simulations and as the study progresses, participants are identifying additional data that is needed for their work. As data sources are identified, the GTO-CCS coordinators and team members are translating the data to digital form for use by all participants. The data selected support the three topical areas defined by the study for the challenge problems: 1) reservoir creation/stimulation, 2) reactive and passive transport, and 3) thermal recovery.

3.1 Challenge Problem 1: Reservoir Creation/Stimulation Data

Chapter 6 of Brown et al. (2012) describes in detail the experiments that were conducted as part of the creation of the Phase II Reservoir at Fenton Hill. Data from the following experiments are provided in digital form to GTO-CCS participants:

1. Experiment 2020 was conducted in September 1982 and was designed to be a very large volume and high-pressure re-stimulation of the EE-2 open-hole interval. The injection pressure and rate in EE-2 (Source: Figure 6-9 of Brown et al. (2012)), and the pressure buildup due to microcrack porosity in EE-2 beginning 10 months after the experiment (Source: Figure 6-15 of Brown et al. (2012)) are provided in digital form.
2. Experiment 2025, a high-pressure injection experiment into EE-3, lasted for 2 days during December 1982. The injection pressure and rate in EE-3 (Source: Figure 6-13 of Brown et al. (2012)) are provided in digital form.

3. The Massive Hydraulic Fracturing (MHF) Test, also known as Experiment 2032 was conducted in December 1983 with the hope of expanding the network of stimulated joints between the boreholes. The injection pressure and rate in EE-2 (Source: Figure 6-21 of Brown et al. (2012)) and for the corresponding pre-pump test (Source: Figure 6-18 of Brown et al. (2012)) are provided in digital form. In addition, the microseismic event data (locations and times) were processed and provided to the GTO-CCS by Dr. Leigh House (LANL, retired) and are available to participants in text file format.

3.2 Challenge Problem 1: Reactive and Passive Transport Data

Experiments during the Phase II Project included the injection and recovery of passive tracers to help understand the nature of the fracture network and chemical analysis of produced water during the circulation flow tests. A Long-Term Flow Test (LTFT) was conducted from April 1992 to July 1995, however, due to unforeseen problems, the testing was carried out in three major segments. In the interim period between the first and second segments of the LTFT, recirculated water was replaced with fresh water and the concentration of dissolved species were measured in the produced water. Tables of dissolved species concentrations prior to the interim flow test (Source: Table 9-11 of Brown et al. (2012)) and concentrations of the same species in the fresh water and produced water at two points in time (Source: Table 9-12 of Brown et al. (2012)) are provided in digital form.

3.3 Challenge Problem 1: Thermal Recovery

A series of circulation experiments referred to as the Long-Term Flow Test (LTFT) were conducted between April 1992 and July 1995. The LTFT comprised three periods of steady-state circulation and thermal recovery, a series of surging flow tests, and interim periods of minimal circulation through the reservoir. Water loss during the first two steady-state production segments of the LTFT (Source: Fig. 9-13 of Brown et al. (2012)), injection and production pressures and rates during the first load-following experiment (Source: Figure 9-6 of Brown et al. (2012)), injection and production surface pressures following shut-in (Source: Fig. 9-14 of Brown et al. (2012)) and tracer recovery profiles for three Fluorescein and one p-TSA experiments (Source: Figure 9-10 of Brown et al. (2012)) are provided in digital form.

3.4 Challenge Problem 2: Reservoir Creation/Stimulation Data

Multiple pressurization and venting experiments were performed in Zone 7 of well GT-2 as part of the Phase I reservoir creation. Surface pressure data during the first hydraulic fracturing test (Source: Figure 3-9 of Brown et al. (2012)) are provided in digital form.

3.5 Challenge Problem 2: Reactive and Passive Transport Data

In November 1976, quartz-leaching experiments (Experiments 137 and 138) were performed on the deep joints connecting Wells EE-1 and GT-2 with the objective of reducing the flow impedance via geochemical means. Fluid injection rates and pressures were recorded and at the end of pumping and a three-fold increase in hydraulic impedance was observed. Complex geochemical responses are described on pages 138-139 in chapter 3 of Brown et al. (2012).

3.6 Challenge Problem 2: Thermal Recovery

Three circulation tests (referred to as Run Segments 1-3) were performed between 1977 and 1978. The production temperature evolution during Run Segment 2 (Source: Tester and Albright (1979)), the evolution of hydraulic impedance during Run Segment 2 (Source: Tester and Albright (1979)), the production well tracer concentration during Run Segment 2 (Source: Tester et al. (1979)) and the drastic reduction in flow impedance during Run Segment 3 (Source: Tester et al. (1979)) are provided in digital form.

4. DATA TRANSLATION

While there are a number of journal articles, technical reports and other documents, in addition to Don Brown's book, that describe the work done at Fenton Hill, the amount of computer or human readable data files is few. Therefore it was necessary to create digital data files for use by participants. One of the main objectives is for all participants to have access to the same digital data. Therefore all resulting digital files are uploaded to GTO-Velo, the project's collaborative data management system. Data that are digitized from existing figures in Fenton Hill reports or in Brown et al. (2012) are imported to Microsoft Excel. Within these Excel files, several worksheets are created: 1) a metadata worksheet which includes the source image and references, and a description of how the data were translated, 2) a worksheet containing the tabular data with column headings, and 3) one or more worksheets with the data plotted for easy comparison with the original image. Some data could be found within tables in scanned reports. However, if the quality of the scan or original document is poor, then Optical Character Recognition (OCR) is not effective and the tabular data must be recreated by manual data entry to Excel. The following subsections provide representative examples of the data translation approaches used in support of the Code Comparison Study Challenge Problems.

4.1 Injection Rate and Pressure Profiles for the MHF Test in EE-2

These data were not available in their original tabular form, however, Figure 6-21 in Brown et al. (2012) was digitized using Plot Digitizer, an open source software package created by Joseph A. Huwaldt and Scott Steinhorst and distributed under the GNU Lesser General Public License. In the case of Figure 6-21 some additional data translation was needed, because the x-axis values were displayed as calendar dates in the plot shown in Brown et al. (2012). The plot digitizing software does not recognize an axis with calendar date format. Therefore, when setting the control points prior to digitization, the origin of the x-axis was set to be 0 and the maximum x-axis value was assigned based on the units of hours. The plot was then digitized assuming hours as the x-axis units. Once imported into Excel, the x-axis times in hours were translated back to calendar dates, so that the final plot can be checked against the original image and ensure that the data translation was done properly. The injection pressure curve was represented by 125 digitized points, and the injection rate curve was represented by 136 digitized points. The resulting date is shown plotted in Figure 1 with the original date and time units on the bottom axis and the digitized units in hours on the top axis.

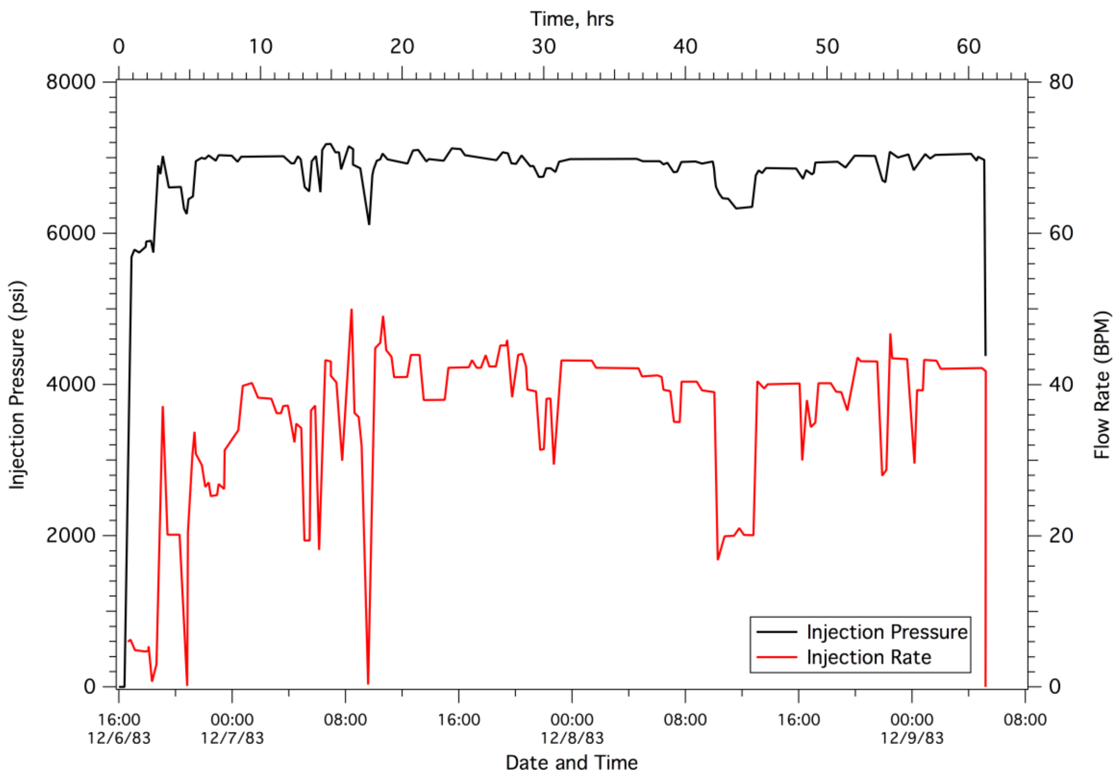

Figure 1: Injection data for MHF test reproduced by digitizing Figure 6-21 of Brown et al. (2012)

4.2 Injection Pressure and Rate for Pre-Pump Test

A Pre-Pump Test (also known as Experiment 2032) was conducted in November 1983 and described by Hugh Murphy in a Los Alamos National Laboratory internal memo distributed March 26, 1984. A scanned copy of the data described in this memo was provided to the GTO-CCS by LANL participants. Although a graph was presented in the documents, the original test data were also provided in a table. In order to preserve the accuracy of the data it was decided that using the tabular data was preferable to digitizing a graph of the same information, even though it required more effort. Because the PDF document was a scanned image instead of being generated from an existing digital file format, using OCR is not reliable and requires a significant amount of cleanup. Therefore, the data were manually entered into an Excel spreadsheet from the table shown in the document, and then graphed for verification through comparison with the originally presented graph. Figure 2 shows the injection data graph reproduced from the entered data.

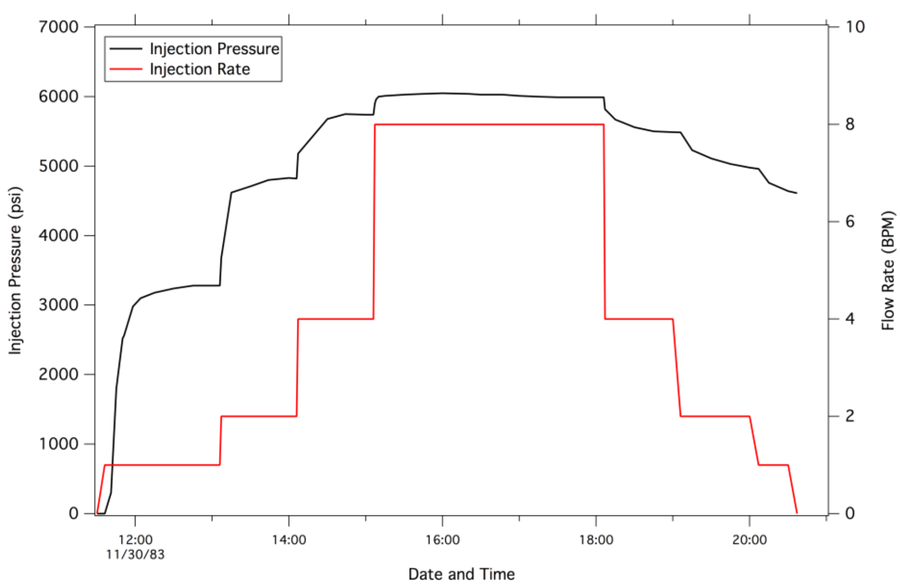

Figure 2: Injection data for pre-pump test reproduced from LANL memorandum

4.3 Fracture Network Data

A digital fracture network data set did not exist at the outset of this project, so GTO-CCS participants at the University of Nevada, Reno generated a fracture network model that can be used by code comparison study participants to model the reservoir. They used AutoCAD to generate a mesh of the fractures, intersections, and well trajectories from data provided in Table II of Smith et al. (1987) and well trajectory files provided as data files by LANL staff. Within AutoCAD, the fractures were moved to adjust the lengths between the intersecting fractures such that they most closely matched the reference data shown in Figure 8 of Smith et al. (1987). Once the fracture network was established, MULTIFLUX-VENTSIM was used to model the network of flow connections.

4.4 Microseismic Data

Based on well trajectories and micro-seismicity catalogs provided by LANL participants, Lawrence Livermore National Laboratory participants converted well trajectories and micro-seismic events into the legacy VTK (Visualization Toolkit) file format. The VTK format is open to the public and can be visualized using ParaView (www.paraview.org) or VisIt (visit.llnl.gov), both of which are free, open-source, scalable, interactive visualization tools accessible to all participating teams. Since most participants also use ParaView or VisIt to post-process their simulation results, the converted well trajectories and micro-seismic events can be analyzed in parallel with the simulation results, thereby providing a convenient and standardized inter-team result comparison mechanism. The visualizations of these data are shown in Figure 3.

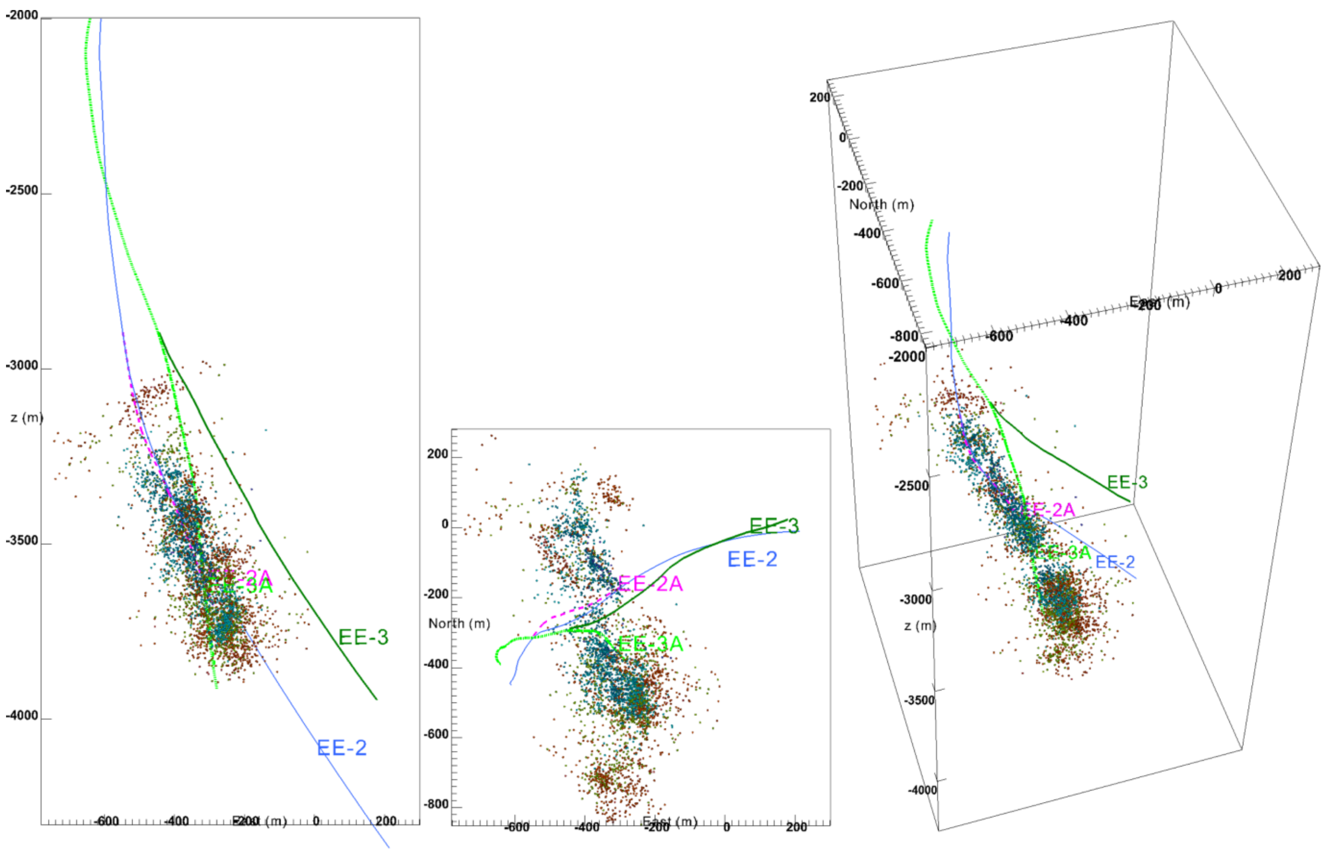

Figure 3: Visualization of microseismic events recorded during the MHF test (Experiment 2032) and the ICFT (Experiment 2067)

4.5 GEOCRACK Model results

During the 1990s, a model called GEOCRACK was developed by Dan Swenson at Kansas State University (Swenson et al. 1991). This 2-D fully coupled model was designed to simulate fluid flow in a pressurized, jointed reservoir, with the Phase II HDR reservoir specifically in mind. This model was used to simulate thermal deformation of the Fenton Hill HDR reservoir (DuTeaux et al. 1996, Swenson and Hardeman 1997). The GTO-CCS was fortunate to have Dan participate in one of our bi-weekly online meetings in which he shared his experiences and lessons learned in modeling the Fenton Hill Phase II reservoir thermal distortion using GEOCRACK. A good description of the model inputs can be found in the papers referenced above, but even more valuable is the pressure, flow rate and temperature data that Dan has provided us for the time period of 1991-1995 during the Long Term Flow Test (LTFT). These data are provided in Microsoft Excel format and have been posted on GTO-Velo to be used by GTO-CCS participants to validate their model results.

4.6 Wellbore Volume Data

The configuration of the wellbore is an important input to modeling the geothermal system. Figure 3-8 in Brown et al. (2012) shows the wellbore configuration for the Zone 7 injection tests. The well is shown to have 5.5 inch drillpipe to 6288 feet, and then 9 5/8 inch diameter open hole to 6702 ft. It was determined by some GTO-CCS participants that there seemed to be a discrepancy between the well volume calculated from Figure 3-8 and the volume of injected fluid documented on page 74 of Brown et al. (2012). Assuming that the thickness of the pipe is 0.4 inches on each side (based on standard drill pipe dimensions), the inner diameter would be 4.7 inches. The wellbore volume to 6288 feet is then calculated to be 21.5 m^3.

The volume of the lower part of the well below 6288 feet is about 4.2 m^3, making the total wellbore volume about 25.7 m^3. Page 74 of Brown et al. (2012) says that 4500 gallons (17 m^3) of treated water were injected during the proppant injection phase. When proppant is injected at the surface, it does not enter the formation until the entire wellbore volume (which does not contain proppant) is first displaced out of the well into the formation. Therefore, the volume of fluid injected appears to be too small to displace all of the fluid out of the well, resulting in all of the proppant still being present in the wellbore at the end of the injection period. Based on conversation with Don Brown about this, it is unclear why there is a discrepancy. Don recalls that they could tell that proppant entered the formation because there was a sharp rise in injection pressure at the surface. After that increase was noticed, they continued injecting for several more minutes, shut-in for a few minutes, and then flowed back. Possibly, because the proppant is denser than water, it flowed downward faster than the injection fluid and entered the formation before the full wellbore volume had been displaced. Or perhaps there could be an error in the measurement of the injection volume. The third possibility is that proppant did not enter the well, and the increase in pressure was caused by some other effect. Each GTO-CCS team is free to address this discrepancy as they wish, but since most simulators do not model the wellbore processes directly, the pragmatic thing to do is to modify the simulation setup to ensure that proppant does enter the formation. For the purposes of the challenge problem the wellbore volume can be modified to be equal to 15 m^3.

5. DATA ACCESS

Efficient and effective communication between, and collaboration among participants is essential in accomplishing the goals of this code comparison study, and the participation of all team members in technical discussions is essential. The disparate geographic location of the national laboratory, university, and industry GTO-CCS participant teams, each of which consists of several members, required the ability to share results in a forum where technical discussions can easily take place without travel to a common location. A version of PNNL's open-source, flexible framework called Velo (Gorton et al. 2011; Gorton et al. 2012) is the tool being used to provide a knowledge management infrastructure for the code comparison study. The customized version of the Velo Framework, called GTO-Velo, is being used to facilitate collaboration, technical discussions, and communication with and among the study teams (White et al. 2015). It is also the data repository for the Fenton Hill digital data and metadata collected by PNNL staff and study participants. Those in the geothermal modeling community who wish to participate in the code comparison can request to join the study and be granted an account on GTO-Velo, where they can access the Fenton Hill digital data being used in the study.

6. CONCLUSIONS

The central concepts behind today's enhanced geothermal systems (EGS) stem from the hot dry rock (HDR) concepts developed and the pioneering experiments conducted at the Fenton Hill Site. The current understanding of the Fenton Hill experiments and knowledge concerning the behavior of deep, jointed, crystalline basement rock in EGS has been captured by Don Brown, the manager of the Hot Dry Rock Project during a period yielding highly fruitful technical results. During the Challenge Problem phase, the GTO Code Comparison Study seeks to demonstrate what new understanding of enhanced geothermal systems can be generated via numerical simulation and the scientists and engineers that apply these analytical tools.

The success of the Challenge Problem Phase of the GTO Code Comparison Study depends in large part on the data collected from the Fenton Hill experiments, not only the data itself, but also the metadata associated with collecting the data. Don Brown and his co-authors have captured both the data and metadata from the 23 years of HDR experiments at Fenton Hill, encapsulating with great detail the reports and notes taken by the scientist and engineers associated with the project. In recognition of the importance of these data the GTO additionally has supported the recent archiving of the Fenton Hill experimental data in the National Geothermal Data System, which currently hold 365 datasets related to Fenton Hill. This study is particularly interested in those data, which define the metrics of the two Challenge Problems in the three topical areas. During the Fenton Hill experiments two EGS reservoirs were created via hydraulic and thermal stimulation, the flow characteristics of those reservoirs measured via tracer tests, and indicators of long-term thermal performance determined from intermediate flow tests. Data collected during these phases of the Fenton Hill experiments are the evidences of the nature and characteristics of the created reservoirs and their potential for long-term production of thermal energy. This study relies on three sources for its data: 1) laboratory records from the Los Alamos National Laboratory, generally now available through the National Geothermal Data System; 2) publically available publications, including Don Brown's work; and 3) communications with staff involved with the research at Fenton Hill. This last data source category has been captured in the recordings of the GTO-CCS teleconferences/web-conferences and now stored within the GTO-Velo repository. These records include discussions with Dr. Daniel Swenson on the modeling he conducted with the GEOCRACK Simulator, discussions with Dr. David Duchane concerning the geochemistry of Fenton Hill and EGS in general, and discussions with Dr. Scott Phillips on the Phase II fracture network and seismic event interpretations. And although Dr. Leigh House has already provided the data processing and interpretations of some of the microseismic data from Fenton Hill, there are still additional data stored in original form at Los Alamos National Laboratory that would require data processing if they are to be used in the code comparison study.

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