Utah FORGE Induced Seismicity Mitigation Plan

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UTAH FORGE INDUCED SEISMICITY MITIGATION PLAN

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Enhanced Geothermal System Testing and Development at the Milford, Utah FORGE Site

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This induced seismicity mitigation plan (ISMP) follows the best practices established by Majer et al. (2016). Information that was collected in Phases 1 and 2 of the Utah FORGE project has been incorporated, as have literature searches and risk assessments. As required, the ISMP and the PSHA (Attachment 1) will be updated and will incorporate new data and new mitigation strategies that may be developed.

December 30, 2020

The ISMP continues to follow best practices as established by Majer et al. (2016). This new version incorporates newly collected seismic data, including data collected during the 2022 stimulation and a PSHA assessment.

June 8, 2023

EXECUTIVE SUMMARY

Enhanced Geothermal Systems (EGS) require the creation of sustainable rock permeability in the subsurface reservoir in order to extract heat. This is carried out by water injection stimulation to create or enhance fractures along favorably oriented trends of weakness in the rock. Seismicity induced by such stimulation must be monitored both to map EGS reservoir growth and to alleviate possible damage to infrastructure and surrounding development. While most EGS induced events are too small to be felt (M <2), some larger ones may be and may cause limited damage. It is thus essential to implement an appropriate and effective induced seismicity mitigation plan (ISMP) that references the natural background geological structures, the state of stress, and the potential impacts of EGS operations upon infrastructure and people.

The Utah FORGE ISMP follows the best practices outlined in Majer et al. (2016) to describe the seismic hazard, seismic risk, plans for seismic monitoring and mitigation, and plans for communicating with stakeholders and the public. Utah FORGE has completed NEPA compliance, all drilling plans have been approved by the Utah State Engineer, and Beaver County has issued needed conditional use permits. There is a great deal of support for the Utah FORGE project at the local, county, and State levels and by the Utah federal congressional delegation. No issues regarding induced seismicity were raised by local stakeholders following presentations specific to the possibility of induced seismicity or in other communications directed to the Utah FORGE team. The seismic monitoring is being done by the University of Utah Seismograph Stations (UUSS), a State funded organization housed at the University of Utah, charged with monitoring seismic (both natural and induced) activity within the State of Utah. UUSS is also the Advanced National Seismic System (ANSS) authoritative agency for monitoring seismic activity in Utah.

Seismic risk is the product of seismic hazard, vulnerability, and cost. We start by describing the hazard. There are no mapped faults under the FORGE footprint. The seismicity surrounding the Utah FORGE site is characterized by low magnitude earthquakes occurring at low rates. The largest earthquake within 20 km was the 1908 M 4 earthquake located near Milford, Utah. Most natural earthquakes in the area occur under the Mineral Mountains to the east of the FORGE site or in a localized area near the Milford airport. Before the borehole injection experiment in April 2019, there was no seismicity recorded within the Utah FORGE footprint. Using deep borehole receivers, only microseismic events (M < -0.5) were detected during the experimental injection activity. In addition to the tectonic earthquakes and induced seismicity pertaining to FORGE, there are seismic events related to quarries to the northwest of Milford and perhaps induced seismicity associated with the Blundell geothermal power plant located east of the Utah FORGE site.

The U.S. Geological Survey National Seismic Hazard Maps (Peterson et al., 2020) characterize the location of Utah FORGE to be low hazard. This is supported by a site specific probabilistic seismic hazard assessment (PSHA) performed by Wood Environmental & Infrastructure Solutions, Inc. The recurrence interval for earthquakes within 50 km of Utah FORGE is ~10 years for M > 4 and ~1000 years for M > 6. Based on the local PSHA there is a 10% probability that peak ground acceleration will exceed 10 to 13% g in the next 50 years. For ground motion frequencies greater than 1 Hz, the 10% in 50-year hazard is largely a function of small to moderate sized earthquakes located within 5 to 10 km of the Utah FORGE site. Using relations developed from other induced seismicity studies that include geothermal, fluid disposal, and hydraulic stimulation data sets, together with estimated fluid injection volumes currently proposed for Utah FORGE operations, we calculate a maximum magnitude for an induced earthquake at the Utah FORGE project of M 3 to M 4. While larger earthquakes are possible, they are much lower probability events, and in a seismic risk calculation would be weighted accordingly.

Moving to vulnerability, the Utah FORGE project is located in remote south-central Utah. The immediate region surrounding Utah FORGE is uninhabited. The closest town, Milford, Utah, (pop. ~1400) is ~16 km to the southwest. Within ~5 km of Utah FORGE there is a geothermal power plant, a wind farm, and scattered pig farms. Based on distance and ground motion prediction equations, earthquakes below M 3 would not likely be felt in Milford, and if felt would be hard to distinguish from background levels of ground motion due to, for example, vehicle traffic including a railroad. Ground motion associated with the calculated maximum magnitude (M 4) will be felt throughout the region (as was experienced by a recent M 3.9 occurring south of Milford), but is unlikely to cause damage even at distances within 5 km of Utah FORGE.

For magnitudes approaching M 5, the potential for moderate damage within 5 km and light damage out to 10 to 15 km increases. To decrease the exposure to the potentially more damaging earthquakes, the mitigation plan (a traffic light system) has been developed in an effort to keep events below M 4. This is accomplished by stopping activities at the Utah FORGE site if an M > 3 earthquake occurs, and by slowing and re-evaluating operations if an M > 2 occurs or if 10 or more M > 1 events occur within a 24-hour period. While we acknowledge that we cannot strictly control seismicity, these mitigation activities will decrease the probability of an M 4 or larger earthquake being induced and thus decrease the overall vulnerability from induced earthquakes at the Utah FORGE site.

The final component of the risk calculation is cost. Given the overall rural nature of the region surrounding Utah FORGE, the low seismic hazard, and the highest probability induced earthquakes being M 4 or smaller, together with the support of the project from local and regional stakeholders, it is difficult to associate a significant cost with induced seismicity.

An operation with the scale of Utah FORGE is obligated to keep its many stakeholders informed. We have had regular interactions with stakeholders and the community. We provide information about the project on the Utah FORGE website and social media channels, plus real-time seismic information, including seismograms, on the UUSS FORGE website.

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., & Wong, I. (2016). Best practices for addressing induced seismicity associated with enhanced geothermal systems (EGS), Topical report, Lawrence Berkeley National Laboratory, prepared at the direction of the Dept. Of Energy

Geothermal Technologies Program, April 8, 115 pp. Petersen, M. D., Shumway, A. M., Powers, P. M., Mueller, C. S., Moschetti, M. P., Frankel, A. D., Rezaeian, S., McNamara, D. E., Luco, N., Boyd, O. S., Rukstales, K. S., Jaiswal, K. S., Thompson, E. M., Hoover, S. M., Clayton, B. S., Field, E. H., & Zeng, Y. (2020). The 2018 update of the US National Seismic Hazard Model: Overview of model and implications. Earthquake Spectra, 36(1), 5–41. https://doi.org/10.1177/8755293019878199.

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ACRONYMS

∑: Seismogenic index
3C: Three-component
ANSS: Advanced National Seismic System
AQMS: ANSS Quake Monitoring System
BLM: Bureau of Land Management
DAS: Distributed Acoustic Sensor
DOE: Department of Energy
DFIT: Diagnostic Fracture Injection Tests
EGI: Energy & Geoscience Institute at the University of Utah
EGS: Enhanced Geothermal System(s)
FORGE: Frontier Observatory for Research in Geothermal Energy
GMPE: Ground Motion Prediction Equation
GPS: Global Positioning System
GRID: Geothermal Risk of Induced seismicity Diagnosis
ISB: Intermountain Seismic Belt
M: Magnitude
M_{comp}: Magnitude of Completeness
MMI: Modified Mercalli Intensity
NGA: National Geospatial-intelligence Agency
NSHM: U.S. Geological Survey National Seismic Hazard Maps
PGA: Peak Ground Acceleration
PGV: Peak Ground Velocity
PSHA: Probabilistic Seismic Hazard Analysis
SAT: Seismic Advisory Team
SPAC: Spatial Autocorrelation
SMP: Seismic Monitoring Plan
TLS: Traffic Light System
UUSS: University of Utah Seismograph Stations
Vs30: average shear velocity in the upper 30 m

FIGURES

INTRODUCTION

Seismicity induced by industrial activities has been known and studied for many years (e.g., Hsieh and Bredehoeft, 1981; Raleigh et al., 1976). With both increased and changing activity in energy sectors and the migration of some of these activities toward more populated areas, reporting and concern about induced seismicity has dramatically increased (e.g., Petersen et al., 2017). Often cited examples of more frequent induced seismicity and its resulting societal impacts include the rapid increase of M > 3 earthquakes in Oklahoma beginning in 2001 (Ellsworth, 2013), the 2006 Basel, Switzerland M_L 3.4 earthquake (Bachmann et al., 2011; Deichmann and Giardini, 2009) and more recently the 2017 Pohang, South Korea M_W 5.5 earthquake (Ellsworth et al., 2019; Grigoli et al, 2018; Lee et al., 2019; Woo et al., 2019). With an increase of induced seismicity worldwide (Foulger et al., 2017), it is important to assess and make plans to mitigate the risk of induced seismicity prior to activities that might lead to these earthquakes (e.g., Majer et al., 2012; Trutnevyte and Wiemer, 2017; Walters et al., 2015).

As a result of increased levels of induced seismicity, much has been learned about how and when induced seismicity is likely to occur and different methods and procedures have been proposed to mitigate the risk. In one such method, Zoback (2012) proposes a five-point checklist: (1) avoid active faults, (2) install seismic monitoring, (3) minimize pore pressure changes at depth, (4) establish modification protocols, and (5) be ready to change plans. In another method, GRID (Trutnevyte and Wiemer, 2017), a relation between seismic hazard, secondary hazards and exposure, and social concerns is developed, and specific mitigation steps are suggested. In yet another method, nuisance events (earthquakes that might be felt but cause no damage) versus damaging events are used to establish protocols (Schultz et al., 2020).

Herein we present an induced seismicity mitigation plan (ISMP) for the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) project that follows the seven-step best practices described in Majer et al. (2016). The resulting plan describes the likelihood of occurrence of, and potential ground motions resulting from, induced seismicity and presents a clear set of procedures in the event that certain seismicity thresholds are reached. The protocol steps are: (1) preliminary screening, (2) outreach and communications, (3) criteria for ground vibration and noise, (4) collection of seismicity data, (5) hazard evaluation of natural and induced seismic events, (6) risk informed decision analysis and tools for design and operation of Enhanced Geothermal Systems (EGS), and (7) risk-based mitigation plan.

PRIMARY ISMP STEPS

Our implementation of the seven steps or procedures particular to defining an ISMP appropriate to the Utah FORGE project is laid out below. The implementation incorporates project area characteristics pertinent to each step, existing institutional infrastructure to process earthquake and site properties information, description of augmented induced seismicity monitoring capability, and action protocols in the event of a significant possible induced earthquake.

1. PRELIMINARY SCREENING EVALUATION

As advised by Majer et al. (2016), "The screening evaluation in Step 1 is not meant to provide a definitive estimate of risk. It is meant to identify the sites that would, most likely, be inappropriate, based on risk of exceeding acceptability criteria of ground shaking". Preliminary screening of the Utah FORGE project was carried out in Phase 2. As part of this screening, an initial version of the ISMP was submitted to DOE. That version included all the aspects of the current ISMP including evaluation of seismic hazard and risk and communication with stakeholders. Based on this work and other aspects of the Utah FORGE project, Utah FORGE was selected by DOE from five candidate project sites as the FORGE project to proceed.

Following Phase 2, the Utah FORGE project has completed NEPA compliance, and all drilling plans have been approved by the Utah State Engineer and Beaver County has issued a Conditional Use Permit for proceeding. Stakeholders are engaged through public meetings with the Beaver County Commissioners and at open meetings in Milford with the town council and through projects at local schools. The prospect of induced seismicity is discussed and to date no concerns regarding induced seismicity have been voiced. The potential for induced seismicity at the Utah FORGE site and the mitigation plan were also presented to the Utah Seismic Safety Commission (October 29, 2020). Again, there were no concerns voiced. There is strong support for the Utah FORGE project to proceed at the local, county and State levels.

Since the Utah FORGE project is now in Phase 3, in this section we present an overview of the area, background seismicity, and an initial assessment of the seismic hazard and risk. Specific and more detailed aspects of hazard and risk will be presented in greater detail in the following steps of this plan. The discussion of hazard and risk developed throughout the document will lead into plans for mitigation, which is one of the main goals of this document.

The Utah FORGE site is located in rural Beaver County, Utah. The nearest population center is the town of Milford, located 16 km to the southwest of the Utah FORGE site, with a population of ~1400 persons. Critical facilities include a hospital, an airport, and schools. Based on 2020 Census Bureau data, there are ~2100 households and a total population of 7,249 in Beaver County, with the majority of the population located in the town of Beaver, 32 km southeast of the deep drilling location. The majority of the built environment is residential. Based on the population density and the built environment, the current assessment is that this is a low seismic risk area — "Can proceed with planning but may require additional analysis to confirm" (Majer et al., 2012). A more complete discussion of risk is in Section 6.

The University of Utah Seismograph Stations (UUSS), a partner in the Utah FORGE team responsible for seismic monitoring, has been doing so throughout Utah and the surrounding region for over 50 years. UUSS is a core agency within the Utah Earthquake Program (https://ussc.utah.gov/pages/help.php?section=Utah+Earthquake+Program) funded by the State of Utah for monitoring seismicity within the State. UUSS is also a funded Advanced National Seismic System (ANSS) network and is the authoritative agency for monitoring seismicity in the Utah region and Yellowstone National Park (Pankow et al., 2019b).

The Utah region has several types of seismic sources (Pankow et al., 2019b). Tectonic earthquakes tend to be located in the Intermountain Seismic Belt (ISB; Smith and Arabasz, 1981), a band of seismicity running from Montana to Arizona. There are also prominent sources of induced seismicity, most notably mining induced seismicity associated with coal mining in the Wasatch Plateau and Book Cliffs in central Utah (Arabasz et al., 1997) and fluid injection seismicity in the Paradox Basin on the Utah Colorado border (Ake et al., 2005; Block et al., 2014). Other cases of induced seismicity have been associated with the Blundell Power Plant (Pankow et al., 2019a) and along the eastern edge of the Wasatch Plateau (Stein, 2016). Other seismic sources in the region include surface and underground blasting associated with mining activity (e.g., Linville et al., 2019; Tibi et al., 2019; Voyles et al. 2020) and explosions related to munitions at military facilities located within the State (e.g., Stump et al., 2009). While there are State regulations related to ground motions and surface air fronts from blasting, induced seismicity is not currently subject to State regulation.

To provide one view of seismic hazard, UUSS has compiled an earthquake catalog going back to 1850 (Arabasz et al., 2015, 2017; Figure 1). This catalog composes one part of a more detailed seismic hazard analysis that will be expanded upon in Section 5. In this historical record, there has been only one M > 4 earthquake in the greater Milford, FORGE study area (yellow box, Figure 1). This was the 1908 M 4.1 Milford earthquake. Within ~50 km of the Utah FORGE site, there have been other earthquakes with M < 4.9, but there is only one earthquake M ≥ 4.9; the 1901 M 6.6 Tushar Mountain earthquake (labeled 'T', Figure 1) located ~50 km to the east within the seismically active ISB. Based on both the UUSS catalog and an early study by Zandt et al. (1982), natural seismicity in the Utah FORGE study area is characterized by small magnitude earthquakes and a low seismicity rate. This will be further discussed in Section 4.

As across much of Utah, there are other known seismic sources near the Utah FORGE site in addition to the earthquake hazard. There is a large quarry operation northwest of Milford producing infrequent seismic events of similar magnitude (M < 2) and ground shaking to the majority of cataloged earthquakes (Pankow et al., 2019a; Potter, 2017). Additionally, there is the possibility of small ground motions associated with railway traffic in the town of Milford, and noise sources related to the railroad and air traffic.

To get an alternate overview of seismic hazard, the 2014 U.S. Geological Survey National Seismic Hazard Maps (NSHM; Petersen et al., 2014) showed the Utah FORGE study area is in a region of low to moderate seismic hazard. The peak ground acceleration (PGA) with a 10% probability of exceedance in 50-years (475-yr return interval) was cited as 10% g. These maps were updated and replaced with the 2018 NSHM (Petersen et al., 2020). In the revised maps, PGA with a 10% probability of exceedance in 50 years is reduced to < 10% g (Figure 2a). The new maps also look at the chance of experiencing a Modified Mercalli Intensity VI (the level of shaking that starts to produce damage, such as cracks to weak plaster and masonry; Wald, 1999) from earthquake shaking in the next 100 years (Figure 2b). For the Utah FORGE area, this probability is ~30%.

Based on: (1) the rural nature of the proposed site, (2) the expectation that induced seismicity will be smaller or equal in magnitude to background tectonic earthquakes (van der Elst et al., 2016), (3) the overall low hazard as found in the NSHM, and (4) the on-going nuisance-level ground motion and noise related to the quarry, railway, and airport; our analysis classifies the overall risk as very low (I) to low (II). This assessment will be further developed and expanded upon in the following best practice steps.

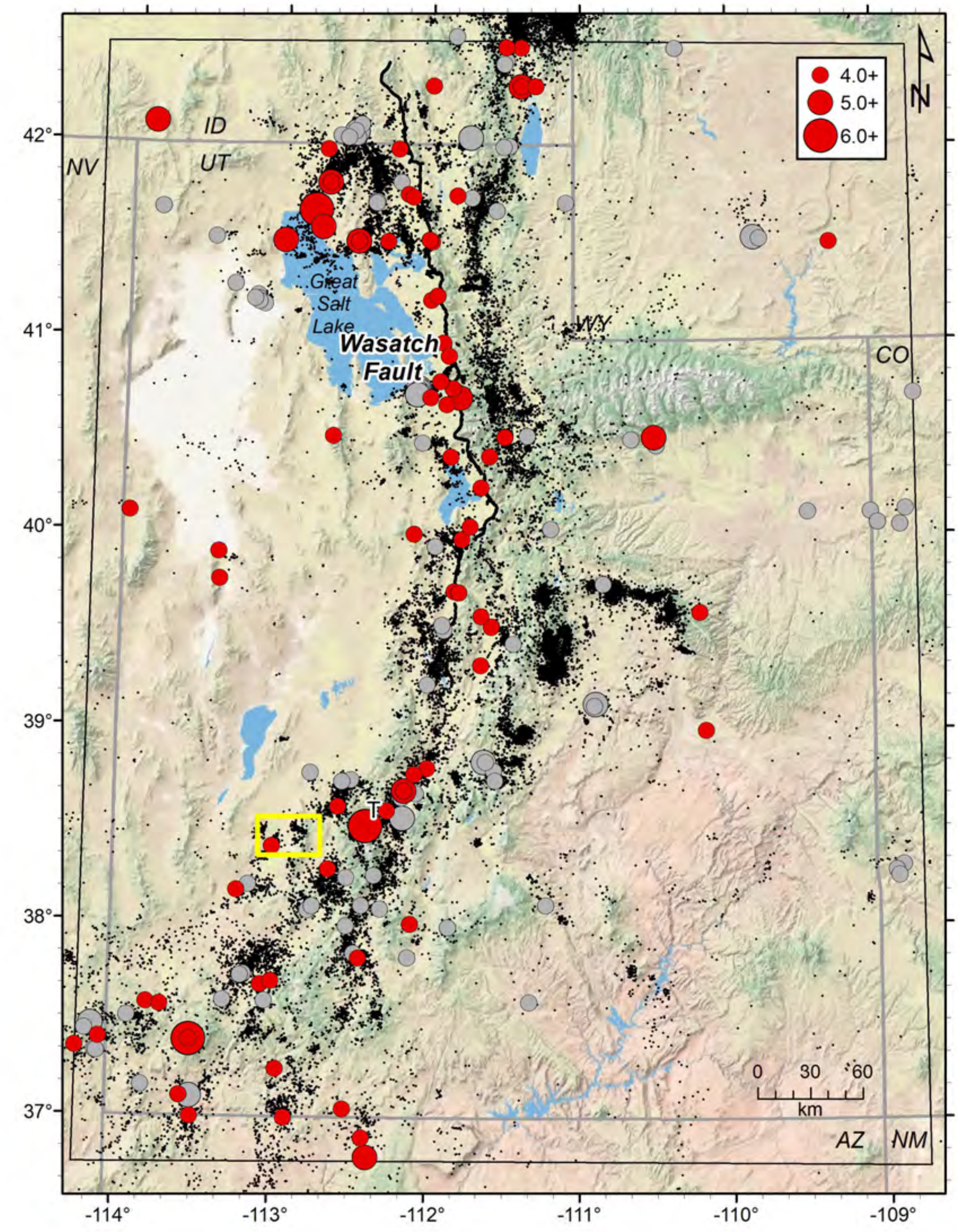


Figure 1. *Epicenter map of mainshocks of moment magnitude, M > 4.0 in the Utah Region, 1850 through September 2012 (red circles, scaled by magnitude; Arabasz et al., 2015, 2017); M > 4.0 2012 through December 2022 (grey circles scaled by magnitude; UUSS catalog). The small black dots show all earthquake epicenters in the UUSS earthquake catalog, July 1962 through December 2022. The yellow box contains the FORGE study area.*

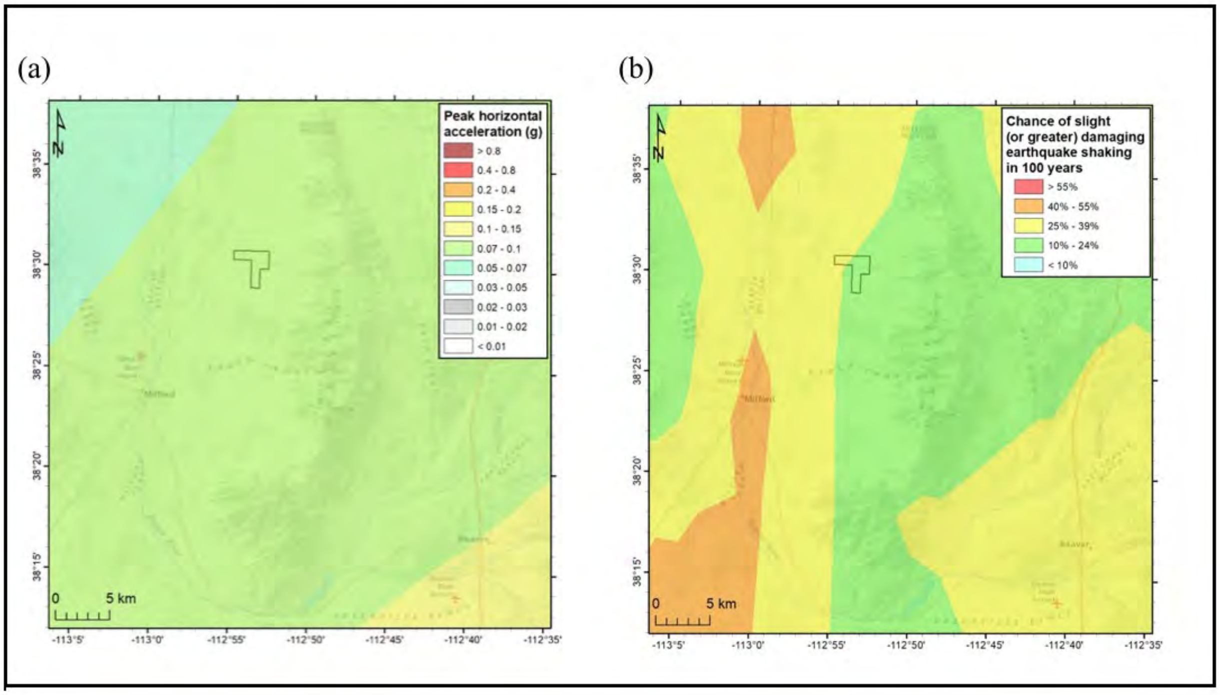


Figure 2. *Probabilistic seismic hazard at the FORGE site from the 2018 National Seismic Hazard map (data from Rukstalis and Petersen, 2019). (a) 10% g in 50 yrs PGA hazard (475 yr return period). (b) Chance of slight to damaging ground motions in the next 100 years.*

2. OUTREACH AND COMMUNICATION PROGRAM

2.1. Program Purpose

As with any EGS project, outreach and communication are essential for ensuring the project's success and acceptance. In order to achieve this success, the identification and proactive engagement of various stakeholders is paramount. Specifically, multidirectional communication is needed to foster acceptance, trust, and involvement by these stakeholders.

It is important to recognize that "one size" does not fit all – this communications and outreach plan is designed particularly to address the Utah FORGE project being conducted approximately 16 km northeast of the town of Milford in Beaver County, Utah, an area designated as a rural community.

2.2. Main Elements of Outreach & Communication Approach

Utah FORGE is implementing a "best practices" approach to its outreach and communication efforts following Majer et al. (2016). Four main requirements, and their essential components, have been identified and are listed below.

1. <u>Identify key stakeholders early in the process.</u> Significant effort and time were invested in identifying stakeholders and engaging them from the beginning of the FORGE project, starting in 2015, which has allowed for effective and targeted outreach (Appendix A). The Utah FORGE Outreach and Communication program has always been designed to encourage multi-fronted communication between a variety of stakeholders, with transparency and community participation at its core.

   Forming an early, transparent, and ongoing dialogue with Utah FORGE's myriad stakeholders established a level of trust and understanding around safety and environmental issues, including induced seismicity. The Utah FORGE Outreach and Communication plan facilitates communication and maintains positive relationships with all of its identified stakeholders including the local community, partners, elected officials, regulators, and landowners. Utah FORGE has implemented the means for stakeholders to provide feedback, ask questions and make comments through its website, public meetings and social media platforms.

2. <u>Establish an appropriate Outreach and Communication team.</u> Utah FORGE has clearly defined the processes for both internal and external communication for the project (refer to the Project Management Plan). Since the outreach team serves as the "face" of the project, a diverse group has been assembled, ensuring the right message is delivered to the appropriately-identified audience by the most suitable team member or "proxy." Therefore, along with the core team responsible for the planning and implementation of day-to-day outreach and communication efforts, additional experts and proponents of the project are tapped as appropriate. These additional outreach team members include – but are not limited to – scientists, engineers, seismologists, and on-site staff. At times, depending on the message, Utah FORGE may elicit assistance from community leaders, public safety officials and regulators.

3. <u>Provide the community with complete and credible information.</u> The ongoing success of the Utah FORGE EGS project depends on the acceptance and support of the community, which encompasses a large group of stakeholders. In turn, this community cannot continue to offer its acceptance and support without having up-to-date information available that reflects their interests, which for residents of the area can include potentially contentious issues such as induced seismicity. The plan for directly communicating about induced seismicity follows below.

   Utah FORGE began this process of providing credible information regarding the history and potential for induced seismicity to stakeholders even before the site was chosen by the Department of Energy. Beginning in September of 2015, outreach began to ensure acceptance, advocacy and cooperation in fulfilling the overall mission of the project. This outreach, which is catalogued in Appendix B, has continued without interruption since. During this time, support and excitement from stakeholders and the local community has grown. Meetings have included presentations on seismic activity, seismic monitoring and the traffic light system (https://www.youtube.com/watch?v=USGysyFKuUU), have been made in Milford and Beaver with local officials, showed strong support expressed for the project.

Moreover, through its Outreach and Communications Plan, Utah FORGE has worked diligently to establish mutually-respectful working relationships with communities and interested members of the public, local groups, government agencies, regulators, and individuals (refer to the Outreach and Communications Plan). Outreach tools have included:

- An interactive website to provide up-to-date information about Utah FORGE, EGS, and geothermal energy. The site also includes several avenues for stakeholders to contact the project with any concerns, comments or questions.
- Email blasts providing updates and information directly to subscribers.
- Wiki pages afford the research community “one stop” access to data.
- In person meetings with elected officials, civil servants, and area partners to provide updates, answer questions, receive input and suggestions.
- Community presentations to apprise stakeholders of the project’s progress.
- Frequent calls and emails to elected officials, administrators and regulators in response to questions, to solicit for concerns and provide updates.
- Several social media accounts to promote information about geothermal energy, EGS technologies, and to spotlight Utah FORGE activities and encourage learning and participation.
- Media relations to educate audiences about the project, its goals, possible effects – both positive and negative – and its progress.
- Educational materials, including lectures, podcasts, videos, informal presentations, articles in general media publications, that raise awareness about Utah FORGE, EGS, and geothermal energy in general.
- Computers placed in the County’s three public libraries permanently set to the UUSS website, allowing residents to monitor seismicity in real time.
- In-class activities in area elementary and secondary schools to encourage curiosity in STEM education.
- Participation in the county fair to engage in direct familiar interactions with the community.

With a new round of drilling and hydraulic stimulations resuming, Utah FORGE will continue its visible presence in Beaver County and the nearby communities of Milford and Minersville. Specific outreach related to induced seismicity is discussed below. We plan again to hold quarterly meetings, have a booth at the annual county fair, provide additional community updates in the local paper, collaborate with local towns for social media postings, and host school activities. Quarterly updates are planned whenever opportunities to meet with various stakeholders (e.g., elected officials, community leaders, school groups, etc.) present themselves. For example, a booth is booked annually at the Beaver County Fair, which attracts 1500-2500 people. Otherwise, we will proactively schedule meetings for around the 15th of each quarter's second month.

<u>Gain a community perspective as a pathway for gaining public trust.</u> Utah FORGE believes understanding the diverse concerns of the community has better equipped the project to demonstrate both its commitment to, and support of, the community. Therefore, stakeholder involvement in the process was initiated early in the project. A broad coalition of stakeholders – including those living closest to the site – has been defined, and the needs of the community have been identified. Efforts have been made to continue expanding the positive economic impact that the project is having on the area.

During recent in-person meetings, various elected officials expressed enthusiastic support for the project, viewing it as a vital part of their vision to develop rural areas in general and the Milford area in particular. Because of the potential positive role geothermal energy may play in the nation's energy portfolio, and since the project is funded by the Department of Energy, all of Utah's Congressional delegation are kept abreast of the project's progress. Sen. Mitt Romney and U.S. Representative John Curtis toured the site on August 16, 2022 and October 11, 2022, respectively.

Figure 3. *Senator Mitt Romney visiting the Utah FORGE site.*

To ensure that Utah FORGE continues to enjoy the public trust it has garnered, members of the community have been encouraged to express their views and concerns throughout the life of the project. Along with frequent in-person meetings and presentations, the Utah FORGE website will always serve as a venue and method for bilateral communication to permit proactive and constructive discussion.

2.3. Outreach and Communication Around Induced Seismicity

Building on Utah FORGE's ongoing and successful outreach and communication activities over the past several years, a specific plan has been developed by UUSS, the State agency charged with monitoring seismic activity within the State. While following the UUSS guidelines, Utah FORGE will also provide additional proactive outreach and communication to the local community and all other stakeholders beyond the requirements of the State.

2.4. The Location of the Utah FORGE Project

Outreach and communication to local stakeholders is tailored to reflect the demographic makeup of the area. For example, the Utah FORGE project is located approximately 16 km northeast from the town of Milford, which has a population of ~1400 residents. Milford is in Beaver County, which ranks 24th out of 29 counties in the state for population density and is designated as a rural region by the State. Milford sits in the center of Utah's Renewable Energy Corridor that includes conventional geothermal plants, solar and wind fields, and a biogas facility. The importance of Utah FORGE as a center of EGS research and development has not gone unnoticed by the local residents and state officials.

The communities of Beaver County are experienced with naturally-occurring seismicity. Most recently, on January 17, 2020, the 3.9 magnitude Minersville Earthquake, a naturally occurring event unrelated to Utah FORGE, occurred 12 km southeast of Milford. No damage was reported. Following the January earthquake, 189 individuals (mostly from the area) proactively logged onto the USGS website's Did You Feel It? page to contribute data to its "Felt Report" (Figure 4). Despite the locals' familiarity with seismicity, it is still paramount to openly discuss the possibility of triggered or induced seismicity frequently.

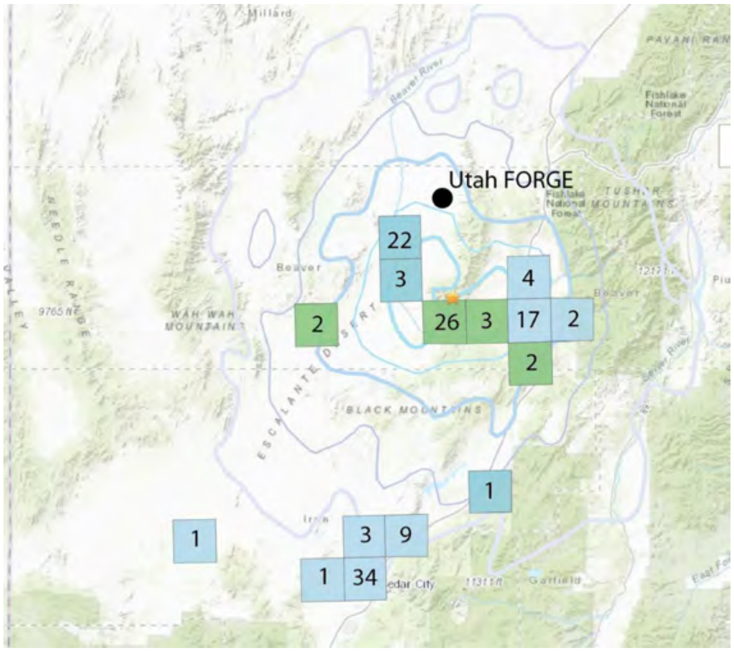


Figure 4. *Number of reports and intensity levels logged on USGS 'Did You Feel It?' website following the M 3.9 Minersville earthquake (https://earthquake.usgs.gov/earthquakes/eventpage/uu60356907/dyfi/intensity)*

2.5. Seismic Mitigation Plan

Continued outreach, education, and communication are the key elements to helping residents understand the meaning of induced seismicity and microseismicity, how it is monitored and what ramifications are associated with it. Transparent and open, multilateral interaction with stakeholders is the cornerstone to Utah FORGE's induced seismicity communication strategy.

An Outreach & Communication Implementation Program is in place to communicate information regarding injection stimulations operations that may or may not induced seismicity. Communication will occur pre-stimulation, during stimulation and post-stimulation to inform various stakeholders of operations and activities (Table 1). The program provides an overview of activities, the intended audience(s) for each action, and the expected timeframe for each.

Table 1. *Communication and Outreach Implementation Program.*

Phase	Type	Audience	Timing
Pre-stimulation	Public outreach, professional meetings, and discussions	Public, media, regulators, elected officials, landowners, other stakeholders	Ongoing since 2014
Pre-stimulation	Social media and website updates	Public	Weekly
Pre-stimulation	Local newspaper / newsletter / social media notices	Public	2-3 weeks prior to stimulation
Pre-stimulation	Informational kiosks on Antelope Point Road near Utah FORGE site	Public	Fall 2020
Pre-stimulation	Public outreach meetings	Elected officials, public	2-4 weeks prior to stimulation
Stimulation	Public outreach meetings	Elected officials, public	Quarterly and as needed
Stimulation	Social media and website updates	Public	Weekly
Stimulation	Daily stimulation and seismicity reports	DOE	Daily
Stimulation	Exception Reports	DOE	As required by triggers
Post-stimulation	Public outreach meetings	Public, local media, elected officials	Following stimulation and ongoing quarterly

Pre-stimulation

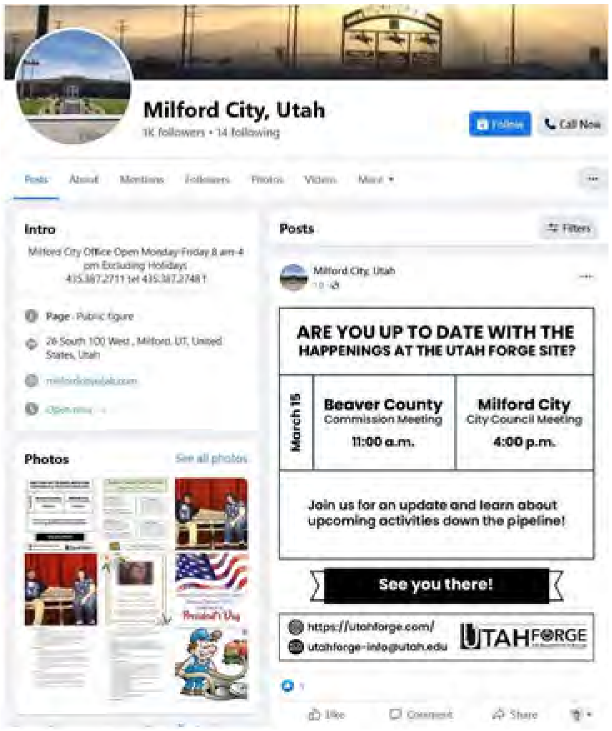
Since its inception, Utah FORGE has laid the groundwork to inform the community and various stakeholders to better understand geothermal energy, EGS, and seismicity. Public meetings and discussions with a variety of stakeholders, including the community, members of the media, elected officials, regulators, and landowners began in 2015. This outreach has included:

1. Open access and communication with all stake holders on a routine basis
2. Up-to-date information on various aspects of the project
3. Regular meetings with all stakeholders
4. Opportunities for the public to ask questions and/or express concerns – both in person and electronically
5. Field trips and visual media

As part of that outreach, the Utah FORGE website (UtahForge.com) has been updated consistently with new content and information. To ensure stakeholders are aware of any new information, as well as to promote other content, the O&C Team proactively posts regularly on its social media platforms. These include:

- Facebook (https://www.facebook.com/utahforge)
- Twitter (https://twitter.com/utahforge)
- LinkedIn (https://www.linkedin.com/company/utah-forge)

To help inform the local community about scheduled drilling and related activities, Utah FORGE collaborates with local media and the area towns to help generate interest in attending public meetings and to educate the community about seismicity (Figures 5 and 6).



Milford City, Utah

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Intro

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Milford City, Utah

ARE YOU UP TO DATE WITH THE HAPPENINGS AT THE UTAH FORGE SITE?

March 15	**Beaver County** Commission Meeting 11:00 a.m.	**Milford City** City Council Meeting 4:00 p.m.

Join us for an update and learn about upcoming activities down the pipeline!

See you there!

https://utahforge.com/
utahforge-info@utah.edu

Figure 5. *Social Media post by Milford City.*

photo by Devin Elliott

THE Beaver County JOURNAL

BEAVER • MILFORD • MINERSVILLE • ADAMSVILLE • GREENVILLE • EAGLE POINT • NORTH CREEK • COVE FORT • MANDERFIELD

Wednesday, March 30, 2022 • Issue # 725

Commission Corner

by Stephanie Laws

In Commission Meeting on March 15th, 2022, Bureau of Land Management (BLM) Field manager, Paul Briggs reported on ongoing and proposed projects including new geothermal leases from Ormat in Beaver and Millard Counties, the BLM has also approved a new communication tower for the Mountain Home area that will expand western Beaver and southwestern Millard Counties' radio coverage for the Utah Highway Patrol, Utah Division of Wildlife Resources, other local and state public safety agencies, as well as federal law enforcement.

New campsites have been added near Hanging Rock. Improvements to the Granite Mountain Recreation Area will include the construction of two trailheads, a new trail system, a campground and other features to enhance recreation. These improvements will help accommodate and manage increasing recreation use. Existing BLM campgrounds will also be repaired. Sulpher HMA (Herd Management Area) gather just completed with Bible Springs Complex and Frisco HMA gathers planned later in the year. All of this information can be found on www.blm.gov.

Jared Whitmer with the Forest Service coordinated with the Commissioners on proposed shared stewardship actions for the Fishlake Ranger District this summer. Whitmer also discussed proposed management projects for the upcoming year. There will be a new law enforcement officer on the mountain this year and he will be coordinating with the Sheriff's Office.

Gosia Skowron and Christopher Katis gave an update on the FORGE project near Milford. They announced that well stimulation will start in mid to late April. New drill rigs and tankers should start showing up in early April. Business owners, hotels and restaurants should see a lot of activity from the FORGE team. For more information on the FORGE project got to *www.utahforge.com*.

It was great to have Beaver City Council members Owen Spencer and Alison Webb, Representative Chris Stewart's staffer Cindy Bullock, and Senator Evan Vickers in attendance for the FORGE update and discussions.

Burke Swindlehurst with Lifetime Fitness spoke to the commissioners about the annual Crusher in the Tushar bike race. Registrations for the event sold out in just over an hour. The Large Public Assembly Permit for the event was unanimously approved by the Commissioners and the race is scheduled for Saturday, July 9th. There will be 850 riders this year. We appreciate Burke and his efforts to bring in this very successful event each year. Information about the event can be found at www.tusharcrusher.com

Jalen Hardy with DieselFam presented the Commission with a new event called the Diesel Days Truck Show. The event will take place at the fairgrounds in Minersville on April 30th. The Commissioners approved the Large Public Assembly Permit for this event and expressed their support for a successful outcome. For more information visit www.dieselfam.us.

The Commissioners, along with Beaver County Road Supervisor Cory Beebe, met with UDOT and property owners to finalize the new Navaho Trail bridge in the Grove. Construction will start later this year. The Commissioners worked closely with UDOT to obtain a fully funded grant for this project.

The Beaver County Commissioners strive to keep residents informed of the activities and projects taking place in Beaver County. Commission meetings are open to the public and anyone is welcome to attend, commission meetings are the 1st and 3rd Tuesdays of every month at 10:00AM. They are public meeting.

***Figure 6.** Story in The Beaver County Journal noting stimulation discussion.*

To continue educating the community about geothermal energy and the Utah FORGE project, seasonal posters have been installed in a 3-sided display kiosk located in Milford's visitor information center, also known as Caboose Park.

Figure 7. *One of the posters installed in Caboose Park.*

To prepare the community for stimulation, outreach includes focused education about EGS and induced seismicity during meetings with the Beaver County Commission, Milford City Council and Beaver County Planning. All the meetings are open to the public. Topics in the presentations include:

- Why is seismicity associated with EGS activities: The formation of an EGS reservoir involves the release of energy (stored strain) in the form of microseismicity (very small earthquakes). Since these earthquakes are the result of industrial (manmade) activities, these earthquakes are referred to as induced seismicity.
- The cause of induced seismicity: The fundamental causes of induced seismicity are generally well understood. They include changes in pore pressure, thermal stress, volume change, and chemical alteration of rock slip surfaces.
- Monitoring for Induced seismicity: All drilling and stimulation activities will be monitored using an extensive network of very sensitive seismic monitoring instruments. The instruments can monitor microseismicity long before it reaches a level that can be felt. A detailed plan, referred to as a Traffic Light System (TLS) has been developed to mitigate against the generation of larger earthquakes. The plan defines mitigation measures. These measures may include ramping-down or stopping activities associated with the EGS operations entirely.
- How the public can follow the seismic monitoring: Microseismicity can be followed in real time on the Utah FORGE website (quake.utah.edu/forge-map) Additionally, each of the three area libraries has a computer set to the UUSS page to allow residents to monitor seismicity in real time.

Public meetings, local media coverage, stakeholder social media and one-on-one discussions with influencers and partners facilitate this successful outreach.

Stimulation

Stimulation is the process of creating the fractured EGS reservoir through high-pressure water injection. Microseismicity is typically generated during these injection periods. Felt seismicity, while still a low probability, is more likely to be generated during these injections. To ensure the community is proactively kept updated during simulation, Utah FORGE will continue to provide complete and credible information on the project's activities and progress, and address potentially all issues such as the possibility of a seismic event.

To encourage the discussion throughout the stimulations, Utah FORGE will hold quarterly meetings, publish additional information in the local media, post on its social media platforms (and whenever possible collaborate with local stakeholders such as the town of Milford to repost or produce their own social media postings), and update the website regularly.

The content and outreach will focus on the status of the project, progress being made, any issues, and learnings. In-person presentations specifically for students to discuss geothermal energy, EGS, and seismicity will continue. The page on the Utah FORGE website that serves as a compendium of seismic information, including helpful downloadable information for students and their families (https://utahforge.com/seismic-monitoring/), will continue to be updated.

Continuing to foster an open dialogue, the local community and all other interested parties will have the opportunity to express any concerns and raise questions both at these public meetings, as well as by contacting Utah FORGE directly.

While meetings are a beneficial way to share overall plans and information, when the public feels unexpected ground motion, they will be able to obtain rapid confirmation and details regarding the seismic event. Seismic monitoring is conducted by UUSS. This agency is charged with monitoring seismic activity in Utah and maintains a public website (https://quake.utah.edu/) to disseminate information regarding Utah earthquakes. A link to this site is available on the Utah FORGE website, along with real-time, interactive information about monitored seismicity at the FORGE site (https://quake.utah.edu/forge-map). As stated above, to facilitate access to digital information, like these and the Utah FORGE website (https://utahforge.com), computers have been provided to the libraries in Milford, Beaver, and Minersville.

For the Utah FORGE immediate area, the plan is to issue alarms to key project personnel and emergency managers and post information to the UUSS, U.S. Geological Survey, and Utah FORGE websites about earthquakes with M ≥ 2 and generate ShakeMaps for earthquakes M ≥ 2.5 within approximately one hour. The information will also be automatically shared through social media. For widely-felt events or those with M ≥ 3.5 UUSS will issue a press release. The press release will be shared on the UUSS and the Utah FORGE websites and through social media channels. Since all earthquakes are contributed to the USGS comprehensive catalog

(Comcat), others desiring automatic alarms are recommended to sign up for the USGS ENS service (https://earthquake.usgs.gov/ens/).

For M < 2 events, routine location and magnitude determination is conducted during business hours and posted to the web at that time. These events will not be felt. Waveform seismic data are also available in near-real-time via webicorders (https://quake.utah.edu/forge-map). The Project Manager's contact information and the contact information for UUSS are on the FORGE website, and available from local first responder officials.

Finally, a "calling tree" has been established in order for FORGE management to be notified of M ≥ 2 events located within the immediate FORGE area or for M ≥ 3 in the larger FORGE region.

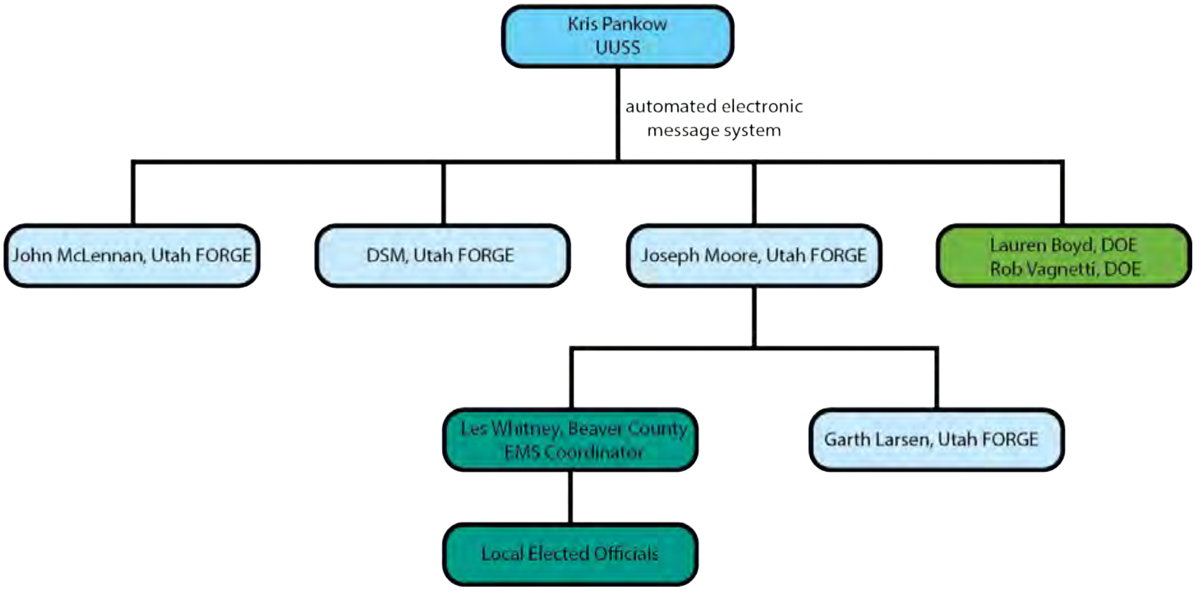


Figure 8. *"Calling tree" protocol for seismic events M≥2*.

The Utah FORGE Principal Investigator will also contact the outreach and communications team to ensure information is shared on the website and through social media channels in a timely manner, and to help prepare for any potential media requests.

During the stimulation period, daily stimulation and seismicity reports will be sent to the Department of Energy. Exception reports will be sent to the DOE as warranted.

Post stimulation

Following stimulation, representatives from Utah FORGE will hold a public meeting in the area to provide an overview of the stimulation, report findings, and discuss future activities. Going forward, additional quarterly update meetings will serve as a vehicle for continued community reporting.

Finally, to continually grow its presence within the community, Utah FORGE will have a presence at local events such as the Beaver County Fair, as noted above. Also, as discussed previously, a virtual visitor center is being developed to provide information on the project.

2.6. Conclusion

Utah FORGE is committed to being a good neighbor. The Outreach and Communications Seismic Mitigation Plan is designed to showcase this commitment. The groundwork has been laid. Utah FORGE is a known entity and a trusted partner to its various stakeholders. By clear, open communication provided through myriad vehicles, the project endeavors to continue earning the trust and cooperation of the community.

3. CRITERIA FOR GROUND VIBRATION AND NOISE

“This section provides guidelines for selecting criteria for vibration and ground-borne noise to assess the potential impact of EGS-induced seismicity on the built environment and human activity.” (Majer et al., 2016). While it seems that the intent of the best practices is more general, in this document we want to establish the criteria for ground vibration and noise specific to the Utah FORGE site. This is the information that is needed in the subsequent sections to assess risk and to design for mitigation.

Following from Schultz et al. (2020), we consider the Utah FORGE area to be uninhabited transitioning to rural. While there are scattered farms, the region surrounding Utah FORGE is largely uninhabited. The town of Milford, 16 km to the south, would be considered rural given a total population of ~1400. Apart from population considerations, there are three nearby industry-related facilities. The Blundell geothermal power plant, scattered industrial pig farms, and a wind farm within ~5 km of the Utah FORGE site (Figure 9).

Based on the rural nature (see overview in Figure 9) and the distance to these facilities. We review ground shaking thresholds from different studies. Richter (1958) proposed thresholds in terms of acceleration—10% g for damage to weak structures and 0.1% g as a lower limit for the felt threshold. Siskind et al. (1980) argue that particle velocity is the best ground motion predictor and proposed a threshold of 0.1 – 0.2 cm/s for cosmetic damage, 12.5 – 25 cm/s for structural damage, and 0.12 cm/s as a felt threshold. Schultz et al. (2020) take a more conservative approach and propose thresholds for ground motions that would be considered a nuisance versus those that might cause damage (0.03 to 0.4 cm/s). Worden et al. (2012) map various ground motion levels both PGA and peak ground velocity (PGV) to intensity, which is a measure of perceived ground shaking and impact of the ground motion (Figure 10). Based on this analysis, the felt threshold is at 0.3% g or 0.1 cm/s, levels of shaking that may produce very light damage start at 6.2%g or 4.7 cm/s, and moderate damage is consistent with 22% g or 20 cm/s. We summarize these values in Table 2.

Other threshold considerations relate directly to the industrial activities. Vibration is actively monitored at the Blundell power plant (Michael Saunders, personal communication 2018) and plant operators have not voiced any concern regarding potential induced seismicity from Utah FORGE. They have also agreed to host a seismic station on their property. Seismic analysis of wind turbines has been performed in various studies. Factors that influence how ground motion translates into the structure include resonance frequencies, the operational status of the windmill, and soil effects (Katsanos et al., 2016). Kjørlaug et al. (2014) looked at the effect of both vertical and horizontal ground motions and found that small to moderate (moderate is typically defined to be M 5.0 to 5.9) earthquakes will not govern the design for windmills located in stiff soils. The average shear velocity in the upper 30 m in the area near the Utah FORGE operations site and the wind farms is 422 m/s (Zhang and Pankow, 2020), classifying as a stiff soil. It is also relevant that, per Utah building codes, windmills need to meet material design limits as well as structure design requirements for earthquakes and wind (Barry Welliver, structural engineer and former Chair of the Utah Seismic Safety Commission, personal communication, August, 2020).

Table 2. *Summary of ground motion thresholds.*

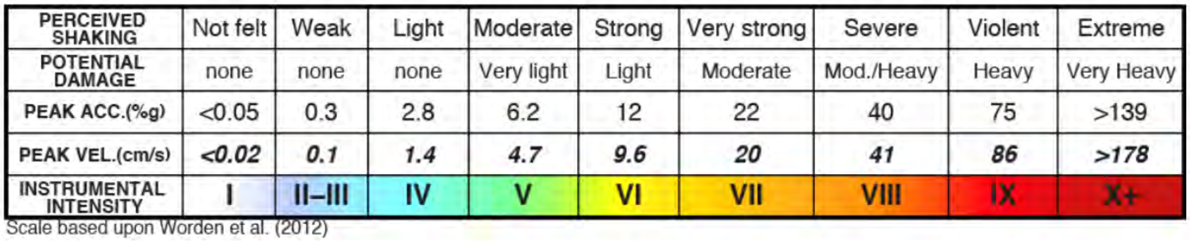
	Felt	Very Light Damage	Moderate Damage
PGA %g	0.1 to 0.3	6.2 to 10	> 22
PGV cm/s	0.1 to 0.12	0.1 to 4.7	12.5 to 20

Having established felt and damaging ground motion criteria, we next look at background ground motion levels in the Utah FORGE area. As pointed out in Majer et al. (2016), it is unreasonable to require “that EGS-induced ground motion never exceed a certain magnitude in areas where that magnitude is often exceeded by natural seismicity.” Here we extrapolate from magnitude to ground motion and find that it is unreasonable for EGS induced ground motions to have lower ground motion thresholds than background ground shaking that may come from other seismic sources (e.g., earthquakes, explosions, trains, airplanes) provided local background shaking is not considered a nuisance. To establish the background ground motion levels for the town of Milford and near the Utah FORGE site, we calculated PGV for each hour from September 2017 through January 2018, using data collected by a strong-motion instrument located in Milford and station FOR3 located at the FORGE site, and for the Blundell power plant for each hour from January 2019 through May 2019 using data collected at station FORB. Figure 11 shows that other than a few outliers, PGV tends to be < 0.1 cm/s in Milford and < 0.05 cm/s at the Utah FORGE site and power plant. Further, two earthquakes (M 3.2 and M 3.0) struck 9 – 10 km southwest of Milford in 2021. The Milford High School accelerometer recorded PGA 0.55%g and 0.24%g and PGV 0.13 cm/s and 0.06 cm/s for the two earthquakes respectively. There were three felt reports for the M 3.2 earthquake and none for the M3.0. Using these ground motion recordings, we bound the nuisance threshold for Milford to be PGV

> 0.12 cm/s. Seismic events with M > 3 at the Utah FORGE site would be needed to produce this level of ground motion (Figure 12).

To bring this information together, we plot PGV versus epicentral distance for a M 3, 4, and 5 earthquakes with a depth of 1 km using the Chiou et al. (2010) ground motion relation for small earthquakes. (Figure 12). The Chiou et al. (2010) relation was shown to fit ground motions recorded from 163 Utah earthquakes (3 < M < 5.5) at distances from 4 to 200 km with little to no bias (Pankow, 2012). In conclusion, for the M 4 or smaller events typical of induced seismicity, we do not anticipate ground vibration and noise to be an issue. Risk is further discussed in Section 6.

Figure 9. *Map from Google Earth showing the rural nature of the area and the relative distances between the FORGE site and the limited structures.*



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Figure 10. *Mapping of ground motion to intensity that is used in generating ShakeMaps (Wald et al., 2001; Worden et al., 2012).*

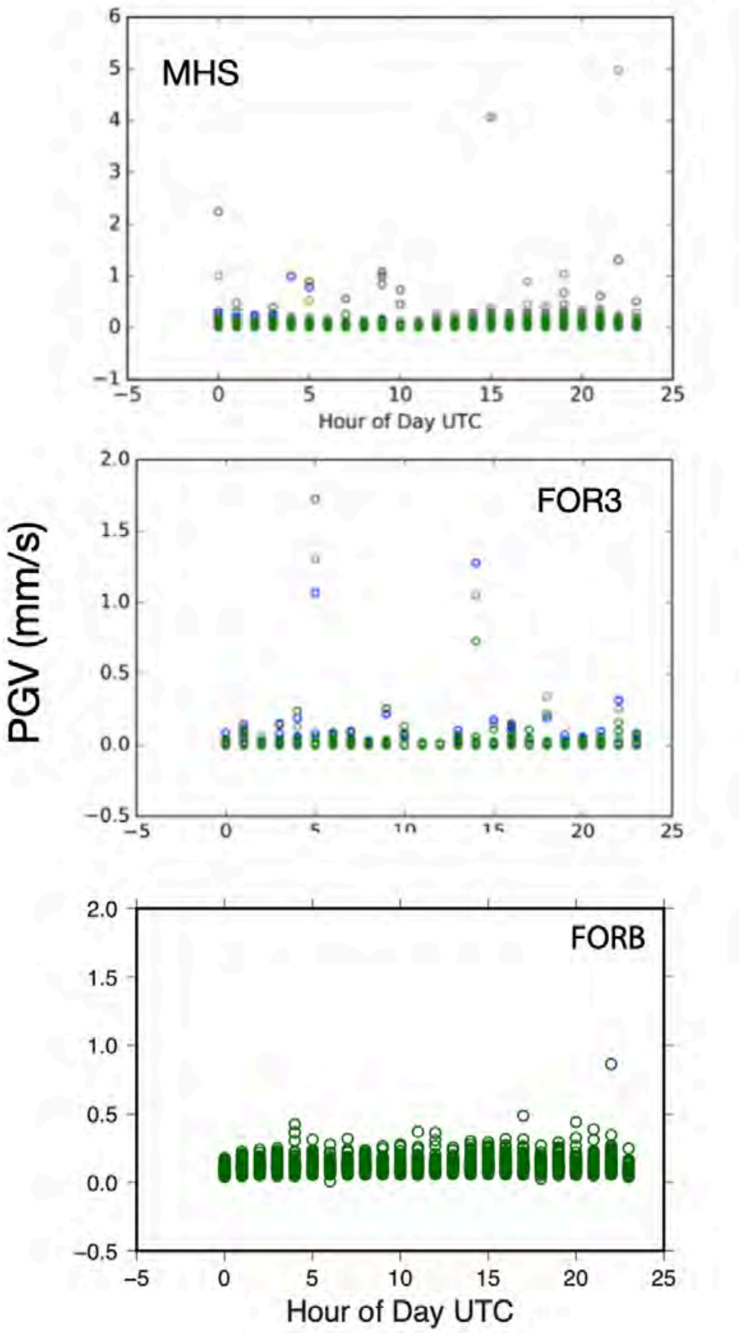


Figure 11. *Background peak ground velocity levels for each hour September 2017 through January 2018 for seismic stations MHS located in the town of Milford and station FOR3 located within the Utah FORGE polygon (right). Colors indicate components: east (green), north (blue), and vertical (gray). Background maximum horizontal peak ground velocity levels for each hour January 2019 through May 2019 for seismic stations FORB located near the Blundell power plant. Time is plotted by hour to show the diurnal cycle.*

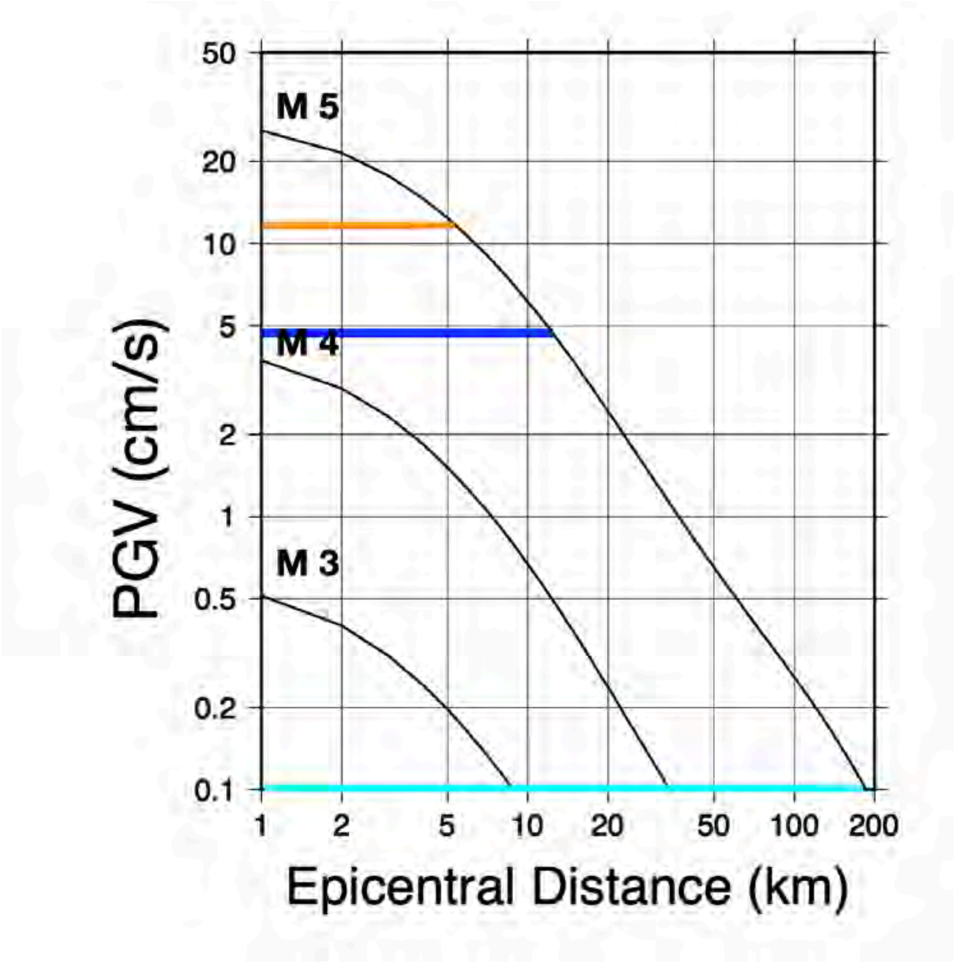


Figure 12. *PGV curves (Chiou et al., 2010) for M 3, 4, and 5 earthquakes (depth 1km). Colored lines indicate threshold levels for felt (cyan), very light potential damage (blue), and moderate damage (orange) following Figure 10 (Worden et al., 2012).*

4. COLLECTION OF SEISMICITY DATA

“The purpose of this step is to gather the data on seismicity that will be needed to accomplish the objectives of the EGS/Geothermal project” (Majer et al., 2016). Local seismic monitoring involves two main aspects. First, we need to know characteristic natural seismicity levels as a standard for comparing seismic activity during Utah FORGE project operations. Second, we wish to establish a permanent seismic network for capturing seismicity that may be related to Utah FORGE such as induced events or reservoir development events occurring outside of deep borehole monitoring volumes or times.

4.1 Collect unbiased (in time and space) local seismic data prior to Utah FORGE operation

Seismic activity in the area surrounding the Utah FORGE site has been steadily monitored by UUSS since 1981. Event locations and magnitudes are captured in the UUSS catalog. To evaluate the historical seismicity, we review four relevant earthquake catalogs: (1) a uniform moment magnitude catalog (1850–September 2012; Arabasz et al., 2015, 2017) (Figure 1); (2) the microseismic catalog (August 1979–August 1981) collected by Zandt et al. (1982) (Figure 13); (3) the UUSS earthquake catalog, 1981–2016 (Figure 13); and (4) the catalog collected as part of the Utah FORGE project (November, 2016–March 31, 2023) (Figure 14). For all four catalogs, seismicity near the Utah FORGE site is characterized by low-magnitudes (M < 2.5) occurring at low rates (on average ~5 earthquakes/yr with the regional seismic network and ~195 earthquakes/yr with the more dense and, hence, more sensitive Utah FORGE network). Only 10 earthquakes with M > 2.5, the largest being M 3.8, occurred in the almost 40 years between 1981 and 2020.

Using the Arabasz et al. (2015) catalog of tectonic earthquakes, we observe that the largest event in the study area (M_W 4.05) occurred in 1908 and was located near the town of Milford (Figures 1 and 13). The closest significant earthquake (M > 6) occurred in 1901 in the Tushar Mountains north of Beaver ~50 km to the northeast of the Utah FORGE site (Figure 1). The largest recent tectonic event in the general vicinity to Utah FORGE was the January 2020 M_L 3.9 earthquake that occurred under the Mineral Mountains 12 km southeast of Milford (outside of the FORGE study area). This recent event is a good proxy for what might be expected from an M 4 induced earthquake at Utah FORGE, given the comparable distance to Milford. Figure 15 shows the PGA map generated by ShakeMap for this event. The peak ground motion is 2.19% g (0.87 cm/s) near the source and for the town of Milford it is 1.1% g (0.4 cm/s). One hundred fifty-six people reported to the U. S. Geological Survey “Did You Feel It?” web site (Figure 4). The maximum shaking was a Modified Mercalli Intensity (MMI) of V corresponding to moderate shaking and perhaps very light damage. The majority of reports were less than MMI IV.

Before geothermal production at Roosevelt Hot Springs[1], Zandt et al. (1982) installed a local seismic array to detail the background seismicity. During the approximate 2-year deployment, they concluded that there are few earthquakes M > 2. They did capture one energetic seismic swarm (1044 earthquakes M ≤ 1.5) during June through August 1981. This swarm occurred east of the present borehole field at the Blundell power plant, primarily in the Mineral Mountains (Figure 16). The seismicity trend was mostly east-west. There is a clear depth separation for events locating on the east side of the swarm zone versus the west side. We interpret the deeper events to be tectonic in origin. The smearing of events to the west is a function of the asymmetric seismic network geometry, where all seismic stations are located to the west of the source zone. Zandt concluded that the swarm was primarily naturally occurring and was consistent with either (or both) seismicity occurring along the projection of the east-west trending Mag Lee fault or along northwest-trending faults mapped by Nielson et al. (1978). A few of the earthquakes located at shallow depths on the west end of the swarm zone and Zandt

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[1] This is the Blundell power plant.

et al. (1982) speculated that these may have occurred along the Opal Mound Fault or were the result of seismicity induced by the development activities associated with the power plant.

Pankow et al. (2019a) showed that the events in the Zandt swarm zone form two distinct clusters. The first cluster appears related to activities associated with the Blundell power plant. The events are shallow (< 2km) and epicentrally dispersed. The second cluster locates at greater depths and further to the east. Many of the larger events in the Zandt catalog from 1981 were also detected and located by UUSS using the regional network. These events all locate in the cluster to the east of the Blundell swarm (Figure 16). Depths for these events range from 0 to 8 km relative to sea level. Mesimeri et al. (2021) looked in detail at seismicity occurring within this swarm zone from 2016 – 2019. Using earthquakes from the UUSS catalog located within the swarm zone as templates, they used matched-filters to expand the earthquake catalog by over 1000 events ($-2 < M < 2$). During this time-period 15 bursts of swarm-like activity were identified. Locations indicate that these events cluster ~ 4 km east of the Blundell Power Plant in a concentrated < 2km long E-W striking zone. The most recent energetic swarm that locates in this same concentrated region occurred in 2020 (Petersen and Pankow, 2023).

In support of the Utah FORGE project, events in the UUSS catalog (1981–2016) were relocated using *HYPOINVERSE-2000* (Klein, 2001) configured with 14 velocity models for the entire Utah region. The main change was to calculate hypocentral depth relative to sea level (Figure 13). The relocation of the events caused slight changes in location, and overall provided tighter spatial clustering. No earthquakes in this time period locate within the proposed Utah FORGE footprint (Figure 13). Earthquakes occurring outside the Utah FORGE footprint during this time period range in magnitude from M -0.09 to 3.91. The average horizontal and vertical 90% confidence errors for these earthquakes are 0.879 km and 4.863 km, respectively. Spatially, there are three distinct clusters: (1) north northwest of Milford, (2) northeast of Milford, and (3) scattered seismicity including the swarm zone found by Zandt in the Mineral Mountains (Figure 13 and 14).

Waveform analysis and event timing indicates that events to the northwest of Milford (labeled Quarry, Figure 13) are quarry blasts, not tectonic earthquakes (Pankow et al. 2019a). Evidence for this conclusion includes their epicentral proximity to quarries (conspicuous on Google maps), small magnitudes (M 0.49 to 2.05), shallow depths, restricted timing (all events occur during daylight hours), and highly correlated waveforms implying a similar location and source mechanism. The second cluster is located northeast of Milford near the Milford airport and not far from the M_W 4.05 1908 Milford earthquake (Figure 13). The magnitudes in this cluster range from M 0.46 to 3.91, and the events occur throughout the day and night (random timing). This cluster is interpreted as tectonic in origin. Of the remaining seismicity located in the Mineral Mountains, most locates east of the Opal Mound Fault in the Zandt swarm zone with a second cluster to the south near station FOR7 (Figure 14). In 2021 an energetic swarm occurred south of Milford, Utah in an area of minimal prior cataloged seismic activity (Whidden et al., 2023).

To ensure that we detect seismicity down to magnitude 0, in November 2016 (under Phase 2A of the FORGE project) a five-station surface seismic network was installed (Figure 14). This array remains largely operational to date and was augmented in 2019 to include a borehole sensor

(FORK) and three strong-motion accelerometers: (1) FORB, near the Blundell power plant; (2) FORW, in the wind farm; and (3) upgraded FOR3 to include an accelerometer). The network was further updated in 2020 through 2022. New surface broadband stations (FOR5, FOR6, FOR7, and FOR8) were added to the network. FOR4 was removed and FOR 3 was upgraded to a shallow borehole site and renamed FSB3. FSB3 and two additional sites (FSB1 and FSB2) located ~3 km from the 58-32 pad are shallow (~80’) boreholes instrumented with three-component broadband and three-component accelerometer sensors. Three additional shallow boreholes (~100’) located at a radius of 8km form 58-32 were instrumented with three-component broadband sensors (FSB4, FSB5, FSB6). Data from this network is combined with data from the regional seismic network to locate and determine magnitudes for new seismic events (Figure 14). The improved monitoring network with stations closer to the source zone also improved location accuracy. The 90% confidence location errors decreased to 0.79 and 6.56 km horizontal and vertical, respectively. Spatially, most of the seismic events locate east of the Opal Mound Fault primarily in or near to the Zandt swarm region (Figure 14). There is also a small cluster in the southern Mineral Mountain source zone. Of importance, outside of stimulation time periods, no events are located in the FORGE footprint.

Additional seismic instrumentation in the area includes, an accelerometer at Milford High School, which was re-installed in December 2020. Seismic instrumentation for this site was provided by the State of Utah. This seismic station provides background monitoring of ground motions for Milford, the closest town to Utah FORGE. UUSS also operates accelerometers located in Beaver, the next closest town to Utah FORGE. To further augment seismic monitoring, four stand-alone, dense, short-period digital Fairfield Nodal temporary seismic arrays were installed within and/or adjacent to the proposed Utah FORGE site for approximately one-month duration per deployment (data available at the EarthScope Data Management Center). Trow et al. (2018) used data from those Nodal deployments to detect and locate seismic events not found in the UUSS catalog (Figure 13).

Analysis of the Utah regional catalog for the period 1 January 2000 to 30 June 2003 found a minimum magnitude of completeness (M_{comp}) for the Utah FORGE site of 1.5 (Pankow et al., 2004). Potter (2017) using only UUSS catalog data local to Utah FORGE determined an M_{comp} for the Utah FORGE site of 1.7 and when using the Utah FORGE catalog for events occurring in 2017 an M_{comp} of ~0.5. Most detections after the installation in the FORGE catalog (Figure 14) are well-below the regional network M_{comp} of 1.5 to 1.7 and tend to be $M < 1$ with several events $M < 0$. After the installation of stations FOR5-8 in late 2021, the M_{comp} in the Utah FORGE area is 0.5.

In conclusion, based on the multiple-levels of seismic monitoring: (1) no naturally occurring seismic events locate within the Utah FORGE footprint; (2) natural seismicity over the FORGE region occurs at low rates and with low magnitudes, typically $M < 1.5$; and (3) most seismic events in this area occur under the Mineral Mountains to the east of the Opal Mound Fault with a less pronounced source zone near the Milford airport.

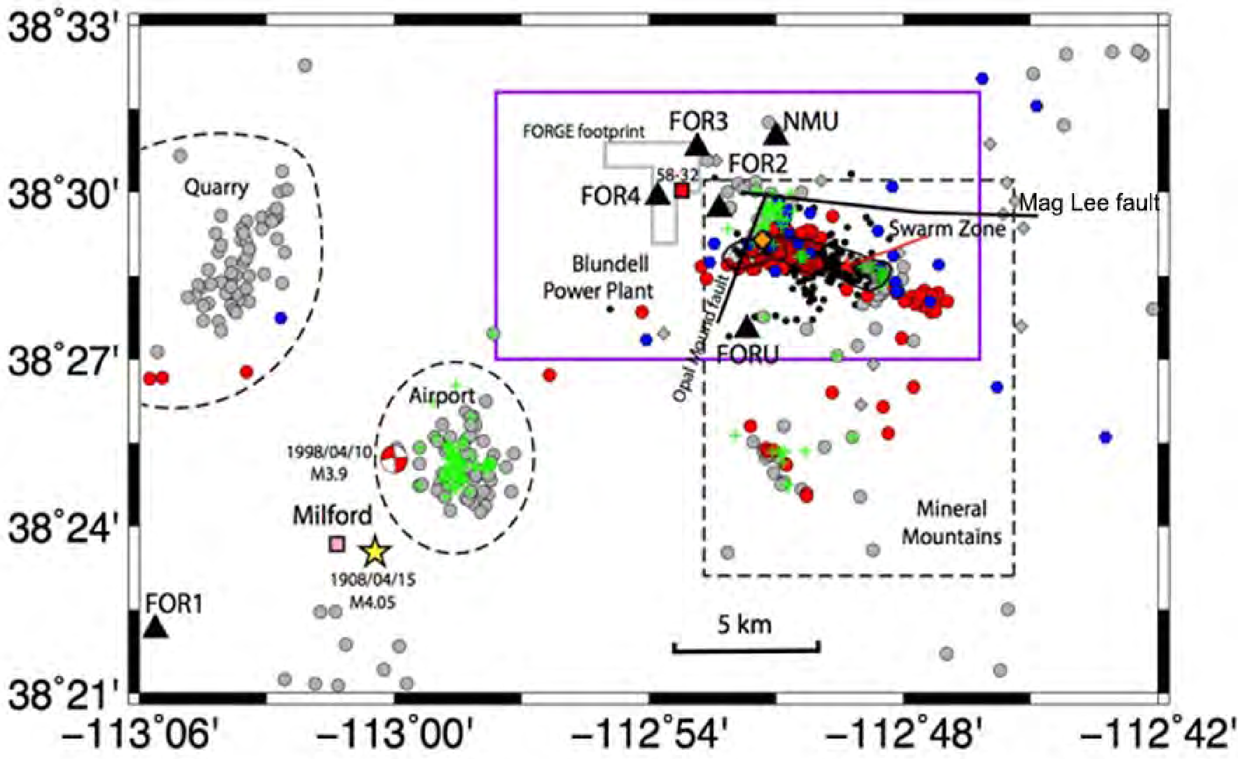
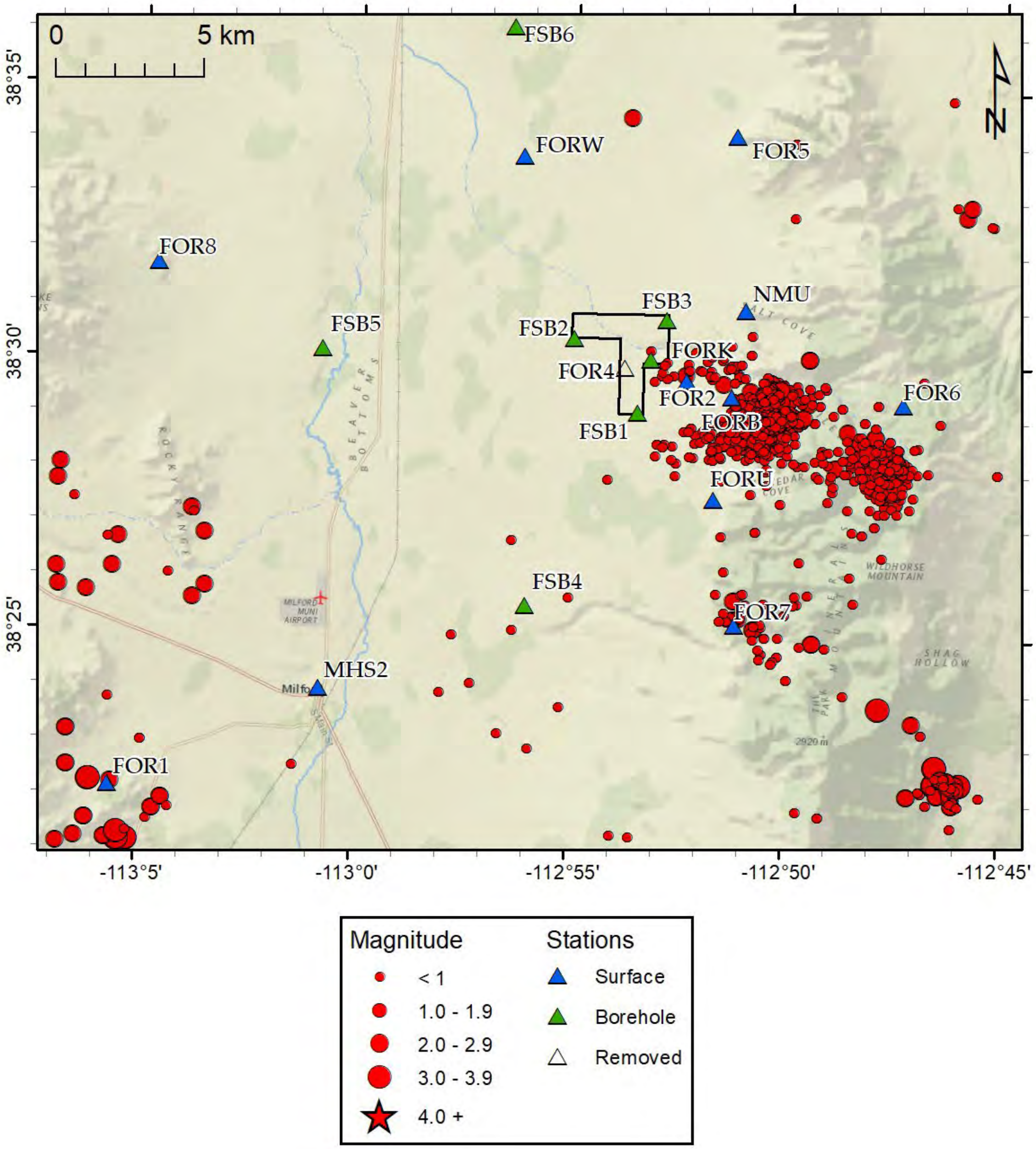


Figure 13.*Utah FORGE earthquake catalog. Grey circles, earthquakes from the UUSS catalog 1981–2016 relocated with an updated velocity model. Black dots, earthquakes from Zandt et al. (1982). Red circles, earthquakes located after installation of the broadband network. Green crosses, events detected by Potter (2017). Blue hexagons, events found from Nodal geophone deployment (Trow et al., 2018). Dashed polygons denote the three source zones discussed in the text. Black triangles, locations of seismic sensors. Grey shaded polygon labeled Swarm Zone, boundaries for earthquake swarm identified in Zandt et al. (1982).*

FORGE Region

(November 1, 2016 – March 31, 2023)



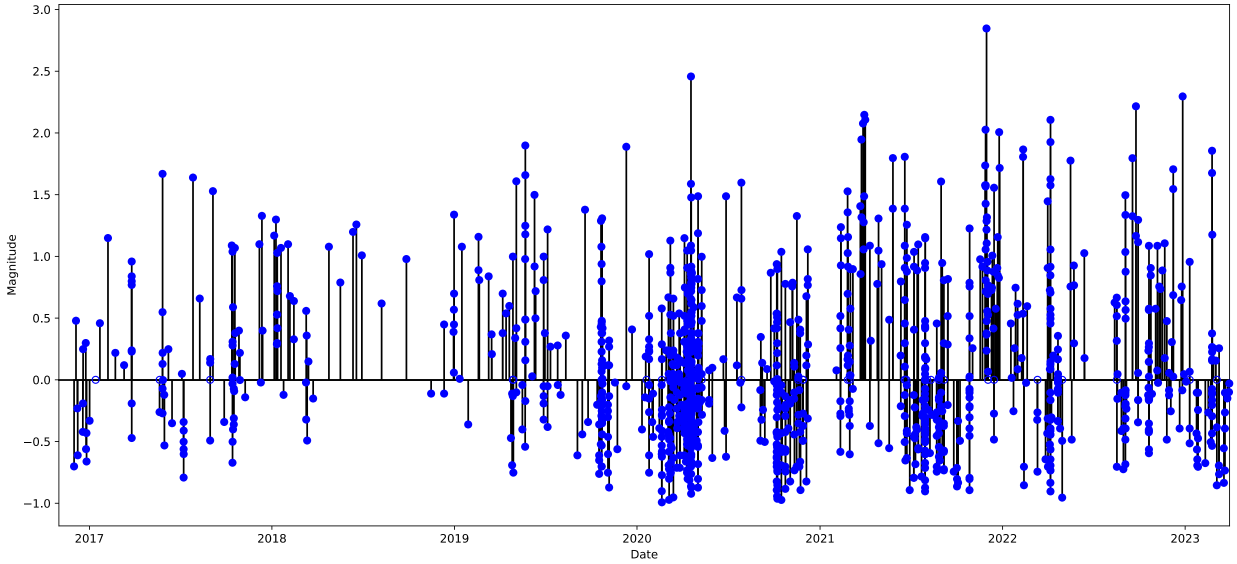


Figure 14. *Map and magnitude time history of earthquakes recorded using the Utah FORGE seismic network, including network updates since 2019 of stations FORK, FORB, FORW, FOR5-8 and FSB1-6.*

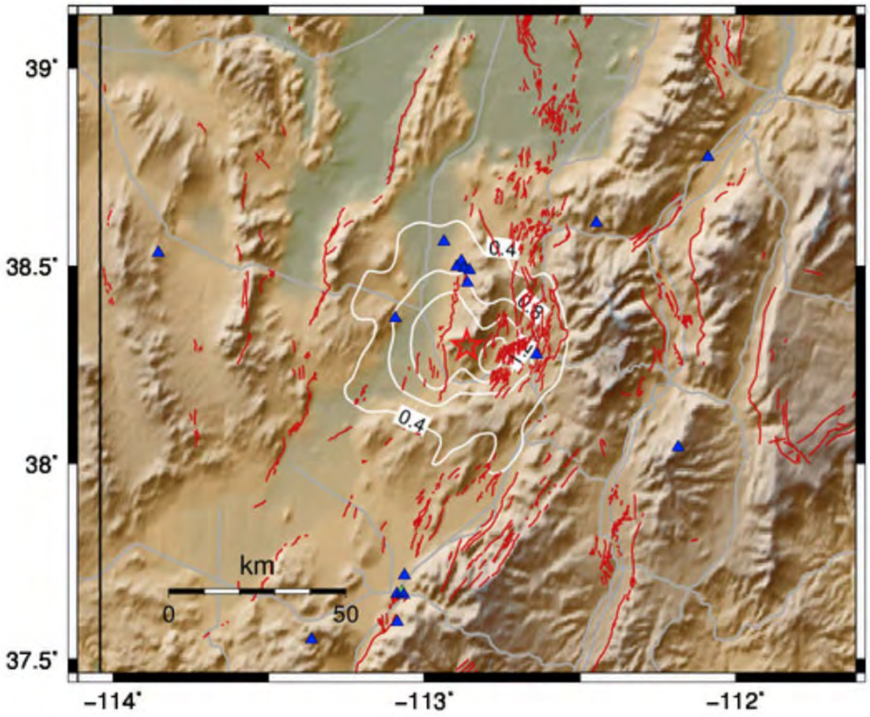


Figure 15. *PGA contours (% g) generated by ShakeMap for the January 2020 M 3.9 earthquake located in the Mineral Mountains south of Milford (red star). Ground motion values are constrained by recordings at the nearby seismic stations. Red lines show the Quaternary faults. Blue triangles are seismic stations.*

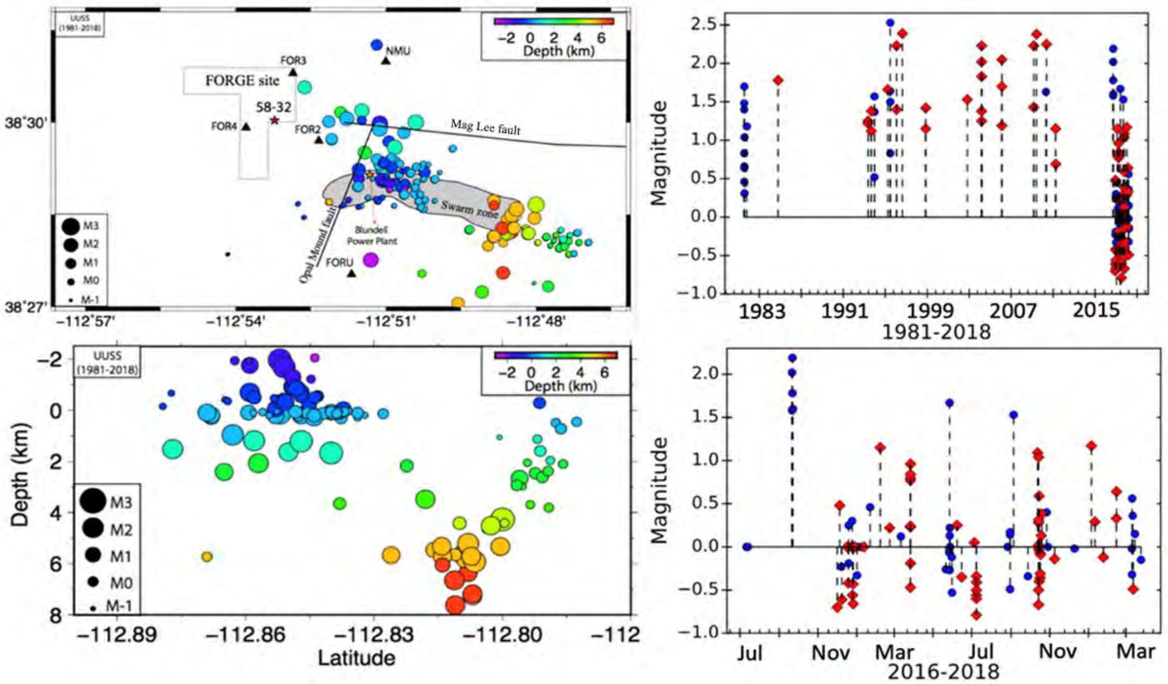


Figure 16. *Seismicity from the UUSS catalog surrounding the swarm zone first identified by Zandt et al. (1982). Left column: epicenters and hypocenters (color signifies depth). Note the two well separated clusters, shallow west and deeper east. Right column: magnitude time history. Blue symbols, events that locate in the east cluster and red symbols, events to the west that are typically shallower than 2 km.*

4.2 Network array design to capture all aspects of seismicity

For seismic monitoring at the Utah FORGE site, there are two main goals: (1) capturing events at an M_{comp} level of 0 (Majer et al., 2012) in order to monitor seismic hazard and inform risk decision metrics, such as a TLS for risk mitigation; and (2) monitoring fracture growth in the reservoir during all injection or production activities to an M_{comp} -2. Infrastructure-related Seismic Monitoring Plans (SMP) are separate documents that are reviewed by the Utah FORGE Seismic Advisory Team (SAT) and DOE-GTO. Rutledge et al. (2020) describes the seismic monitoring plan for the drilling of 16A and the first injection. Pankow et al. (2023) describes seismic monitoring activities since the 2022 stimulation and plans for monitoring the upcoming winter 2023/2024 stimulation.

To inform the 2020 SMP, microseismic data from a hydraulic injection experiment conducted in April and May, 2019, in well 58-32, were processed and presented with requirements for FORGE monitoring to the Utah FORGE SAT in November, 2019. The experiment consisted of low-volume (1 – 15 bbl/min) water injection at three depth levels below 6500 ft in the well. For the experiment, the local Utah FORGE seismic network (Figure 14) was augmented with instrumentation (a 3C geophone and 3C accelerometer) in a shallow (925’) borehole 68-32 (sensor FORK). Separately, a deeper borehole 78-32 was drilled into the granite to a depth of

~3300 ft and was instrumented with a DAS cable cemented in the annulus (Figure 16). Also, during the 2019 injection phases, a 12-level 3C geophone string with 100' spacing was lowered to near the bottom of 78-32. The DAS and string instrumentation were monitored and processed by contractors, Silixa and Schlumberger, respectively. Also, 151 3C Nodal geophones were installed in concentric rings centered on borehole 58-32 where the injection tests were being conducted.

Figure 17 summarizes the detections from the various systems. The geophone string recorded the smallest events and had the most complete detection levels (435 events, M_W -2.0 to -0.5). The detection level from the DAS processing by Silixa found 40 events (Schlumberger determined magnitudes M_W -1.7 to -0.5), and 19 events were identified in the shallow borehole instrumentation (M_W -0.5 to 0.8). Subsequent reprocessing of the DAS data detected 113 events in a highly active 24-hr period with M_{comp} -1.4 (Lellouch et al., 2020). The Schlumberger catalog for the same 24-hour period produced 299 detected events. In the initial processing of the Nodal array data, only 5 events (M_W -0.9 to -0.5) were identified. Reprocessing of the Nodal array data identified 23 events in common with the geophone string catalog (M_W -1.7 to -0.5) (Mesimeri and Pankow, 2020). While it was hoped that the injection testing might help to establish the b-value for the localized FORGE site, there were relatively few events (< 1000) and the events spanned a narrow magnitude range (M_W -2.0 to -0.5) making the calculation of a robust and reliable b-value difficult to obtain.

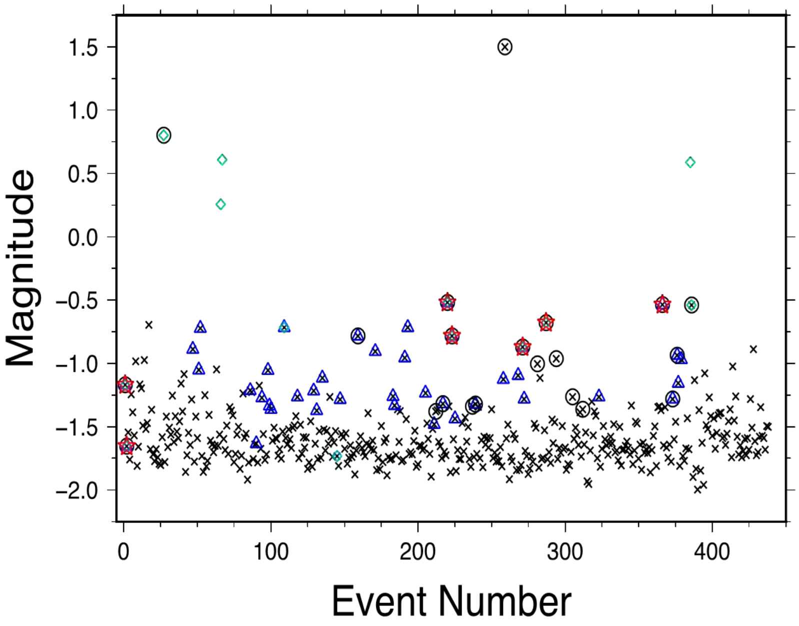


Figure 17. *Initial event detection of seismic events during the mini-stimulation experiment at the Utah FORGE site in April 2019. The first two events are check shots detected by all networks. Black crosses, detections from the geophone string; Blue triangles, detections from the DAS; Black circles, detections on shallow borehole 68-32 instrumentation; Red stars, detections on the Nodal array; and Cyan diamonds, detections by local array. All magnitudes were determined by Schlumberger using data from the geophone string.*

Based upon the event population and detection thresholds, and the desire to have monitoring capability in place at the commencement of the drilling of an extended reach well 16A(78)-32[2], an augmented seismic monitoring instrument array was defined and described in detail including a time-line for installation in an SMP document (Rutledge et al., 2020). Combined broadband and strong-motions sensors were emplaced in shallow boreholes FSB-1, 2, and 3 before drilling well 16A (78)-32 (Figure 14). Together with existing sites FORK, NMU, FORB, and FORU, these constitute a well-sampled, 3 km radius inner ring of sensors to monitor drilling events. Based upon the experience described above, these will achieve the desired M_{comp} 0 or lower beneath the entire Utah FORGE footprint.

Subsequently, a second ring of broadband sensors in shallow boreholes (FSB) or on bedrock (FOR) was established with a diameter of 8 km relative to well 16A(78)-32 (Figure 14). Complementing the good event depth (hypocentral) control of the 3 km ring, the outer ring provides good event horizontal location (epicentral) control. The rings also allow for tracking seismicity that migrates away from the injection zone. The primary monitoring goal of the ring arrays is for induced or natural earthquakes occurring near and below the Utah FORGE footprint.

Seismicity associated with reservoir development was planned to be monitored with deployments of short-term string arrays at depths of several thousand feet in boreholes 58-32, 78-32, and 56-32 (Figure 18). The plan was to have the geophones at reservoir depths. Instrumentation for sensors and wirelines did not meet the manufacturer specification and the monitoring was adjusted on-site. Details of the seismic monitoring can be found in the Seismic Workshop report (Pankow et al. 2022). Despite the modifications to the monitoring, Geo Energie Suisse, produced a high resolutions earthquake catalog (REF) with location precision as low as 40’ for stage 3 (Figure 19) and a magnitude of completeness of -1.3.

For the 2023 SMP, we build on lessons learned from the 2022 stimulation, as documented in the Seismic Workshop report (Pankow et al., 2022). Key elements of the monitoring for the next stimulation include, instrumenting 58-32 and 78B-32 with geophone strings with the maximum temperature for the bottom tool set to 150°C. For 56-32, a two-level tool will be installed at a depth appropriate for the sensor. A sub-sample of the DAS data from 16B(78)-32 collected by OptaSense will also be integrated into the real-time processing. Additionally, a surface network of nodal geophones will be deployed.

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[2] Current plans are for well 16A(78)-32 to be drilled to a depth of 10,938 ft MD, 8540 ft TVD, at an inclination of 65° to the vertical.

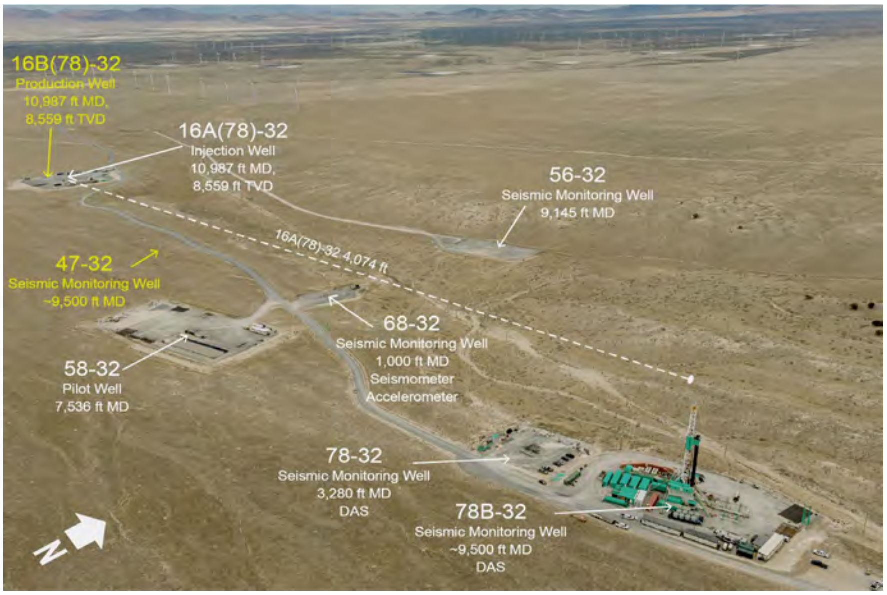


Figure 18. *Photo of borehole locations, indicating depths. The dashed line is the horizontal projection of the deviated 16A(78)-32 well.*

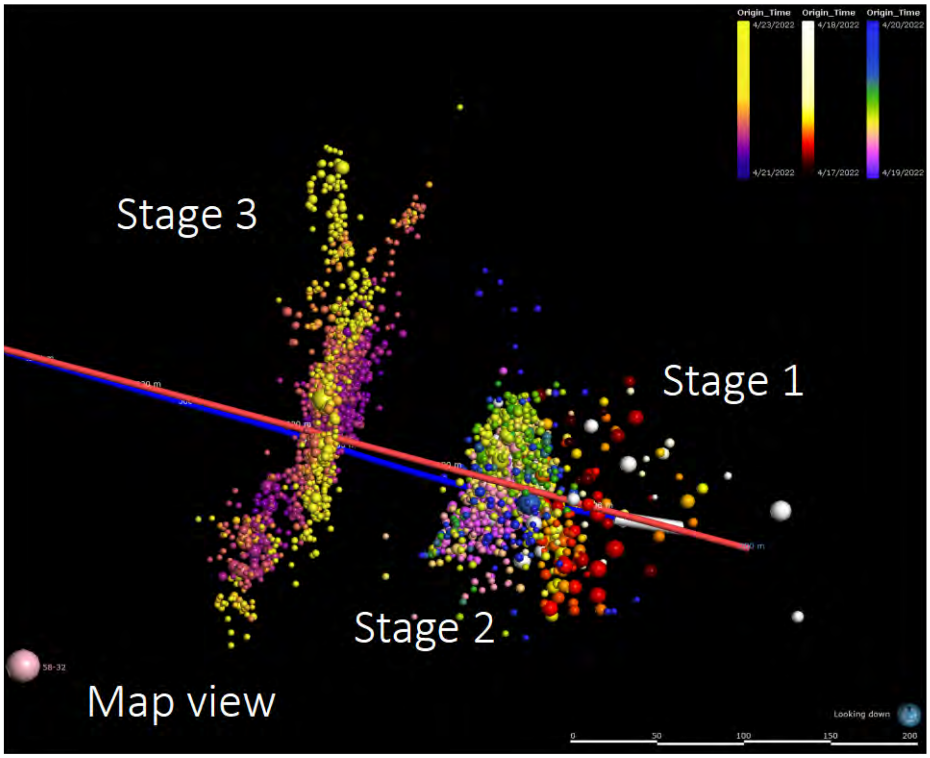


Figure 19. *Map view of microseismicity located by GES catalog. Colors indicate time of occurrence. Blue line is projection of 16A(78)32, white sections, injection zones. Red line potential location of 16B(78)-32.*

5. HAZARD FROM NATURAL AND INDUCED SEISMIC EVENTS

Quoting Majer et al. (2016), “The purpose of Step 5 is to estimate the ground shaking hazard at a proposed EGS site due to natural (tectonic) seismicity and induced seismicity.” The hazard from natural seismicity is determined following a Probabilistic Seismic Hazard Analysis (PSHA) approach. Full details of this analysis, including all the model inputs, are available in the report provided by Wood Environment & Infrastructure Solutions, Inc. (Attachment 1). This PSHA followed an initial PSHA performed by Amec Foster Wheeler (2018), and used new information and model parameters including updated earthquake catalogs, new research on fault parameters, and the availability of more detailed local shallow velocity information. The PSHA was evaluated given newly available information in 2022 by WSP USA Environment and Infrastructure Inc. (formerly Wood Environment & Infrastructure Solutions, Inc.). The recommendation from that analysis (Attachment 2) was that there were no changes to expected earthquake rates; there may be a slight increase in hazard for T 1.0 s if new seismic sources that are being considered for an update to the U. S. Geological Survey 2023 update to the National Seismic Hazard Map (NSHM) are included; and there may be merit in including 1-D site-specific response analyses depending on the approaches used in the 2023 NHSM. It was concluded to not update the model now but wait and re-evaluate after the release of the 2023 NSHM.

To address hazard from earthquakes that could possibly be induced by Utah FORGE operations, we also conducted a literature review of other induced seismic events and methods for estimating the potential maximum magnitude. Based on information available in the peer-reviewed literature, we calculate a range of potential maximum magnitudes for the Utah FORGE project. We then use these magnitudes to calculate deterministic ground motions.

It is important to remember that this section, and PSHA in general, addresses seismic hazard. The purpose is to assess the potential for strong/damaging ground motions and the expected maximum magnitudes for earthquakes in the study area. A PSHA or hazard assessment in general does not evaluate the effect of the hazard on the built environment and population. The consequences of the ground motion are the topic of seismic risk, which is addressed in Section 6 using the criteria established in Section 3.

5.1 Seismic hazard analysis from natural seismicity

There are three key data inputs to the PSHA for natural seismicity. First, a uniform magnitude seismic catalog is needed to determine earthquake recurrence intervals and the spatial distribution of earthquakes. Second, details on nearby faults are needed to constrain potential source zones for larger earthquakes. Third, estimates of site-specific ground motion are needed to constrain the shaking hazard.

5.1.1 Evaluate historical catalog

The earthquake catalog used in the PSHA calculations is a combination of the Utah uniform magnitude catalog (Arabasz et al., 2017) and the catalog used in the 2014 NSHM (Petersen et al., 2014). These catalogs were chosen because a PSHA requires uniform magnitude calculations and must cover an area that encompasses all earthquakes that might cause damaging ground motions in the study area. Great care was taken in combining these catalogs (refer to Attachment 1). Based on these catalogs, the PSHA recurrence modeling indicates an annual frequency for a M > 4 earthquake within 50 km of the Utah FORGE site to be once every 10 years and for M > 6 once every 1000 years approximately (Figure 20).

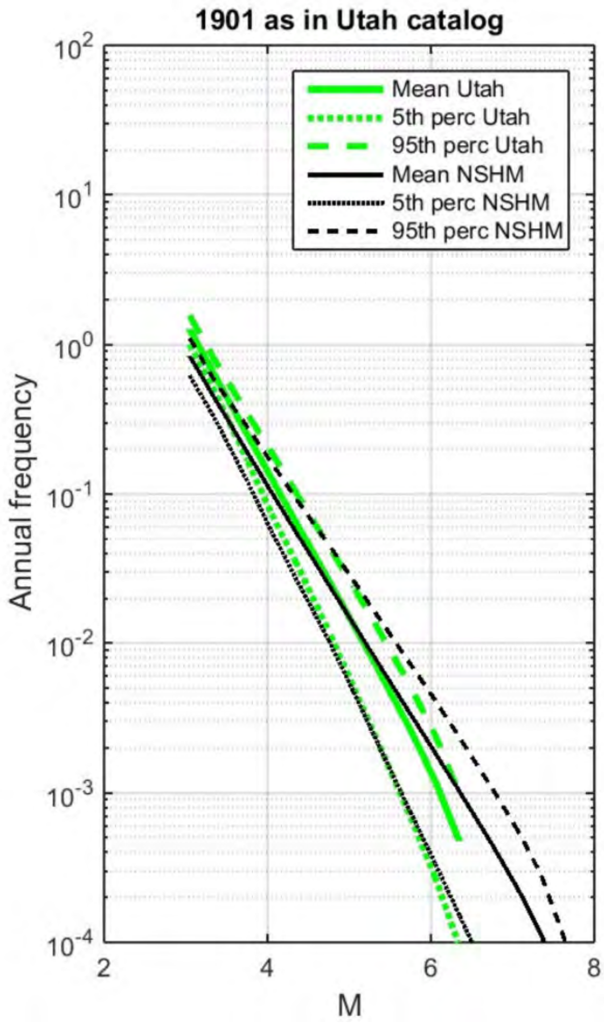


Figure 20. *Earthquake recurrence curves for a region within a 50 km radius of the FORGE site from the PSHA.*

5.1.2 Characterize any active or potentially active fault and estimate source parameters

Details regarding the seismic sources, areal fault sources and both local and regional faults are available in the PSHA (Attachment 1). One aspect of a PSHA is to try and account for seismicity from potential unknown faults. This is done with an areal source where distributed seismicity is modeled with varying weights for the probability calculation. Regarding the mapped fault sources (Table 3.2, Attachment 1), an important observation is that the larger mapped faults in the analysis tend to be regional in nature (at larger distances from FORGE), so are not likely to be directly impacted from activities at FORGE (Figure 3.3, Attachment 1). There are four faults local to the FORGE area that we discuss in more detail in this section (Figure 21).

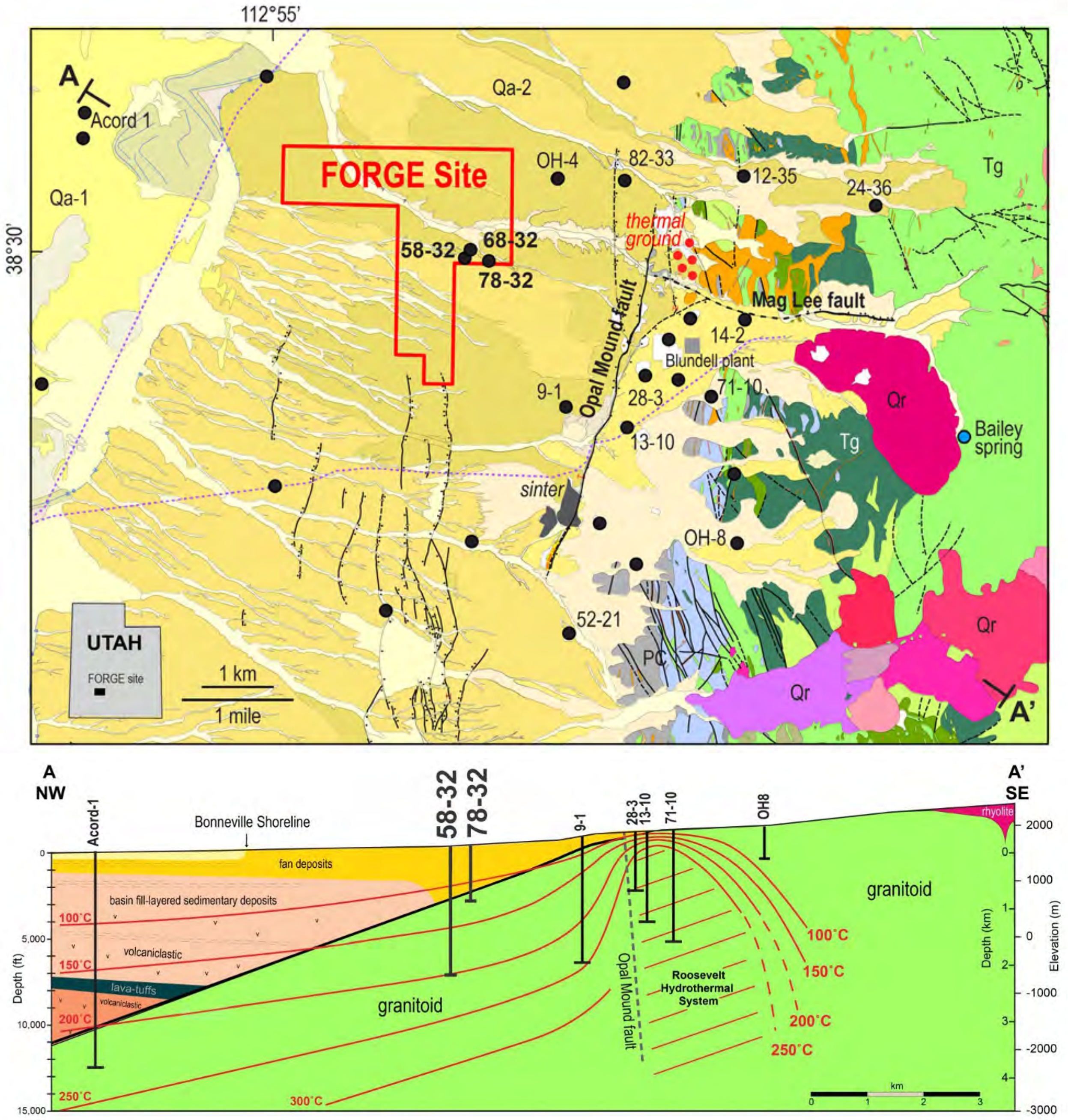


Figure 21. *Geological map and cross-section for the Utah FORGE site. Shown are locations of mapped faults relative to the FORGE footprint and locations of earthquakes located with seismometers installed for the FORGE project December 2016 through January 2018). Also shown on the cross-section are geotherms and location of nearby wells.*

First, the Opal Mound fault (OMF) extends ~7 km in a north-northeast direction, branching in the northernmost part. Displacement is down to the east, and most researchers infer a steep eastward dip (e.g., Nielson et al., 1986). The majority of recent movement is late Pleistocene (12 – 126 ka) with cumulative alluvial offsets up to 18 m (Knudsen et al., 2019). The OMF marks the western boundary of the Roosevelt Hot Springs hydrothermal system and, importantly, forms a hydrological barrier to westward hydrothermal flow as revealed by pressure profiles from wells either side of the fault (Allis and Larsen, 2012; Allis et al., 2016).

Second, the Mag Lee fault (MLF) is an east-west striking structure that dips to the north and extends ~10 kilometers eastward from the north-south trending Opal Mound fault. The MLF can be traced on the surface over a distance of ~1 km where it pierces an old alluvial fan deposit, creating an east-west ridge or scarp in the middle of Mag Lee wash. Siliceous sinter of the OMF near its north end is not deflected by the MLF implying that the MLF is older, and furthermore it is not favorably aligned for slip in the current stress field (Knudsen et al., 2019). A paleoseismic analysis of this structure concluded the fault is pre-Quaternary in age and the scarp is the result of differential erosion of a geological unit contact rather than faulting (Knudsen et al., 2019).

Third, the Mineral Mountains West fault system represents a corridor of north-south trending fault scarps that are mappable in fan deposits south of the Utah FORGE site (Figure 21). The system is up to 3 km wide, and runs for at least 30 km, west of and parallel to the range front along the southern part of the Mineral Mountains, south of the Utah FORGE footprint. Individual strands are marked by scarps that extend continuously for several km, having heights <5m. At the surface, these faults do not enter the FORGE footprint. The faults have not been detected in legacy seismic reflection profiles (Smith and Bruhn, 1984; Smith et al. 1989) or in the modern vibroseis reflection surveying performed in Phase 2B of the Utah FORGE project (Miller et al., 2019). There is also no evidence of structural offsetting along the alluvium-granite interface to within the vibroseis seismic resolution of 25 m (Miller et al., 2019; Wannamaker et al., 2020). The most recent movement on these also is late Pleistocene (Knudsen et al., 2019).

Fourth, perhaps the most significant of the four fault structures is that comprising the unconformable contact between overlying basin fill and the underlying crystalline basement rock. This structure has been penetrated by wells west of the Opal Mound fault, including well 58-32 within the Utah FORGE footprint. These well data and the notably strong reflector in seismic reflection profiles strongly suggest the top of basement contact forms an inclined ramp, which dips ~20° west and intersects the surface near the Opal Mound fault. However, direct evidence of fault offset across the contact is lacking. Large scale down-dip detachment displacement along the interface of >10 km is deduced from seismic reflection profiles, regional outcrop patterns, the uniform eastward dip of stratified rocks in the Mineral Mountains, the uniform westward dip of late Miocene dikes in the Mineral Mountains, paleomagnetic data, and cooling patterns interpreted from thermochronology (Smith and Bruhn, 1984; Nielson et al., 1986; Smith et al., 1989; Coleman and Walker, 1992, 1994; Coleman et al., 1997, 2001; Bartley, 2019). From these studies, it appears that most of the large-scale extension occurred during a spasm of accelerated displacement in the late Miocene (~8 Ma), and this caused uplift, exhumation, and tilting of the Mineral Mountains (Coleman and Walker, 1994; Coleman et al., 2001; Bartley, 2019).

The prior detachment faulting probably initiated as a moderate to steeply dipping plane(s) that rotated with extension in response to a rolling hinge associated with isostatic rebound of the footwall block (Wernicke and Axen, 1988; Buck, 1988; Coleman and Walker, 1994; Bartley, 2019). After acquiring low angle orientations, however, slip along these structures greatly diminished or ceased after ~8 Ma based, for example, upon the horizontal disposition of alluvial sediments as resolved by the seismic reflection survey (Wannamaker et al., 2020) and in spatial autocorrelation (SPAC) imaging (Zhang and Pankow, 2020). Given that the reflection survey resolved that slip offset across the bedrock interface is < 25m over this long time period, natural seismic rupture potential on existing faults is concluded to be low. In fact, from interpretation of both the reflection survey (Miller et al., 2019; Wannamaker et al., 2020) and the SPAC velocity model (Zhang and Pankow, 2020), topography on the alluvium-granite interface is consistent with an erosional surface rather than faulting.

In summary, the Opal Mound and Mag Lee faults are relatively short length structures that intersect orthogonally to form the boundaries of the Roosevelt Hot Springs reservoir. The Mineral Mountains West fault system comprises a series of parallel north-south trending, discontinuous normal fault segments with small offsets. These probably sole into the unnamed low angle detachment fault comprising the bedrock interface, which appears to have accommodated most of the extension (>10 km) in the late Miocene to form the North Milford valley. Recent movement on the detachment appears to be minimal, as reflected in the basin profile, and the absence of significant fault scarps and faceted spurs along the Mineral Mountains range front.

The lengths of the mapped/projected traces of the Opal Mound fault and the Mag Lee fault (Figure 21) are ~7 km and ~10 km, respectively. Assuming the entire length ruptures in a normal faulting event, the maximum magnitude for these faults is calculated to be M 5.9 (Wells and Coppersmith, 1994). This moderate magnitude is consistent with the lack of well-defined scarps. The mapped length of the Mineral Mountains West Fault is 38 km (Lund, 2014), which is long enough to generate an M 7.0 earthquake. However, as described, given the lack of geophysical evidence for basement displacement and the discontinuous nature of the mapped fault trace (Kleber et al., 2017), it is unlikely that this fault is capable of generating large magnitude events. Based on these observations, the seismogenic potential of the Mineral Mountains West Fault system is doubtful, and we assume a maximum magnitude of 6.5, which is the approximate magnitude threshold for surface faulting in the Basin and Range Province (dePolo, 1994).

5.1.3 Geological site conditions and shallow shear-wave velocity

The shallow shear-wave velocity structure, often described using the average velocity in the upper 30 m (Vs30), is a key parameter used for estimating ground motions. For the FORGE project, we conducted spatial autocorrelation (SPAC) surveys to measure shear-wave velocity profiles that could be used for Vs30 calculations at three locations: (1) within the Utah FORGE footprint, (2) near the Blundell Power Plant, and (3) in the town of Milford. For these three locations, the measured Vs30 was 400, 408, and 333 m/s (Zhang et al., 2019). More recently, we expanded the SPAC methodology to create a three-dimensional shear-wave velocity model of the upper 1.5 km for the region directly above the Utah FORGE footprint (Zhang and Pankow, 2020). The advantage of the expanded SPAC methodology is that we recover the velocity profile to greater depths. With the velocity profile, other parameters (depth to 1.0 and 2.5 km/s) important for ground motion calculations can also be recovered. The full velocity profile was used in the PSHA modeling.

For calculations in ShakeMap, UUSS uses a generalized shear-wave velocity map based mainly on mapped geologic units *(*http://quake.utah.edu/monitoring-research/uuss-urban-strong-motion-network/geological-site-conditions*)*. Vs30 values for each unit are based on Vs30 measurements collected for the Wasatch Front in northern Utah (McDonald and Ashland, 2008). The default Quaternary Vs30 for Utah is 230 m/s. Because the soils near FORGE are stiffer (have larger measured Vs30 values) compared to the default values used in generating ShakeMap scenarios, ground motions estimated for deterministic scenarios presented later are slightly over-predicted and hence conservative.

5.1.4 Select appropriate ground-motion prediction models

For earthquakes with magnitudes greater than M 5, UUSS currently uses the Chiou and Youngs (2008) ground motion prediction equation (GMPE) to generate deterministic scenarios with ShakeMap. Data from normal faulting earthquakes are scarce for Basin and Range earthquakes. However, ground motion modeling exercises can be used to provide some validation of GMPEs. For models developed for the Salt Lake Valley (Roten et al, 2012) reasonable agreement was found between the modeling results and older GMPEs, like Chiou and Youngs (2008). For the PSHA, a suite of ground motion models was used including the NGA West 2 GMPEs (Abrahamson et al., 2014; Boore et al., 2014, Bozorgnia et al., 2014; Chiou and Youngs, 2014).

5.1.5 Perform a PSHA and produce hazard curves

An updated site-specific PSHA analysis for the Utah FORGE site down to M 4 was performed by Wood Environment & Infrastructure Solutions, Inc. (full report, Attachment 1). Figure 22 summarizes the 10% probability that a level of ground motion will be exceeded in the next 50 years. These curves can also be interpreted as 2% probability in 10 years (more appropriate for the lifetime of FORGE). For the four locations (FORGE site, Blundell Power Plant, wind farm, and Milford), we see that there is a 2% chance of exceeding a PGA (highest frequencies, Figure 22) of 10 to 13% g in the next 10 years. For building types four-stories or less resonant frequencies tend to be between ~2 (four story building) and ~10 Hz (one story building), for these frequencies there is a 2% chance of exceeding ~15 to 30%g in the next 10 years. Overall, this is a low hazard and represents a 30 - 50% decrease from the Amec Foster Wheeler (2018) calculations. The deaggregation of the hazard shows that the largest contribution to the 10% in 50 years hazard for frequencies ≥ 1 Hz is controlled by relatively small background events not associated with specific faults. The decrease in hazard can be attributed to a correction in how M_{comp} was propagated in the Amec Foster Wheeler (2018) calculations and the incorporation of new information from fault studies, specifically new information on the Wasatch and Mag Lee faults.

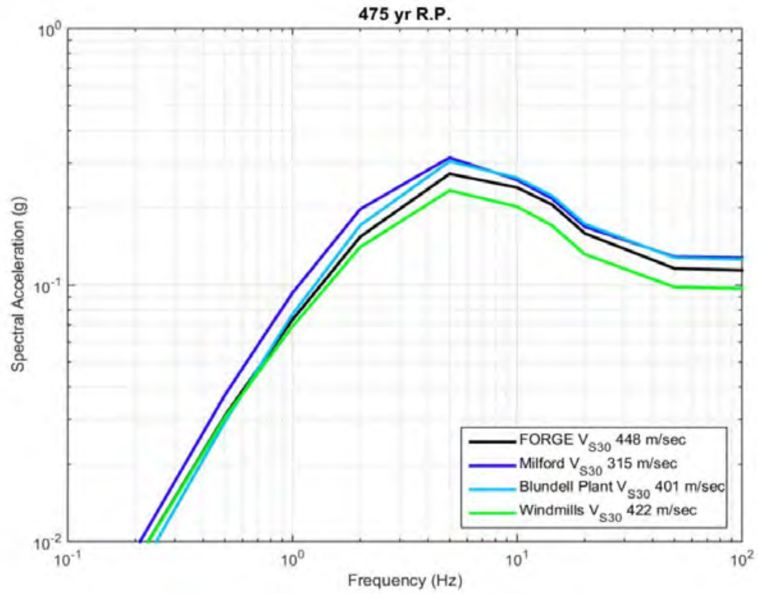


Figure 22. *Comparison of the 475 years return period uniform hazard response spectra for the four sites denoted in the legend. This return period corresponds to 10% probability in 50 years.*

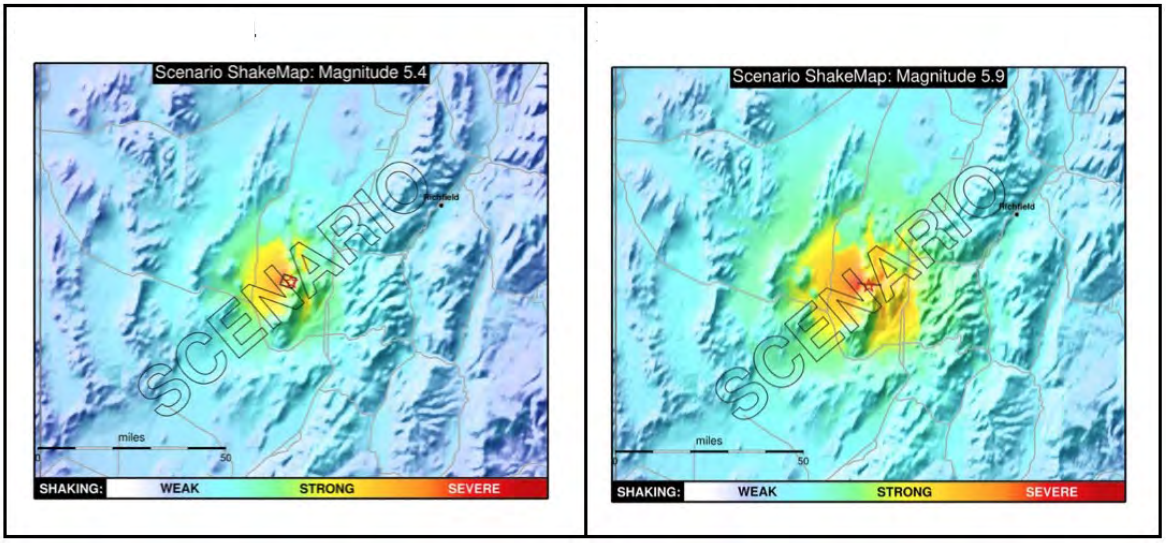


Figure 23. *Deterministic intensity maps for two potential scenario earthquakes near the Utah FORGE site: Left, Opal Mound M 5.4 and right, Mag Lee M 5.9. Maps were generated using ShakeMap (Wald et al., 2005; Worden and Wald, 2016). Maximum magnitude (ground motions) based on fault dimension for the Opal Mound and Mag Lee scenarios (gray box surface projection of fault trace).*

We compare the expected ground motions from the PSHA to deterministic scenarios generated using ShakeMap (Wald et al. 1999; Worden and Wald 2016) for an M 5.4 Opal Mound fault earthquake and an M 5.9 Mag Lee earthquake (Figure 23). Based on the recurrence modeling, these earthquakes represent 100 to 1000-year events (Figure 20). The scenarios were generated using the Chiou and Youngs (2008) GMPE and site amplification factors from the statewide Vs30 database (McDonald and Ashland, 2008). The Vs30 clearly dominates the pattern of ground motions, as seen by the significantly larger amplitudes in the basin. The difference in amplification between the measured and assumed Vs30 is a function of magnitude, but the ShakeMap values for these magnitudes will be slightly larger because of the lower default Vs30.

The maximum PGA for the Opal Mound earthquake scenario is ~28% g over the rupture area (close to the Utah FORGE site) and falls off to ~10% g in Milford. PGV values are ~30 cm/s and 8 cm/s for the same two areas. Based on ShakeMap relations, this translates to the potential for moderate damage at the epicenter, but light potential for any damage in Milford. For the Mag Lee scenario PGA near the Utah FORGE site is ~35% g (PGV ~35 cm/s) and for Milford PGA is ~12% g (PGV 12 cm/sec). For the area near the Utah FORGE site, potential damage could be moderate. Structures in this area include the well-site, wind farm, and the Blundell power plant. Based on the limits for cosmetic and structural damage discussed in Section 3, the Opal Mound and Mag Lee scenarios would be felt in Milford and possibly Beaver. There could be limited damage to weak structures (near the epicenter) and some cosmetic damage (at distances of ~10 km or ~30 km, respectively).

5.2 Estimate hazard from induced seismicity

With natural seismicity hazard quantified above in Section 5.1, we proceed to define factors that control the generation and magnitude of induced seismicity. Steps in determining the factors include reviewing cases of) induced seismicity during creation of Enhanced Geothermal System (EGS) reservoirs, reviewing models for maximum magnitude of induced seismicity, and evaluating the characteristics of pre-existing faults and the geologic framework.

5.2.1 Review known cases of induced seismicity and compare tectonic framework

Fluid related induced seismicity has been associated with several types of energy production, including oil and gas, unconventional oil and gas, carbon capture and storage, and geothermal. Induced seismicity results from the injection of fluids when the net pore pressure change exceeds a critical value (National Research Council, 2013). The volume change appears to correlate with the maximum magnitude induced earthquake (McGarr, 2014). Therefore, the largest magnitude induced events are expected when large volumes of fluid are injected or withdrawn from a reservoir or from the cumulative effect of wastewater disposal or carbon capture (National Research Council, 2013). Unlike some of these other industries, the goal in geothermal is a net zero fluid balance with extraction roughly equaling injection. In addition to an increase in pore pressure for fluid induced seismicity, there must also be a fault or faults of substantial size optimally oriented for failure in the current stress field close to the point of fluid injection (National Research Council, 2013) or a fluid pathway to basement faults of substantial size (e.g., BC Oil and Gas Commission, 2012; Skuomal et al., 2017; Zhang et al., 2013).

EGS is an artificial underground heat exchanger designed to extract geothermal energy by circulating fluid between an injection well and a production well through an engineered or enhanced volume of fractures in the subsurface. In geothermal environments, induced seismicity can result from multiple factors, including fluid induced pore-pressure increases that result in effective stress reduction, temperature decreases that result in the contraction of fracture surfaces, volumetric changes from poroelastic and thermoelastic stress effects driven by pore-pressure and temperature changes associated with fluid withdrawal and injection, and chemical alteration of fracture surfaces that change the coefficient of friction (Majer et al., 2007). The extent and degree to which these subsurface phenomena are active is contingent on the orientation and magnitude of the deviatoric stress field relative to existing faults, the extent of faults and fractures, and the area of fault slippage and stress drop across a fault (Majer et al., 2007).

Natural geothermal systems have sufficient permeability for fluid convection and heat extraction to occur. Although hot rock is abundant in the subsurface, few areas have the permeability required for fluid circulation. Permeabilities can be enhanced by opening existing fractures or creating new fractures by injection of fluid into the rocks. Most often EGS development has been attempted in areas where there is hot impermeable rock near the Earth’s surface, either on the periphery of natural geothermal systems or in areas where a preexisting geothermal resource did not exist, but temperature gradients were sufficient to provide hot rock at depths that could be accessed practically by drilling. Techniques that have been investigated to increase the permeability of these rocks include high-pressure and high-rate hydraulic stimulations, low-rate, low-pressure hydraulic shearing, long-term injection/circulation of cool fluids, high-rate gas fracturing or deflagration, and acidization. EGS projects have been ongoing since 1974 when the first EGS research was undertaken at Fenton Hill, New Mexico. Subsequently, EGS projects have been conducted in North and Central America, Europe, Japan, and Australia (Breede et al., 2013).

Factors that influence geothermal induced seismicity include the depth at which the stimulation is carried out, initial stress state of the formation, formation temperature, and rock type, as well as stimulation types (hydraulic, long-term circulation, and chemical/acidizing). Other factors include stimulation parameters such as injected fluid volume, wellhead pressure, injection rate, and duration of injection/circulation. Summaries of EGS systems and the induced seismicity have been presented by Tester et al. (2006), Majer et al. (2007), Ghasemi et al. (2010), Bromely and Majer, (2012) and Breede et al. (2013). Maximum magnitudes are typically M < 4.

Two high profile EGS induced seismicity cases include the 2006 Basel, Switzerland M 3 earthquakes (Deichmann and Giardini, 2009) and the 2017 Mw 5.5 Pohang, Korea earthquake. In both cases the induced events were located near urban areas and both cases highlight the need for both seismic mitigation plans (like this one) and the need for additional research located in areas of low seismic hazard and risk (like at Utah FORGE). For Basel, there was a

Traffic Light System (TLS) in place. When a M_L 2.6 earthquake occurred during injection, activities were stopped. However, the largest event M_L 3.4 occurred later in the day leading the operator to open the well and allow flow back to more rapidly dissipate the pore pressure at depth. Three additional $M_L > 3$ events occurred over the next couple of months. The mainshock was widely felt in the area leading to concerns from the public. Damage was non-structural in nature (e. g. Bachmann et al., 2011; Deichmann and Giardini, 2009). The maximum magnitude (M_L 3.4) is consistent with estimates based on the injected volume (McGarr, 2014) and the number of seismic events decayed following cessation of injection operations (Bachmann et al., 2011). A high-quality seismic data set was collected during this experiment and enhanced detection algorithms have further refined the available catalog (Hermann et al., 2019). This catalogue will assist in understanding the evolution of the seismic sequence with the hope of providing better tools for forecasting and development of improved TLSs.

Unlike the Basel earthquake, which occurred during stimulation, the Pohang earthquake occurred during the drilling of one of the geothermal wells and was consistent in time with the loss of a significant volume of drilling mud (Ellsworth et al. 2019). This event was larger than what would have been expected for an induced earthquake given the injected volume (McGarr, 2014) or when considering the Gutenberg-Richter relation for tectonic earthquakes (van der Elst et al., 2016), and initially it was unclear if it was induced. After careful review, it was concluded by an advisory committee formed by the Korean government that earthquakes induced by high-pressure fluid injection triggered the Mw 5.5 earthquake on a previously unmapped fault (Ellsworth et al., 2019). However, in the preceding year there was an M 5.5 earthquake 40 km south of the Pohang sequence in September 2016 (Grigoli et al., 2018; McGarr et al., 2018). So, while the Pohang earthquake was likely triggered by activities related to EGS, a careful PSHA analysis would have identified and included the recent increased seismicity in the area and adjusted the hazard and perhaps the stimulation and monitoring accordingly. Lessons learned from the Pohang earthquake regarding monitoring induced seismicity at geothermal locations are detailed in Ellsworth et al. (2019).

While not an EGS project, a potential analog for investigating induced events at the Utah FORGE site is the adjacent Roosevelt Hot Springs geothermal system and operations at the Blundell power plant. This plant has been in operation since 1984. Electricity is produced by binary and flash plants. Over 1.57×10^8 m^3 (4.16×10^{10} gallons) of water have been injected and recovered for power generation. Associated seismic activity is minimal, with $M < 2$ occurring at average rates of a few events/month.

Lessons that we should heed from the literature review include that induced seismicity from EGS can result from pore fluid pressures changes, temperature differences, or chemical changes. For the events related to pore fluid pressure changes, instances of induced seismicity are related to the volume and rate of injected fluids, fluid pathways to larger faults, and the orientation of the background stress field. Most earthquakes are $M < 2$ (called microseisms) and are below the felt threshold. This is true for both natural and induced earthquakes and is described by the Gutenberg-Richter relation (Gutenberg and Richter, 1956), which is a log-based relation between the number and magnitude of earthquakes. Thus, most EGS induced earthquakes will go unnoticed. The maximum induced earthquake for many fluid related earthquakes has been shown to be bounded by the volume of injected fluid (McGarr, 2014), to the size and shape of the injection-influenced reservoir volume (Shapiro et al., 2011) and/or to the distribution of tectonic earthquakes following the Gutenberg-Richter relation (van der Elst et al., 2016). However, if there is a fluid pathway to pre-existing faults, the maximum magnitude is a function of the tectonic environment versus the reservoir development. These lessons seem to hold for seismic activity associated with the Blundell Power Plant, where the rates and magnitudes are low, consistent with a net fluid balance.

Other lessons that should be considered in devising mitigation plans include: that the largest earthquake often occurs after shut-in (perhaps several years later) and away from the injection well (potentially several tens of kilometers) often near the edge of the seismic cloud (Baisch et al., 2010); Rock failure associated with fluid injection can be tensile (Hubbert and Willis, 1957) or by shear failure of pre-existing joint or fracture sets (Hubbert and Rubey, 1961) or both; and Seismicity tends to migrate away from the injection well, and the source types as well as b-values also can change as the seismicity migrates to larger distances from the well (e.g., Zang et al., 2014, and references therein).

5.2.2 Review models for induced seismicity that estimate the maximum magnitude

In early work, McGarr (1976) used the volume of injection (fluids) or extraction (mining environments) to determine the maximum magnitude of induced earthquakes. This work was updated for fluid injection-induced earthquakes (McGarr, 2014). The new relation limits the maximum seismic moment to the product of the injected volume and the modulus of rigidity. In comparing this relation to many examples where volume and magnitude are known, the relation does an impressive job of bounding the maximum observed magnitude. However, van der Elst et al. (2016) concluded that the number of induced earthquakes is proportional to the injection volume and that the magnitude limit is the same as for tectonic earthquakes. In other studies, Shapiro et al. (2011) showed that the magnitudes of induced earthquakes are controlled by the interactions between preexisting faults and the crustal volume influenced by the pore pressure increase. Gishig (2015) showed that the maximum magnitude depends on fault properties, the orientation of the natural faults, and the stress field.

To estimate an upper bound on the maximum induced earthquake for the Utah FORGE site, we use two different relations, McGarr (2014) and van der Elst et al. (2016). In the 2022 stimulation phase for the Utah FORGE site, we anticipated the total fluid injection volume for the three stages of stimulation to be less than 1200 m^3. We assumed a modulus of rigidity of 2.85×10^{10} Pa. Using these values and the McGarr relation, we get a maximum moment of 3.42×10^{13} N m. This moment is equivalent to an M_W 3.0 earthquake. This moment is less than those for the EGS sites analyzed in the McGarr (2014) study but consistent with the lower anticipated injected volumes. If instead we use the relation developed by van der Elst et al. (2016), and a range of possible b-values and values for seismogenic index (∑), the maximum magnitude ranges from less than 1 to almost 4 (Table 3). To reach a magnitude 5 with this range of b and ∑, the injected volume would have to be at least ~10^5 m^3 (or about 630,000 barrels).

The maximum magnitude event observed in the 2022 stimulation was an M 0.5 that occurred during stage 3. This is roughly consistent with the expectation from the van der Elst (2016) relation and what has been learned from the 2019 stimulation. For the 2019 stimulation Bradshaw et al. (2022) used a b-value of 1.61 (Dzubay et al., 2022) and varied ∑. The data suggests a ∑ value of -2.

Table 3. *Maximum Magnitude for injection volume of 1200 m3 (van der Elst et al., 2016)*

	b = 0.8	b = 1.0	b = 1.2
Σ = -2	M 1.4	M 1.1	M 0.92
Σ = -1	M 2.6	M 2.1	M 1.8
Σ = 0	M 3.9	M 3.1	M 2.6

5.3 Evaluate geologic framework, characteristics and distribution of pre-existing faults

There are four requirements to evaluating the geologic framework of induced seismicity, as follows:

1. Characterize the local stress field: The Utah FORGE site is located in the Basin and Range physiographic province, an area known for east-west extension and primarily north-south striking faults. The basin fill stratigraphy is dominated by volcaniclastic and alluvial material overlying basement granitoid. As previously discussed, there are four known fault structures in the Utah FORGE area. The Mineral Mountains West fault system and the unconformable contact between basement and basin strike mostly north-south. The Opal Mound Fault strikes northeast-southwest, while the Mag Lee fault strikes east-west. Seismic activity does not correlate with these structures (Figure 21). Importantly, no additional faults have been imaged in 3D seismic surveying. Based on both seismic data and the core from test well 58-32, the basement rock is granitoid with no significant faulting.

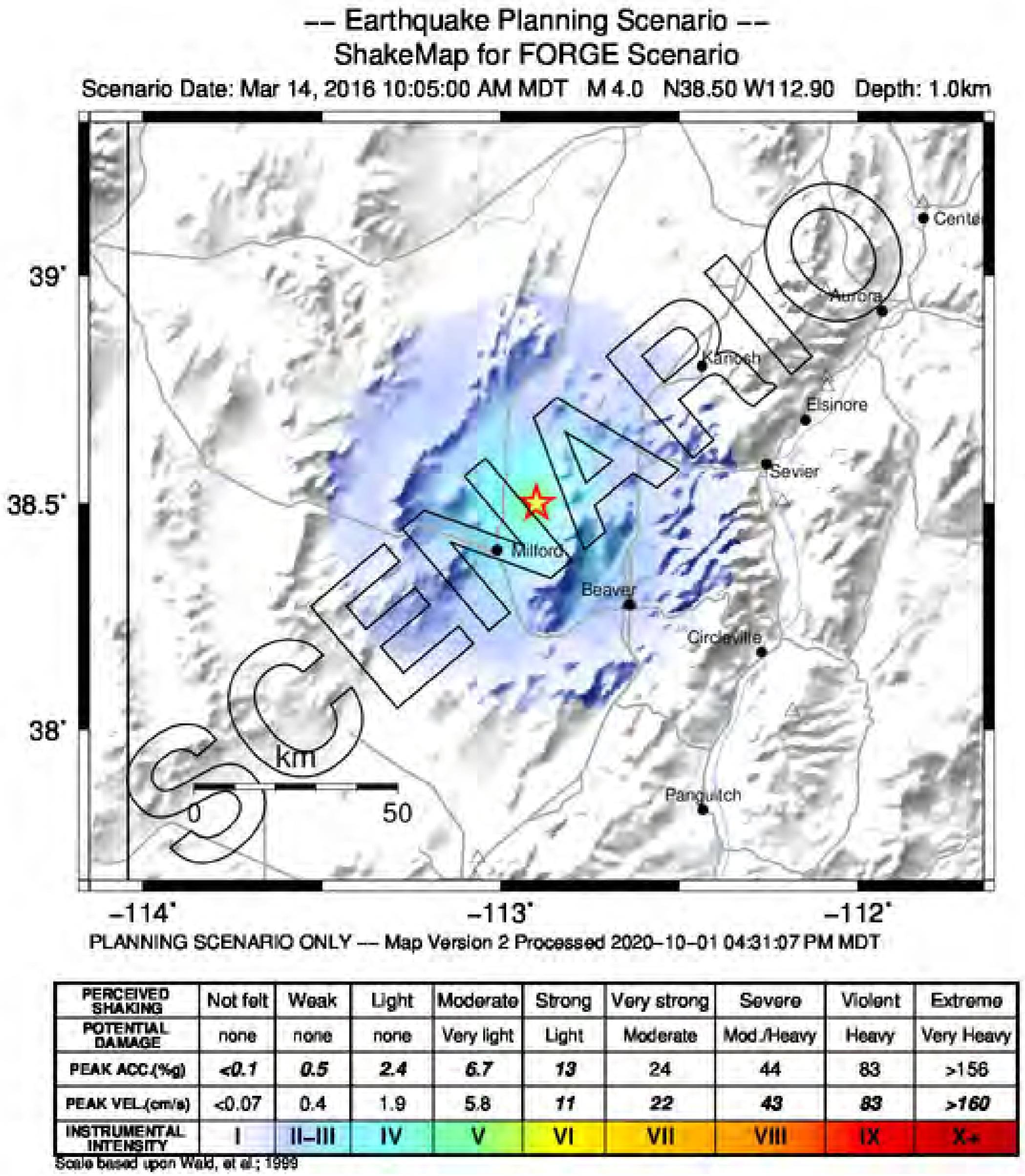
Regarding fractures, an FMI log for the deeper granitic section of test well 58-32 identified ~2000 apparent fractures. The north-south fracture population has moderate dips (<70°) to the west, and the east-west population has dips that cluster between 50–90° to the south. The northeast-southwest population has dips that are scattered, ranging from moderate to steep dips to the southeast and northwest. These patterns strongly resemble the spacings and orientations of fractures in granitic rocks in the Mineral Mountains, especially those occurring east of Roosevelt Hot Springs (Bartley, 2019). They are also different from the fractures and joint patterns occurring in young rhyolite flows, suggesting that most of the fractures in granitic rocks formed before 0.5–0.8 Ma (Bartley, 2019).

For comparison, induced fractures produced during drilling show a narrow range of orientations, predominantly NNE-SSW with near vertical dips. This direction is taken to represent the maximum total horizontal stress, σ_{Hmax}, and is consistent with the orientation of σ_{Hmax} determined from geological observations to the east. Well testing suggests permeabilities of the granite near the bottom of the hole are small, at approximately 30 microdarcies, consistent with a measurement of 6 microdarcies that was acquired on core plugs at EGI. These values indicate that the proposed EGS reservoir has very low natural permeability. The apparent lack of basement faulting and the low permeability reduce the likelihood of significant induced seismicity.

2. Characterize maximum dimensions of pre-existing faults: Details on each of the faults is available in section 5.1.2. Notably, 3D seismic reflection (Miller et al., 2019) and quasi-3-D Vs models (Zhang and Pankow, 2021) do not show displacement across the sediment bedrock interface from which deeper basement faulting would be inferred. The three mapped faults in the study area include the Opal Mound fault, the Mag Lee fault, and the Mineral Mountains West fault system. The lengths of the mapped traces are 5 km, 10 km, and 38 km, respectively. Assuming the entire length ruptures in a normal faulting event, the maximum magnitude for the Opal Mound and Mag Lee faults are calculated to be M 5.4 and M 5.9, respectively (Wells and Coppersmith, 1994). These moderate magnitudes are consistent with the lack of well-defined scarps. For the Mineral Mountains Fault, we assume a maximum M of 6.5. This is consistent with surface scarp amplitudes, but is considered unlikely given no resolvable displacement observed across the basement interface.

3. Review and select empirical relations appropriate for small magnitude events: Pankow (2012) compiled ground motion data for all M 3 to M 5 earthquakes recorded by the state-wide seismic network in Utah. Using PGA and PGV, she compared the data to three ground motion prediction equations developed for M<5 earthquakes: Chiou et al. (2010), Atkinson and Boore (2011), and TriNet (Wald et al., 2005). The Chiou et al. (2010) predictive equations for Southern California fit the Utah data quite well. There was a large distance bias in the Atkinson and Boore (2011) relation for both PGA and PGV and a distance bias for PGV for the TriNet relation.

4. Calculate scenario ground motions from the maximum induced seismic event: Given the distance from the mapped faults to the Utah FORGE site and the low permeabilities, it appears unlikely that earthquakes will be induced on these structures. We therefore use a conservative estimate of M 4 and 1 km depth to generate an induced seismic scenario. The deterministic scenario was generated using ShakeMap (Wald et al. 1999; Worden and Wald, 2016) for an M 4 induced earthquake located at the proposed Utah FORGE site (Figure 24). The scenario was generated using the Chiou et al. (2010) Southern California GMPE, and the statewide Vs30 database (McDonald and Ashland, 2008). The default Vs30 values used in this analysis are based on Vs30 measurements from northern Utah, which are low compared to Vs30 measured at the Utah FORGE site, power plant, and town of Milford. The difference in amplification between the measured and assumed Vs30 is a function of magnitude, but the ShakeMap values for these magnitudes will be slightly larger because of the lower Vs30. The maximum PGA is ~10% g at the epicenter, which based on ShakeMap relates to light perceived shaking and no potential for structural damage. The maximum PGV is ~7 cm/s.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Figure 24. *Deterministic intensity map for an induced scenario earthquake located near the Utah FORGE site (depth 1 km). Map was generated using ShakeMap (Wald et al., 1999; Worden and Wald, 2016). A point source is assumed because of the small magnitude.*

5.4 Summary of Induced Seismicity Hazard Analysis

Based on all the information in this section, the literature review, the absence of imaged basement faults near the Utah FORGE site, low permeabilities (limited fluid pathways), and low injection volumes coupled with recovery of the fluid, the hazard related to induced seismicity from the Utah FORGE site is concluded to be constrained by the tectonic stresses (as modeled in the PSHA). However, the hazard is more likely to be lower, as constrained by the maximum magnitude calculations following van der Elst et al. (2016).

6. RISK FROM INDUCED SEISMIC EVENTS

Risk is the product of vulnerability, hazard, and cost or the product of probability and consequence. In the first definition, risk has monetary implications. The second definition acknowledges that consequences can relate aspects beyond direct monetary issues. These other costs might relate to the societal effects of increased exposure to felt ground motions or to perceptions around safety of technologies. As will be detailed in this section, the rural location of the Utah FORGE site combined with low seismic hazard results in low monetary risk. The distance to populations centers results in a lower risk from exposure to ground shaking.

To address vulnerability, we return to a description of the Utah FORGE area. The Utah FORGE site is located in an uninhabited area in southcentral Utah. The closest town, Milford, Utah is located 16 km to the southwest and has a population of ~1400. Within ~5 km of the Utah FORGE site, there is a power plant, a wind farm, and barns associated with pig farms. Based on the ground motion threshold criteria discussed in Section 3 and the estimates of ground motion presented in that section, for earthquakes to be felt in Milford (present a nuisance) the magnitudes will have to be at least M 3, the threshold for light damage for the distance of 16 km is M 5 and for distances < 5 km is at least M 4. The threshold for moderate damage at distances < 5 km requires a magnitude approaching 5 (Figure 12).

To address hazard, we note that we have not identified, through 3D geophysical surveys or planar alignments of seismic events, faults within the Utah FORGE footprint where injection will occur. The closest fault, the Opal Mound fault, is also not defined by seismic sequences (Figure 16). Previously we calculated the maximum magnitude expected for an induced earthquake to be M 4 using the relation from van der Elst et al. (2016) that incorporates tectonic earthquakes. Based on this assessment together with the results of the Utah FORGE specific PSHA and the 2018 NSHM, the seismic hazard in the Utah FORGE area is low.

The last parameter is cost. Given the distance to the population center and the felt threshold being M 3, the cost associated with producing nuisance events is minimal. Regarding cost associated with the industrial facilities, there is a chance of light damage if magnitudes exceed 4 and more extreme damage if magnitudes exceed 5. As seen from the hazard assessment these are low probability events. Moreover, the Blundell power plant has vibration monitors to mitigate damage (cost) to the turbines. Windmills should remain undamaged if located in stiff soil for moderate earthquakes as required by state code, thus addressing their potential vulnerability to earthquakes. Finally, the pig farms are relatively new, with simple rectangular construction which will limit damage. So, while there could be some cost associated with a low probability M > 5 earthquake, the cost should be minimal.

In another approach to estimate seismic risk from induced earthquakes, Trutnevyte and Wiemer (2017) provided tools (GRID) for estimating to what extent induced seismicity is a concern to a specific project and then provides a suggested framework for risk governance. GRID provides a mechanism for relating seismic hazard, secondary hazards and exposure, and social concerns, The Utah FORGE project is in GRID Category I (damaging events are unlikely, no significant social concerns). Recommendations from GRID include active seismic monitoring, assessing the hazard and potential ground motions, development of a TLS, and developing a seismic events communications plan. All recommendations have been addressed as part of this ISMP.

In summary, based on (1) the rural nature of the location of Utah FORGE and the distance to a population center, the associated vulnerability to felt induced seismic events (M < 4) is low; (2) the seismic history of low rates, low magnitudes and the local faults present, the seismic hazard is low; and (3) the existing infrastructure, potential cost is low. Following Majer et al. (2016) best practices and GRID (Trutnevyte and Wiemer, 2017), risk assessments developed for induced earthquakes, the overall local risk from the Utah FORGE project is low. This makes the Utah FORGE site an ideal laboratory for developing EGS. That is not only can we develop new engineering technologies, but we can develop these technologies in an environment with low societal risk, and thereby improve and develop seismic risk-based mitigation techniques that can be applied in future projects closer to higher-risk, urbanized areas.

7. RISK-BASED MITIGATION PLAN

The purpose of a seismic risk-based mitigation system is to provide metrics for responding to changes in seismic activity in a way that reduces the risk from a potential, damaging earthquake. A TLS is a common means for organizing and communicating the strategy (Bommer et al., 2006), with amber defining when operational changes are required and red defining when operational activities must cease.

In the TLS, a series of observations controls the alert level and is associated with specific actions. Two metrics often used in a seismic TLS are (1) measured ground motions and (2) earthquake magnitudes. Ground motions have the advantage that they are more easily interpreted in terms of consequences (Siskind et al., 1980). Magnitude thresholds have the advantage that they are quick to calculate and can be used to monitor changes in background hazard including the potential for runaway earthquakes, i.e. earthquakes triggered by operational activities that grow and release tectonic strain (e.g., van der Elst et al., 2016). At Utah FORGE, given the rural nature, we are more concerned with triggering a large earthquake than ground motions following induced events and will thus use magnitudes to define the alert levels. In defining magnitude thresholds, it is important to set the amber level threshold low enough that there is time to change operations before reaching red levels. We elaborate upon threshold criteria below.

The first determination to be made is what defines red, when operations cease. In states with higher population densities (e.g., Kansas, Ohio, Oklahoma), M ≥ 2 is used to initiate action plans and may lead to ceasing operational activities. Based on the hazard and risk assessment performed in this report, we set the red level as M ≥ 3. This level is below where we expect damage at the wind farms and power plant, but it will be felt and might cause concern among nearby residents. Ellsworth et al. (2019) suggest that amber level magnitude thresholds be two units below the red level in order to have time for operational mitigations to lower the seismic hazard. The goal is to never reach red. For Utah FORGE, the monitoring threshold for amber will be ten M ≥ 1 earthquakes in 24 hours within 3 km of the FORGE footprint and/or an M ≥ 2 within 3 km of the FORGE footprint. These levels are set to be consistent with the Gutenberg-Richter relation (Gutenberg and Richter, 1956), which is a log-based relationship between magnitude M and the log of the number of events N(M) of magnitude M and larger. This relation implies that if you get 10 M > 1 events you should start to expect an M ≥ 2 and the chance for an M ≥ 3 is also increased. Our real-time detection limits using the augmented seismic monitoring array discussed in Section 4 are at least as low as M_{comp} 0, and so easily meet the TLS detection requirements.

In addition to the magnitude-based thresholds, we include two additional criteria for the TLS. First, leveraging what was learned from the Pohang earthquake, if while drilling excessive mud losses are encountered, the TLS will move to amber, until the losses are cured. Second, high precision relative relocations will be performed daily for events M ≥ 0 to monitor if seismic activity is illuminating a fault plane. This will only be possible if enough events (n > 20) occur to perform a stable inversion. M ≥ 0 is chosen to separate events associated with small fractures and reservoir development from events occurring on larger fault surfaces.

Table 4 shows observations and actions for the Utah FORGE TLS. The observational thresholds are independent of well pad activities. However, actions are dependent on whether stimulation/injection activities are current or impending.

Automatic alarms are established to alert UUSS duty seismologists for any M ≥ 2 earthquake within ~15 km of the FORGE footprint and ShakeMaps are automatically generated for M ≥ 2.5 earthquakes within 3 km of the FORGE footprint. Alarming events are reviewed by a duty seismologist within approximately one hour to verify location and magnitude. In addition, a cron job will check reviewed triggers and detections and if 10 M ≥ 1 events occurred within 24 hours an additional alarm will be emailed to both UUSS personnel and the FORGE group. Reviewed events will also initiate the communication tree (Figure 8). Increased scrutiny of events in the region will take place for a minimum of two weeks and until background seismic levels are restored. For the case of a red alert during injection into a well, the Project Manager will communicate instructions to the field supervisor to cease pumping and immediately begin flowback.

Table 4. *Traffic Light System. If any of the events in the first column occur, the steps of the second or third column are activated.*

Observations	**Actions: Stimulation**	**Actions: Non-Stimulation**
● No anomalous seismic events	● No actions. Follow good engineering and safety practices.	● No actions. Follow good engineering and safety practices.
● M ≥ 2 within 3 km ● 10 M ≥ 1 in 24 hr within 3 km ● Events propagating along imaged fault plane ● Total loss of drilling mud that cannot be cured in 30 minutes.	● The Drilling Site Manager (DSM), the Operations Superintendent and the Project Manager must be immediately notified, and the DSM will coordinate appropriate activities on location. ● Assemble all personnel at designated muster point and hold an offsite safety meeting ● DSM will immediately terminate pumping ● DSM will initiate controlled flow back with first occurrence of orange. If the well is shut-in, the well will be also be flowed back. Do this in an orderly, controlled manner. Ensure that this is done in a safe fashion for personnel, the rig and surface peripherals, integrity of the well and downhole equipment (if feasible). This is done under the authority of the Drilling Site Manager and the Operations Manager, unless directed otherwise by the project manager. ● Wait for instructions to resume injection. ● Notify all personnel on the FORGE footprint including FORGE staff, contractors, service personnel and visitors. ● All unnecessary personnel are to move away from the wellhead. ● Ensure the safety of personnel first and the integrity of the rig and peripheral equipment if that can be safely done.	● The Drilling Site Manager (DSM), the Operations Superintendent and the Project Manager must be immediately notified, and the DSM will coordinate appropriate activities on location. ● Assemble all personnel at designated muster point and hold an offsite safety meeting ● If Orange is triggered because of losses, rig crew and DSM will continue to work on curing the losses. ● It may be possible that drilling is resumed with or without returns AFTER consultation with FORGE management, and possibly the DOE and key STAT representatives. ● Regardless of the trigger, ensure the safety of all personnel on location, the rig (if present), the integrity of downhole equipment if feasible and safe. ● Notify all personnel on the FORGE footprint including FORGE staff, contractors, service personnel and visitors. ● All unnecessary personnel are to move away from the wellhead. ● Ensure the safety of personnel first and the integrity of the rig and peripheral equipment if that

	● **Operations will cease until a plan to continue is approved by DOE and the STAT.** ● **Resumption of injection could include continuation of pumping at a lower rate or with modified protocols**	can be safely done. ● If drilling is ongoing and conditions are stabilized, POOH or pull into a cased section of the hole. ● *If the issue is loss of circulation, cure the losses without shutting down until the losses are cured.* ● *If cementing is ongoing, and it is deemed safe to do so, continue until the plug has bumped and secure the well.* ● *If logging is ongoing, pull out of the hole.* ● *If activities such as setting packers are ongoing, stabilize the well and wait for instructions.* ● *Wait for instructions to resume operations.* ● ***Operations will cease until a plan to continue is approved by DOE and the STAT.***
● M ≥ 3 within ~15 km	● The Drilling Site Manager (DSM), the Operations Superintendent and the Project Manager **must be immediately notified.** ● **Contact information is available in Section III, page 7 of this document.** ● Assemble all personnel at designated muster point and hold an offsite safety meeting ● DSM will immediately terminate pumping and flow back with first occurrence of red. If the well is shut-in, the well will be flowed back. Do this in an orderly, controlled manner. Ensure that this is done in a safe fashion for personnel, the rig and surface peripherals, integrity of the well and downhole equipment (if	● The Drilling Site Manager (DSM), the Operations Superintendent and the Project Manager must be immediately notified, and the DSM will coordinate appropriate activities on location. ● The Drilling Site Manager (DSM), the Operations Superintendent and the Project Manager must be immediately notified. ● Contact information is available in Section III, page 7 of this document. ● Assemble all personnel at designated muster point and hold an offsite safety meeting

	feasible). This is done under the authority of the Drilling Site Manager and the Operations Superintendent, unless directed otherwise by the Project Manager. ● All unnecessary personnel are to leave the location. ● Ensure the safety of personnel and the integrity of the rig and peripheral equipment. ● **Secure the well. When it is established to be safe to do so, POOH, and rig down service company.** ● **Operations will cease until a plan to continue is approved by DOE and the STAT**	● Ensure the safety of all personnel on location, the rig (if present), the integrity of downhole equipment if feasible and safe ● Notify all personnel on the FORGE footprint including FORGE staff, contractors, service personnel and visitors, ● All unnecessary personnel are to leave the location. ● Ensure the safety of personnel and the integrity of the rig and peripheral equipment. ● **Secure the well.** ● **Operations will cease until a plan to continue is approved by DOE and the STAT.**

SUMMARY AND CONCLUSIONS

The risk of damaging induced earthquakes from the Utah FORGE EGS research project is low. This was determined based on the rural area, low seismic rates and magnitudes, no earthquakes located within the Utah FORGE footprint, no mapped faults within the Utah FORGE footprint, and low proposed injection volumes. The hazard and risk from background tectonic earthquakes located within 50 km of the FORGE project are low to moderate. Because of the distance to known faults, it is unlikely that injection related to Utah FORGE will trigger an earthquake on one of these faults. UUSS operates a well-established earthquake information center, which includes maintaining and operating the seismic center, recording and processing of recorded data, and communicating earthquake activity to the public and researchers. For the Utah region, UUSS is the authoritative network for seismic monitoring of both tectonic and induced earthquakes. To guide monitoring at the Utah FORGE site, a TLS has been developed to identify potential changes in the hazard level (facilitated with automated alarming) and to guide operational activities for mitigating the effects of these changes. A key element of the plan is clear communication with stakeholders and the public through timely information on websites.

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APPENDIX A:

STAKEHOLDERS

Property Owners
- Smithfield
- Utah School and Institutional Trust Land Administration (SITLA)
- Bureau of Land Management
- Unitarian Universalist Service Committee
- Toni and Pat Rule
- Ft. Churchill Corp.

Interested Public
- City of Milford
- Milford High School
- Beaver High School
- Minersville School
- Beaver County Commissioners
- Paiute Indian Tribe of Utah
- Residents of Beaver County

Private Power Developers
- Cyrq Energy
- PacifiCorp (Blundell geothermal plant)
- Milford Solar Project (solar)
- Milford Wind Farm
- Blue Mountain Biogas
- Rocky Mountain Power
- ENEL

Federal and State Organizations
- Idaho National Laboratory
- U.S. Geological Survey
- Utah Geological Survey

Federal and Utah State Government Agencies
- U.S. Bureau of Land Management
- Utah School and Institutional Trust Land Administration (SITLA)
- Utah Department of Environmental Quality (DEQ)
- Utah Underground Injection Control Program

- Utah Division of Water Rights / State Engineer
- State Historic Preservation Office (SHPO)
- U.S. Fish and Wildlife Service Natural Resources, Agriculture, and Environmental Quality Appropriations Sub-committee
- Utah Governor's Office of Economic Development
- Utah Governor's Office of Management and Budget
- Utah Governor's Office of Energy Development
- University of Utah
    - Dept. of Chemical Engineering
    - Dept. of Geology and Geophysics
    - Univ. of Utah Seismograph Stations (UUSS)
    - Office of Sponsored Projects
    - Vice President of Research
    - Department of Communications
    - College of Education

APPENDIX B:

COMMUNICATIONS AND OUTREACH HISTORY

Year 2015

April 27, 2015
A press release was issued by the University of Utah announcing the Phase 1 grant awarded to EGI.

September 2015
Article in September issue of UGS' "Survey Notes" on the FORGE project and the Milford, Utah site selected as one of five possibilities for the field laboratory. Written by Rick Allis.

November 18 – 25, 2015
Project contacts David Cluff, Principal of Milford High School, about setting up a seismometer on the school grounds. A strong-motion instrument will be installed in small out-building on the school property.

December 3, 2015:
Rick Allis and Stuart Simmons conducted a site visit for landowners, regulators and interested stakeholders, including the BLM, Beaver County representative, DEQ, PacifiCorp, Murphy Brown, SITLA and SunEdison. The locations of the deep drill holes, the potential access routes, and the main groundwater collection facility were visited.

December 15, 2015:
Joseph Moore gave an invited presentation at the 6th Annual Program on Energy and Sustainable Development (PESD) convened by the Stanford Precourt Institute for Energy. The theme of the conference was Building Risky Energy. Joseph Moore discussed the role geothermal energy can play in today's energy mix. He discussed challenges facing conventional geothermal development and the potential of EGS. He stressed the importance of the FORGE laboratory where new techniques for EGS development could be developed and tested.

Year 2016

January 15, 2016
Joseph Moore met with D. Hollett, S. Hamm and L. Boyd at DOE headquarters to review our vision of the FORGE project. Meetings were also held with the BLM, who are familiar with the area because of other infrastructure development, and representatives of Senator Hatch and

Representative Stewart. The BLM considered potential environmental or archeological risks posed by the project to be low.

January 27, 2016:
Joseph Moore presented an invited talk to a class in NUCLEAR ENGINEERING at the University of Utah. The presentation covered the basics of geothermal energy and the need for EGS development and a national FORGE laboratory, where new technologies can be tested.

February 2-4, 2016:
STEM Fest (Science-Technology-Engineering-Mathematics) is a unique gathering of Utah educational and business leaders engaged in science and technology. The event offers students in 7th through 10th grades the opportunity to learn exciting and innovative career opportunities in Utah. EGI hosted a booth in conjunction with the Utah Governor's Office of Energy Development that highlighted the Utah FORGE project.

February 8, 2016
FORGE Utah website goes live. The website address is http://www.forgeutah.com/outreach/

February 9, 2016
Rick Allis presents FORGE summary to Natural Resources Appropriations sub-committee of the Utah Legislature.

February 18, 2016
The University of Utah has signed an MOU with Southwest Petroleum University (SPU) of China to exchange information on EGS development. SPU has been working on an EGS project in granite in Korea. The graduate student working on the project will spend a year at EGI beginning in early summer.

February 22 - 25, 2016
Three papers on the Utah FORGE site presented at Stanford Geothermal Workshop.

March 3, 2016
Facebook page published. The Facebook address is https://www.facebook.com/forgeutah/

March 4, 2016
Email to David Cluff, Principal, offering a talk to Milford High School about Utah earthquakes and the FORGE project. Offer not followed up.

March 2016
Utah FORGE Team collaborated with Utah Office of Energy Development on a video about geothermal energy in Utah, including the FORGE project: https://www.youtube.com/watch?v=4-6UgHq_Xe4

March 23, 2016
Joseph Moore presented an invited talk to a class in Sustainable Energy (Dept. of Geography at the University of Utah. The presentation covered the basics of geothermal energy and the need for EGS development and a national FORGE laboratory, where new technologies can be tested.

March 30, 2016
Rick Allis met with Utah Division of Wildlife to discuss biological clearances at FORGE site.

April 4, 2016
Joseph Moore and Rick Allis give presentation concerning the status of the FORGE project to Utah School and Institutional Trust Lands Administration.

April 19, 2016
Representatives of the BLM and Paiute Indian Tribe of Utah met to discuss the FORGE project. The tribe had no objections to the project moving forward. They only requested to be kept informed of changes or updates.

May 6, 2016
Manuscript on the revised thermal regime of the Milford FORGE site submitted to Geothermal Resources Council for their October 2016 meeting in Sacramento, California.

October 11 – 15, 2016
Joseph Moore presented invited lectures at the International Seminar on Exploration and Development of Hot Dry Rock Resources, sponsored by the College of Environment and Resources, Jilin University, Changchun, China, and the Institute of Hydrogeology and Environmental Geology, China Geological Survey Beijing, China.

October 18, 2016
Discussions with Bill Dent (Manager) at SunEdison wind farm maintenance facility and Scott Albrecht (Beaver County Commission) and Jim Webb (Smithfield), followed by presentations to PacifiCorp staff at Blundell Geothermal Power Plant and the monthly meeting of Milford City Council about FORGE project.

October 22, 2016
Joseph Moore presented an invited talk entitled “Overview of the Utah FORGE site at the GRC Workshop on Reservoir Stimulation: Recent Field Practices, Monitoring Techniques and Theoretical/Laboratory Investigations.”

October 28, 2016
Phone call from reporter Linda Peterson of Beaver County Journal. Interviewed about FORGE project as a result of the Milford City Council presentation. Article prepared for Beaver County Journal.

November 30, 2016
Email exchange between University of Utah and Principal of Milford High School about a suitable backyard in the city for a nodal seismometer for the one month of the survey planned for December-January time period. The Principal, David Cluff offered his own backyard for the nodal seismometer.

December 6, 2016
Meeting with Scott Albrecht, Beaver County, to discuss ownership of roads around the FORGE site and activities planned for 2017. Discussion of County requirements for Conditional Use Permit (CUP).

December 7, 2016
Meeting with Rocky Mountain Power in Cedar City and Kent Sorensen from Richfield office who was connected by phone. Discussed power requirements for FORGE. Rocky Mountain Power to prepare assessment of issues and cost.

December 12, 2016
Joseph Moore presented an invited talk entitled "Overview of the Utah FORGE Site" to the Utah Geological Association, Salt Lake City, Utah.

Year 2017

January 4, 2017
Feedback from Beaver County that they are applying to BLM for an easement to allow power to be run in the corridor adjacent to Antelope Point Road. They expect this to be relatively quick approval because of past paperwork and activities on and beside the road.

January 5, 2017
Jim Webb, Smithfield, reaffirms support for the FORGE project in an email.

January 10, 2017
Email letters sent to the two landowners in Section 32 updating them on the project and plans for 2017 which could involve crossing their land.

January 2017
School and Institutional Trust Lands updated on project progress (email correspondence).
January 11, 2017
An article featuring the FORGE project in Milford, Utah as well as its partnership with Smithfield was published in the October issue of the Beaver County Journal.

March 16, 2017
Christian Hardwick gave a presentation on Utah FORGE developments at the meeting of the Association of Environmental and Engineering Geologists, Utah Chapter.

March 21, 2017
Joseph Moore and Mark Gwynn presented to the Beaver County Planning Commission, which unanimously approved the project and recommended review by the County Commission.

April 4, 2017
A presentation by Rick Allis was provided to the Beaver County Commission as the final phase of the Conditional Use Permit.

April 13, 2017
Rick Allis gave the Distinguished Lecture to the Department of Geology and Geophysics at the University of Utah and included material about Utah FORGE.

April 17, 2017
Stephen Potter presented a poster on the seismicity in the Milford – Mineral Mountains region at the annual meeting of the Seismological Society of America.

April 2017
A Peltier teaching module and head exchanger module were both completed.

May 2017
A seismometer module was completed, which uses an accelerometer to detect small vibrations in a classroom.

July 10, 2017
Dr. Tony Butterfield and his team validated the above-mentioned modules by demonstrating them at the Utah Energy Career Expo.

August 2017
Four field trips were conducted. The tours were held for DOE Managers, interested local stakeholder and regulatory administrators, students from the Dept. of Chemical Engineering at the University of Utah taking a course in drilling, and a contingent from the Chinese Geological Survey tasked with developing an Enhanced Geothermal System program. The tours included discussions of the FORGE project, visits to the FORGE site and tours of the drilling rig, the mud system and the logging facilities, and a tour of PacifiCorp's Blundell geothermal plant.

September 7, 2017
ThinkGeoEnergy published photos and a wrap up of the test well.

September 2017
Clay Jones presented a lecture to students in Chemical Engineering on geothermal energy and development.

October 4, 2017
Dr. Tony Butterfield demonstrated the Peltier module and his students developed at the Utah FORGE booth during the Annual Meeting of the Geothermal Resources Council, which was held in Salt Lake City.

October 23-24, 2017
During STEM Fest, over 150 participating students grades 7 through 10 learned about geothermal energy and the Utah FORGE project from Dr. Tony Butterfield and other team members.

October 2017
Approximately 20 individuals attended a field trip to the Utah FORGE site.

December 19, 2017
Dr. Tony Butterfield, several graduate students from the Department of Chemical Engineering, and Clay Jones of EGI, visited Milford High School’s Career Day.

December 2017
Visitors from SINOPEC toured the Utah FORGE site and the surrounding geothermal features and power plant.

Year 2018

January 2018
The Utah FORGE project was featured in Survey Notes, published by the Utah Geological Survey.

June 14, 2018
The Salt Lake Tribune carried a story announcing the selection of the Utah FORGE site, as did the University of Utah’s UNews. ThinkGeoEnergy and Energy Central News both also ran the story.

June 15, 2018
Story about Utah FORGE selection appeared in The Spectrum.

June 18, 2018
A story about the selection of the Milford site ran in Kallanish Energy e-newsletter.

June 26, 2018
A question-and-answer piece was carried by CleanTechnica following the selection of the Utah FORGE site.

June 2018

Prof. Butterfield's undergraduate outreach mentors from the University of Utah's Chemical Engineering department presented two different STEM modules demonstrating concepts applicable to geothermal energy at the Explore Engineering Summer Camp for STEM focused high school students and Hi-GEAR Summer Camp (exclusively for high school girls).

July 25, 2018
ThinkGeoEnergy had a story about Utah FORGE receiving an Office of Energy grant for powerline construction.

July 2018
Two teaching modules titled 'Thermoelectric Human Power' and 'Turbine Electric Generator' were created and made available.

August 4, 2018
An article providing an overview of Utah FORGE ran in The Deseret News.

October 22-23, 2018
Utah FORGE participated in the annual STEM FEST during which the team interacted with school children from elementary to high school age from all over Utah, as well as parents and educators. In addition to the kids, the team interacted with other exhibitors including Utah division of oil and gas, various departments within the U of U, Salt Lake Community College, Utah Valley University, Kennecott/Rio Tinto, and Governor's office of Energy development.

Year 2019

January 31, 2019
Dr. Anthony Butterfield and the outreach team attended Family Night at the Leonardo Gallery from 5 PM to 8 PM. This three-hour tabling event included the Turbine and the Thermoelectric Power modules and the 3D printed site map of the FORGE project.

February 2, 2019
A short article announcing a forum featuring Dr. John McLennan to discuss geothermal energy at Utah FORGE appeared in The St. George News.

February 25, 2019
ThinkGeoEnergy included a story about the U.S. Department of Energy's Geothermal Technology Office's webinar updating listeners about the roadmap for Utah FORGE.

March 12, 2019
Dr. Anthony Butterfield and the outreach team spoke at the Taylorsville Library's Teen Homeschool Program. During the energy portion of the talk the team introduced the FORGE project, and Dr. Butterfield and the team had the kids attending conduct the turbine module, in which they generate electricity from their blowing into a small turbine to illustrate how steam

from geothermal energy is used to create electricity. They also conducted the Thermoelectric Power module, in which the children use the heat from their hands to create a temperature gradient with ice water to create electricity. This module was related back to the geothermal project to illustrate the need to have both a heat source and sink in order to create useful work.

March 18, 2019
A Serbian delegation representing various ministries and agencies visited the Milford site to learn about the geothermal research program. The trip was led by Joseph Moore and sponsored by the Open World Leadership Program. The site visit included stops at the geothermal power plant, and solar and wind farms to learn about Beaver County's renewable energy resources. The structure seen through the winder is the Ormat binary power plant at the Blundell geothermal facility.

April 5, 2019
The Utah FORGE team participated in the University of Utah's Geology and Geophysics Department's Open House attended by the students and the general public. The team held a booth with posters and handouts about the FORGE project and geothermal energy in Utah.

April 18, 2019
Following the first STAT meeting held in Salt Lake City April 15-17, a field trip to the FORGE site and surrounding area on held.

April 25, 2019 – At Latinos in Action, a 1-hour presentation on chemical engineering at the University of Utah was provided. This event brings high school students from the Latino community to campus for college information and recruitment. We used the FORGE turbine and Peltier hands-on projects with students during this event.

May 7-8, 2019
A two-day event at Cyprus High School was by outreach student mentors and team members. Six physics and mathematics classes were visited in which the OED FORGE teaching modules were conducted.

May 13, 2019
ThinkGeoEnergy carried a story about Seequent's collaboration with Utah FORGE.

May 20, 2019
The team visited Hunter High School. The event lasted the entire school day, with the team visiting different chemistry classes. In each, we conducted the OED FORGE modules with the students.

May 30, 2019

The Governor's Energy Development Symposium was attended with example outreach modules. We received multiple requests for information on conducting the modules and we gave out the link to the online material.

June 14, 2019
The outreach team participated at Hi-GEAR Summer Camp which is STEM-focused and intended exclusively for girls. The team offered a chemical engineering presentation and then conducted the OED FORGE outreach hands-on activities. We concluded the event having all the students combine and light as many lights as they could.

June 20, 2019
Dr. Tony Butterfield's outreach team attended the Explore Engineering Summer Camp which is for STEM-focused high school students in which they visit each department in the College of Engineering. The approximately 40 students spent two hours with our outreach team in which we gave a chemical engineering presentation and then conducted the OED FORGE outreach hands-on activities. We concluded the event having all the students combine and light as many lights as they could.

July 18, 2019
A brief announcement about the Utah Governor's Office of Energy releasing the fourth in a series of videos about the Utah FORGE project.

August 31, 2019
Joseph Moore led a field for faculty members from the China University of Geosciences in Chendu, China and EGI students to the site.

September 2019
Joseph Moore gave several invited presentations at the annual meeting of the Geothermal Research Society of Japan.

October 7-8, 2019
Hosted Utah FORGE display at Salt Lake City STEM fest, which included demonstration of the geothermal energy modules and talking about geothermal energy. This is an annual event attended by upwards 20,000 4th through 10th grade students.

October 9-10, 2019
Joseph Moore attended the European Geothermal Workshop in Insheim, Germany.

October 19, 2019
Hosted Utah FORGE display at the Geology and Geophysics, University of Utah, open house, which included demonstration of the geothermal energy modules and talking about geothermal energy.

November 8-11, 2019
Chemical Engineering, University of Utah, undergraduate students participated in outreach competition sponsored by the American Institute of Chemical Engineers (AIChE) Annual Meeting and Student Conference including demonstration of Peltier engine module; the students won the 2nd place prize. The student competition is an annual event attended by over 10,000 participants.

November 23, 2019
Hosted Utah FORGE display at the Engineering Day, University of Utah, which included demonstration of the geothermal energy modules and talking about geothermal energy.

November 25-27, 2019
Stuart Simmons represented the Utah FORGE team at the NZ Geothermal Workshop in Auckland and presented a paper entitled “Overview of the Geoscientific Understanding of the EGS Utah FORGE Site, Utah, USA.”

November 2019
John McLennan delivered an invited presentation on Utah FORGE to the Grand Junction Chamber of Commerce, Colorado.
Rob Podgorney delivered an invited presentation on Utah FORGE to Jackson Hole Geologists at INL.

December 5, 2019
Rob Podgorney was the core speaker at the CODEBREAKER’s day at the Center for Advanced Energy Studies highlighting opportunities to use earth as source of energy.

December 9-13, 2019
Kris Pankow and Phil Wannamaker represented the Utah FORGE team at the AGU Fall Meeting in San Francisco.

December 12, 2019
Rob Podgorney gave a presentation to the DOE-Idaho operations office about INL’s support to the Utah FORGE project.

Year 2020

January 8-9, 2020
Joseph Moore participated at the ICDP workshop at Cornell University providing expert opinion about geothermal projects and Utah FORGE experience.

February 11, 2019
Spring 2020 STEM Career and Internship Fair, Union Bldg., University of Utah. Several of the Chem E students associated with the Utah FORGE project attended the fair.

February 12, 2020
Renewable Energy Press Event/Open House, Architecture Bldg, University of Utah – ad hoc invitation to host a table showcasing the FORGE project on the heels of U of U's recently signed partnership with Cyrq energy. The EGI team and ChemE student team representative attended the event to distribute fliers, show Peltier modules and talk about geothermal energy. The event was attended by about 30 people. https://sustainability.utah.edu/5291-2/

February 10-12, 2020
Seven presentations focusing on Utah FORGE were made by the Utah team members at the Stanford Geothermal Workshop.

February 19, 2020
Science Night at Oquirrh Elementary, West Jordan, UT. The ChemE student team participated in the event bringing some of the FORGE modules. It is estimated that their table saw over 250 visitors and the event had over 400 participants in attendance.

February 2020
General overview presentation about geothermal energy and about the FORGE project at the Reid School in Millcreek, UT. The team of ChemE students brought along several mini turbine and Peltier modules to show to a class of 46 students.

March 2020
University of Utah hosts activities for the refugee program in March. The ChemE. students presented an overview of FORGE, attended by about 10 people.

March 2020
In the first Utah Robotics competition, the ChemE. student team set up a table with FORGE modules and gave a presentation. This event was attended by hundreds of students, mentors and parents. https://www.utfrc.utah.edu/

March 2020
The homepage https://utahforge.com has been expanded to house the "Did You Know" feature, the "Share a Scientific Paper" and the Data Dashboard.

April 28, 2020
The first quarterly newsletter, *At the Core*, was launched and distributed to nearly 200 contacts, and published on the website. https://utahforge.com/at-the-core/

April 30, 2020
The Utah FORGE team released first Solicitation 2020-1 and the website serves as the gate to general information and to the InfoReady site that operates the mechanics of the application processes. https://utahforge.com/rd/solicitations/

May 6, 2020
A pre-recorded, 20-minute webinar on the Geoscientific Overview of Utah FORGE coinciding with the release of Solicitation 2020-1 was created and distributed.

May 14, 2020
The core curation web page has been launched to facilitate core and water sample requests https://utahforge.com/laboratory/sample-curation/.

May 2020
The Data Dashboard was created, allowing those seeking information to access it in a "one stop" location, providing a user-friendly experience. The Data Dashboard can be accessed here.

May 2020
A visual representation of the FORGE project in a short animation was created to summarize in a nutshell the concept of the project https://utahforge.com/outreach/education/education-for-students/

June 8, 2020
The outreach team expanded the social media footprint by launching a LinkedIn profile. LinkedIn allows for professional interaction for the project and those interested in geothermal, while also fostering cross marketing efforts.

June 9, 2020
Utah FORGE worked closely with Professor Sara K. Yeo in the University of Utah's Department of Communications to develop the syllabus for an upcoming Capstone course in the fall. The students will develop a survey instrument to collect data about public opinion, awareness and knowledge of geothermal energy.

June 17, 2020
The June edition featured Pengju Xing and John McLennan, both of the University of Utah, presenting on "Injection Testing and Stress Measurements."

June 25, 2020
Pengju Xing gave a talk at this year's ARMA (American Rocks Mechanics Association) ROBE Talk. The talk's focus was "Using Flowback and Temperature for Closure Stress Diagnosis."

June 2020
A contact lists for email communications of newsletter, news, and announcements was created. In addition, a subscription form was added to the website. The number of subscribers at the end Q3 is 240.

July 1, 2020

Utah FORGE team members met with Jesse Puckett, a representative of the ENEL/Cove Fort geothermal plant, provided an update on Utah FORGE activities, discussed potential future collaboration, and scouted possible locations for additional geothermal-related roadside kiosks. Utah FORGE team members introduced Utah FORGE to Robert Pyles, the new Beaver County Economic Development Director and County Administrator. Provided an overview of Utah FORGE, discussed continuing cooperation opportunities.

July 14, 2020
The second edition of the quarterly newsletter, *At the Core* was published on the Utah FORGE website and promoted to our email distribution list and through our social media platforms.

August 12, 2020
Members of the Utah FORGE team met with representatives from Senator Mike Lee's office. Heath Hansen, Southern Utah Director; Cole LaCroix, Legislative Correspondent / Policy Analyst Environmental Affairs; and Carolyn Phippen, Area Director were provided with an overview of the Utah FORGE project, toured the site, and the existing kiosks.
Members of the Utah FORGE team provided updates on upcoming activities to Beaver County Commissioner Mark Whitney, Beaver County Administrator Robert Pyles, Milford Mayor Nolan Davis, Milford City Councilmen Les Whitney and Scott Symond, Milford City Administrator Makayla Bealer, and Beaver City Mayor Matt Robinson.

August 18, 2020
A university-level lecture / presentation on conventional geothermal resources by Stuart Simmons was produced and promoted to our email distribution list and through our social media platforms. The presentation is the first in a series of two aimed at educating students on geothermal energy.

August 26, 2020
The first episode in a series of podcasts titled *FORGEing Ahead with Geothermal Energy* was released.

August 24, 2020
A Capstone class in the University of Utah Department of Communications was commenced. The Capstone is taught by Professor Sara Yeo. The class theme is focused on better scientific communications and students developed a survey to judge overall understanding of geothermal energy.

August 28, 2020
A short piece announcing the upcoming drilling and inviting the community to attend the planned presentations appeared in the Milford City Newsletter.

August 2020

An overview of Utah FORGE bylined by Joseph Moore appeared in *The Explorer*, the publication of AAPG.

September 2, 2020
An advertorial article appeared in *The Beaver County Journal* announcing drilling would be commencing and inviting the public to attend public meetings to learn more.

September 9, 2020
A reminder advertisement inviting the public to attend public hearings to learn more about the upcoming Utah FORGE drilling appeared in *The Beaver County Journal.*

September 15, 2020
Members of the Utah FORGE team presented to the Beaver County Commission. There were approximately 25 people in attendance. Dr. Joseph Moore provided an overview of the project and outlined upcoming drilling activities. Dr. Kristine Pankow joined the meeting virtually and discussed seismicity. Questions from the public focused on water usage, County investment in the project and what benefits would stem from the project for the people living in the County.

September 15, 2020
The Utah FORGE team met with Adam Snow, Southern Utah Director for U.S. Representative Chris Stewart. Dr. Moore provided him with an update about the project.
A presentation was made to the Milford City Council in advance of planned drilling activities. There were approximately 20 people in attendance. Dr. Joseph Moore provided an overview of the project and outlined upcoming drilling activities. Dr. Kristine Pankow joined the meeting virtually and discussed seismicity.
Joseph Moore presented to the Beaver County Planning and Zoning Commission to secure the required Conditional Use Permit.

September 18, 2020
An online survey was distributed to Utah FORGE's subscribers in order to gain feedback about the overall user experience of visitors to the website.

September 2020
A member of the Utah FORGE team attended all of the classes in the Capstone course at the University of Utah's Department of Communications, answering questions and providing insights when appropriate. The 15+ students are building a survey tool to gauge the public's understanding about geothermal energy. Both Joe Moore and Stuart Simmons presented overviews to the class.
The final kiosk panels were installed on Antelope Point Road. The panels highlight geothermal energy in Utah and the Utah FORGE project specifically.

October 16-18, 2020

During Geothermal Rising's Annual Meeting and Expo, Utah FORGE hosted a virtual booth and invited attendees to visit the booth and/or join our Zoom Room to chat with experts. Within the booth, visitors could view images and videos, as well as link to the data dashboard. Slightly more than 75 people visited the booth throughout the week. Additionally, two e-posters were presented, which are outlined in the Technical Outreach section.

October 21, 2020
Dr. Joseph Moore participated in a panel discussion during the Energy Technology and Innovation Outlook breakout session of the Governor's Energy Summit. He provided information about geothermal and Utah FORGE.

October 30, 2020
A press release was written and promoted to announce the drilling of the first of the two deep deviated wells. It was distributed to the consumer media, trade publications and industry organizations, and also publicized through Utah FORGE's social media platforms and highlighted on the website.

November 10, 2020
A virtual meeting was held with U.S. Representative Chris Stewart whose district includes Beaver County. Joining the Congressman was his legislative assistant, Cam Madsen. Since Rep. Stewart is quite familiar with the Utah FORGE project, Dr. Joseph Moore provided an update highlighting the current drilling and answered questions about next steps and timelines. Rep. Stewart expressed his continued support of Utah FORGE and offered to assist in any way possible.

November 10, 2020
A second virtual meeting was also held with Utah state Senator Evan Vickers, whose district includes Beaver County. Since Sen. Vickers was not as familiar with the project, Dr. Joseph Moore provided him with a more comprehensive overview, including the history of the project, the current drilling, and the next stages. The Senator expressed his support for Utah FORGE and offered to assist the project with any legislation that may be beneficial.

November 2020
Completed the Capstone course in the University of Utah Department of Communications led by Professor Sara Yeo. The course focused on science communication with a geothermal literacy survey serving as an end product. Both Dr. Joseph Moore and Professor Stuart Simmons addressed the class to provide information about general geothermal energy and Utah FORGE specifically. Elisabet Metcalfe also addressed the class.

December 7, 2020
Published and promoted the second edition of FORGEing Ahead with Geothermal Energy, the Utah FORGE podcast. In this edition cohosts Christopher Katis and Stuart Simmons discussed Enhanced Geothermal Systems. This podcast has been listened to over 200 times.

December 2020
The University of Utah College of Education completed the first lesson plan, "Exploring Different Renewable Resources Across the U.S." Teachers can download the plan from the Utah FORGE website's education section. It will also be provided to science coordinators in all of Utah's school districts by our College of Education colleagues.

December 28, 2020
Dr. Joseph Moore provided a tour of the Utah FORGE site to Beaver County Commissioners Mark Whitney and Tammy Pearson. The officials expressed their excitement about the current drilling, discussed the size of the rig, viewed the rig cloud, learned about the well's trajectory, and asked about the location of the next well.

January 6, 2021
The second of two university-level presentations was published and promoted through Utah FORGE's email distribution list and social media platforms. In the presentation, Dr. Stuart Simmons discusses unconventional geothermal resources. The first presentation dealt with conventional geothermal resources. This second presentation has been viewed nearly 7,000 times.

January 7, 2021
Working with the University of Utah's communications department, a story around Utah FORGE's collaboration with the College of Education and Department of Communication was written and published in the University's internal newsletter @TheU. The weekly e-newsletter is available to all students, faculty, and staff.

January 2021
In the November 2020 elections, Wade Hollingshead was elected to the Beaver County Commission. He replaces former Commissioner Mike Dalton, who retired. The Utah FORGE team reached out to Commissioner Hollingshead to introduce the project to him and to provide him with additional information. Per his request, he has been added to the email distribution list. He expressed enthusiasm and support for the Utah FORGE project.

February 2, 2021
A press release was written and distributed announcing the end of drilling for 16A(78)-32, the first deep, highly deviated well. The press release highlighted the success of the drilling, including the depths reached and temperatures found, as well as the fact that it was completed ahead of scheduled. The press release was promoted through Utah FORGE's social media platforms, email distribution list, and to the media. Pre-planned media relations outreach ensured that *ThinkGeoEnergy* "broke" the news by carrying it in their newsletter the morning the press release was distributed. To ensure important stakeholders in Beaver County were kept apprised of the project's progress, an advertorial was prepared and was carried on the front page of the *Beaver County Journal*.

February 4, 2021
U.S. Representative Chris Stewart, whose Congressional District includes the Utah FORGE site, retweeted our announcement about the drilling being completed. We saw over 100 visits to the website immediately following the tweet. The Representative has almost 40,000 followers.

February 24, 2021
In conjunction with our colleagues at the U.S. Department of Energy Geothermal Technology Office, a press release announcing the Solicitation 2020-1 selectees was written and distributed. It was carried in ten publications (a complete list follows below), and the email distribution reached an open rate of nearly 60% (email marketing campaigns usually expect an open rate of 15-25%).

February 2021
To gauge the success of *At the Core* quarterly Utah FORGE newsletter, and to better understand areas that can be improved, a user experience survey was created and distributed. Results will be analyzed in March.

February 2021
The education page of the website was updated to allow for more user-friendly access to information by teachers. It hosts lesson plans (school curriculum), modules, graphics, webinars, and other information.

February 2021
Two student internship positions were filled. The first position is within the University of Utah's Department of Communication. The intern is assisting with various content creation projects and website maintenance. The second intern is from the University of Utah's College of Fine Arts and is creating various graphics and other images.

March 2021
Dr. Joseph Moore presented to Rep. Steve Handy and Rep. Gay Lynn Bennion, both members of the Natural Resources, Agriculture, and Environment Committee. Rep. Handy has requested Dr. Moore present to the American Legislative Exchange Council (ALEC), a forum for legislators from around the country, at the group's annual conference to be held in Salt Lake City in July. Rep. Bennion is working to have Dr. Moore testify before the Committee during an interim meeting.

March 2021
Information about Utah FORGE, geothermal energy, and Enhanced Geothermal Systems was provided to members of the Utah state Legislature's Natural Resources, Agriculture, and Environment Committee, and to the Public Utilities, Energy and Technology Committee. A total of 22 House members and 16 Senate members were contacted, equaling 29% of all House members and 55% of all Senators.

March 2021
Dr. Moore presented information about Utah FORGE, geothermal energy, and Enhanced Geothermal Systems to Quinn Bennion (Vernal City Manager), Joel Brown (Vernal Chamber of Commerce), and Sylvia Wilkins (Uintah County Economic Development Director).

March 2021
The geothermal literacy survey that was developed during the Fall Semester 2020 in the University of Utah Department of Communication capstone course was disseminated, and responses from over 1000 participants in 11 western states were gathered.

March 2021
Initial analysis of some of the raw data provided encouraging insights, including: 45% of respondents expressing support for using geothermal energy; 28% offering support for EGS; and 30% believing EGS is beneficial to society as a whole. More in-depth analysis is being conducted by Dr. Sara Yeo of the University of Utah and Dr. Meagan McKasy of Utah Valley University.

March 2021
Tamara Young, a Ph.D. candidate in the College of Education, presented on energy transfer – including information on geothermal energy and Utah FORGE– in the physics module of the March 4, 2021 Utah Science Teachers' Association virtual monthly conference. Approximately 12 people attended the session, which is also accessible to members online.

March 2021
Information about Utah FORGE, geothermal energy, and Enhanced Geothermal Systems was provided to members of the Utah state Legislature's Natural Resources, Agriculture, and Environment Committee, and to the Public Utilities, Energy and Technology Committee. A total of 22 House members and 16 Senate members were contacted, equaling 29% of all House members and 55% of all Senators.

April 12, 2001
Dr. Kris Pankow of the University of Utah Seismograph Stations addressed Zac Taylor's geology class at Milford High School. She discussed geothermal energy and the Utah FORGE project. There were approximately 12 kids in attendance.

April 2021
The Utah FORGE team traveled to Milford to meet with County Commission Chair Mark Whitney. The team recorded an episode of the Utah FORGE podcast, *FORGEing Ahead with Geothermal Energy*, for which Commission Whitney served as a guest. He discussed the Beaver County renewable energy corridor, including geothermal energy and Utah FORGE. The episode will be promoted later this summer.

April 2021

While in Beaver County, the team delivered and installed a computer to the Milford City Library. The computer is set to the UUSS page to allow users to view real-time seismic activity. Users can also view the Utah FORGE website page on the computer. Computers will also be delivered and installed at the Beaver City and Minersville Libraries in the near future.

April 2021
Additionally, the team designed, printed and placed a poster about the Utah Project in a display booth located in Caboose Park in Milford. The park is home to a Union Pacific caboose, picnic tables, and a seasonal Hawaiian ice stand. Moreover, further discussion with the Beaver County Travel Council resulted in Utah FORGE gaining access to a second panel in the display booth for future use.

April 2021
Dr. Joseph Moore traveled to Milford to provide a tour of the Utah FORGE site to Utah Lt. Governor Deidre Henderson. Dr. Moore discussed the project, its benefit to the area, and the community support Utah FORGE enjoys. Along with Lt. Governor Henderson, the tour guests included: Thom Carter, Energy Advisor to Utah Governor Spencer Cox; Redge Johnson, Executive Director of the Public Lands Policy Coordinating Office; Brian Steed, Executive Director of the Department of Natural Resources; Beaver County Commissioner Mark Whitney; Beaver County Commissioner Tammy Pearson; Councilman Les Whitney, Milford City Council and Beaver County Emergency Services Director; and Jen Robinson, Chief of Staff to Lt. Gov. Henderson.

April 2021
The results of a reader survey to gauge areas in which the Utah FORGE newsletter, *At the Core* can be improved, were analyzed. On a scale from 1-5 in which 1 was Not Very Useful and 5 was Very Useful, the newsletter scored an average 3.8, with one-third of respondents stating the newsletter was “very useful.” *Technical Discoveries* and *Word from the PI* were the most widely-read sections. The next issue of the newsletter will incorporate the most frequently requested additions: of near-term next steps and scientific information.

April 2021
Information about the Utah FORGE project was provided to Congressional staff of Members serving on the U.S. House Energy Subcommittee, the U.S. House Environment and Climate Change Subcommittee, and the U.S. Senate Energy Subcommittee. The outreach yielded requests for virtual meetings with staff from the offices of Representative Diana DeGette’s office and Rep. Kathy Castor, as well as staff serving the Select Committee on the Climate Crisis, which Rep. Castor chairs. These meetings are scheduled for May.

April 2021
Based on earlier outreach to members of the Utah state Legislature, a meeting was scheduled for May with Rep. Kay Christofferson, who serves on the House Public Utilities, Energy and Technology Committee, and Sen. Stuart Adams, who serves on the Senate Transportation,

Public Utilities, Energy and Technology Committee. Sen. Adams is also the President of the Senate.

May 2021
Dr. Joseph Moore met with Utah state Senate President Stuart Adams, Senator Jerry Stevenson, Rep. Kay Christofferson, and Senate Chief of Staff Mark Thomas on May 5. Dr. Moore presented an overview of Utah FORGE and answered questions about the project. President Adams stated he would proactively inform Utah's Congressional delegation of the Senate's continued support for Utah FORGE.

May 6, 2021
Dr. Joseph Moore and the Outreach Team traveled to Milford to provide a tour of the Utah FORGE site and surrounding area to Justin Gillis. Mr. Gillis is a contributing environment opinion columnist for The New York Times, where he also served as the science writer for a decade. Mr. Gillis is finalizing a book about the nation's transition from carbon-based to renewable energy resources. A section of the book focuses on geothermal energy and Enhanced Geothermal Systems will be included in the discussion.

June 14, 2021
An overview presentation was provided by Dr. Joseph Moore to Dr. Nikki Roy, Climate Change and Environment Policy Director for U.S. Rep. Diana DeGette of Colorado on June 14. Rep. DeGette sits on the House Energy Subcommittee.

June 14, 2021
Dr. Joseph Moore provided an overview of the Utah FORGE project to staff members of the U.S. House Select Committee on the Climate Crisis. Attending the briefing were Dr. Zach Pritchard, the American Society of Mechanical Engineers (ASME) Congressional Fellow assigned to the office of the Select Committee Chair U.S. Rep. Cathy Castor of Florida, and Samantha Medlock the Select Committee's general counsel.

June 2021
Stemming from a briefing provided to Utah state Representative Gay Lynn Bennion in March 2021, Dr. Joseph Moore presented an overview to members of the Utah Legislature's Natural Resources, Agriculture and Environment Interim Committee. Along with Rep. Bennion, six other Committee members were in attendance: Sen. Scott Sandall, Chair; Sen. David Hinckens; Sen. Jani Iwamoto; Sen. Derrin Owens; Sen. Evan Vickers; and Rep. Elizabeth Weight. Sen. Vickers represents Beaver County. Three staff members also participated, and approximately 50 citizens attended the meeting in person or virtually through Zoom. A recording of the full meeting is archived and available on the Committee's webpage.

July 2021

Published and distributed the quarterly newsletter At the Core. Along with being posted on the Utah FORGE website, the newsletter is also sent to our over 350 email subscribers, as well as being promoted through our social media platforms.

July 2021
To extend outreach to younger students, we completed and published a webinar intended for grade school students. Titled The Heat Beneath Our Feet, the webinar presents geothermal energy and introduces Enhanced Geothermal Systems at an age-appropriate level. We will work with our colleagues at the University of Utah College of Education to promote the webinar to science teachers in August just prior to classes resuming.

July 8, 2021
Members of the Utah FORGE Outreach and Communication team traveled to Beaver County to provide updates of the project and discuss upcoming stimulation. The team met with Robert Pyles, Beaver County Administrator and Stephanie Laws, Beaver County Commission Secretary; newly appointed Milford City Councilman Terry Wiseman; and Jim Webb, Director of Environmental and Public Affairs at Smithfield Foods.

July 13, 2021
Dr. Joseph Moore provided an overview of geothermal energy and the Utah FORGE project to members of the Citizen Climate Lobby - Utah Valley Chapter. The meeting, which was held virtually, was attended by approximately 22 people.

July 27, 2021
Dr. Ben Barker and Christopher Katis presented an overview of Utah FORGE to the Utah Energy Tour breakout session of the American Legislative Exchange Council (ALEC) annual conference. Approximately 25 participants attended, including elected officials from Arizona, Michigan, Oregon and Utah, legislative staff, members of the Conservative Energy Network, the energy advisor to Utah’s governor, representatives from the Utah Municipal Power Systems, and members of the Utah Mining Association.

July 27, 2021
Stemming from the ALEC presentation, additional information about Utah FORGE, geothermal energy, and EGS was provided specifically to state Sen. Dennis Linthicum of Oregon, state Rep. Gail Griffin of Arizona, state Rep. Philip Green of Michigan, state Rep. Jeff Stenquist of Utah, and state Rep. Rex Shipp of Utah.

July 19, 2021
Dr. Joseph Moore led a tour of the Utah FORGE site for 16 students plus instructors participating in the National Science Foundation-funded Research Experience in Utah for Sustainable Materials in Engineering (ReUSE) at the University of Utah’s Materials Science and Engineering Department. The students were from a variety of universities such as Carnegie

Melon, University of California, Berkeley, Wellesley, and University of California, Los Angeles. Several students proactively reached out to Dr. Moore to express their gratitude.

August 2, 2021
Dr. Joe Moore provided an overview of geothermal energy and an update about Utah FORGE to U.S. Representative Chris Stewart in whose district the project site is located, and U.S. Representative Ed Case of Hawaii. The two toured the University of Utah's Energy and Geoscience Institute as part of the American Congressional Exchange. Approximately 25 people were in attendance, including Congressional staff and University of Utah students.

August 4, 2021
Tamara Young, the PhD candidate in the College of Education presented Energy Transformation with Utah FORGE: Keys to Sustainable Energy Solutions at the American Association of Physics Teachers (AAPT) Summer Meeting. Approximately 15 people attended. Additionally, during the AAPT Summer Meeting Tamara Young attended the "30 Demos in 60 Minutes" session and demonstrated a module created by Dr. Tony Butterfield and his students from the University of Utah's Department of Chemical Engineering. Some 60 people attended.

August 2021
The Utah FORGE Outreach and Communication team provided information on the project and Enhanced Geothermal Systems to Kelsey Berg, Deputy Chief of Staff for Senate Mitt Romney.

August 2021
The Utah FORGE Outreach and Communication team invited various stakeholders to attend the August 17 community meetings at the Beaver County Commission and Milford City Council through direct email outreach. These invitees included nearby landowners, elected officials, regulators, local media, and other renewable energy organizations in the area.

August 2021
To alert the residents of Beaver County and Milford City that Utah FORGE would be presenting at the Beaver County Commission and Milford City Council meetings on August 17 and to invite them to attend, an advertisement was created and placed in the local weekly newspaper, The Beaver County Journal. The ad ran on the front page of the newspaper in the August 11 edition. Milford City also carried the advertisement on its webpage and Facebook page.

August 17, 2021
Dr. Joseph Moore presented at the Beaver County Commission meeting. He provided an update on the Utah FORGE project's activities over the past several months, including the successful drilling of wells 16A(78)-32, 56-32 and 78B-32, future stimulation plans, the induced seismicity mitigation plan, and upcoming activities. Approximately 12 people were in attendance. The County Commissioners mentioned that they were impressed with the advancements made in drilling speed. There were only two questions: whether there has been a change in Federal

commitment to the project under the new administration, and how the Commission could help to ensure the project continues beyond 2024.

August 2021
To alert the residents of Beaver County that Utah FORGE would be hosting a booth at the Beaver County Fair on August 27 and August 28, an advertisement was created and placed in the local weekly newspaper, The Beaver County Journal, which ran on the front page of the August 25 edition.

August 27 – 28, 2021
The Outreach and Communication team members staffed a booth at the Beaver County Fair in Minersville, Utah. The team provided information, answered questions, listened to concerns and comments, and interacted with the fair attendees. The booth included a thermal camera and monitor, which drew attendees' attention and allowed for an organic discussion about heat and heat transfer. There were also core samples on the table, a sample drill bit, written information for adults, and a child-specific flyer. A packet containing information about granite, a small piece of granite and a magnifying glass was also given away to children. Many of the questions were technical, and the comments were all extremely positive in support of the project. Overall, about 350 people visited the booth. Fair officials estimated that approximately 1750 people visited the Fair one or both days.

September 2021
Dr. Stuart Simmons also updated the geoscientific webinar that reflects the current site activities, and the results achieved thus far. Titled Current Geoscientific Understanding of the Utah FORGE Site, the webinar was promoted through social media platforms and to the over 450 subscribers on the email distribution list. In the one week since it was published, the webinar has been viewed over 50 times (now more than 2500 times.)

September 2021
Dr. Joseph Moore finalized an opinion piece, which discussed the potential of geothermal energy and Enhanced Geothermal System technologies. The article was offered as an exclusive to The Salt Lake Tribune. It was carried in the paper's online edition on September 23 and in the print edition on Sept. 26.

September 26 – October 1, 2021
Members of the Utah FORGE Communication and Outreach team along with colleagues from the University of Utah's Energy & Geoscience Institute (EGI) attended IMAGE 20201, the Annual Conference and Exposition of the American Association of Petroleum Geologists to help staff a booth in the exhibit hall. The team provided information on Enhanced Geothermal Systems and answered questions. Among visitors to the booth were representatives from Utah FORGE partners (e.g., Seequent), the industry media e.g., The Explorer), industry organizations (e.g., The Rocky Mountain Association of Geologists), seismologists, geologists, academics, and students.

October 5, 2021
Released and promoted video focused on the successful drilling of 16A(78)-32. To date, the video has had over 660 views (no almost 7900.)

Year 2021

On October 7, 2021
Dr. Joseph Moore traveled to Beaver County to provide an overview and update of the Utah FORGE project to several elected officials, governmental personnel, and others. The group included:

- Members of the U.S. House of Representatives Chris Stewart (UT), Dan Newhouse (WA), and Markwayne Mullin (OK)
- Congressional staff members Heath Hanson, Southern Utah Director for U.S. Sen. Mike Lee; Celeste Maloy, Counsel for U.S. Rep. Chris Stewart; and Adam Snow, Washington County Commissioner and Southern Utah Regional Director for U.S. Rep. Chris Stewart
- Beaver County Commissioners Tammy Pearson, Mark Whitney, and Wade Hollingshed
- Beaver County Economic Development Director Robert Pyles, Beaver County, and Beaver County Secretary Stephanie Laws
- U.S. Department of Commerce Deputy Economic Development Representative Jamie Hackbarth
- Staff from the Five County Association of Governments (Beaver, Garfield, Iron, Kane, and Washington Counties), Bryan Thiriot, Executive Director; Nathan Wiberg, Associate Planner; Nathanuel Martinez, Economic Development Planner; and Alyssa Gamble, Community Planner
- Executive Director, Six County Association of Governments (Juab, Millard, Piute, Sanpete, Sevier, and Wayne Counties) Travis Kyhl
- President of the National Association of Counties, Larry Johnson, and Senior Program Manager Jack Morgan
- Director of Environmental and Public Affairs at Smithfield Foods, Jim Webb.

A video focused on the successful drilling of 16A(78)-32 was released and promoted.

October 14, 2021
Dr. Joseph Moore participated on a panel titled Powering Economies Through New Energy Innovation at the National Association of Counties Western Interstate Region Conference. The panel was moderated by Beaver County Commissioner Mark Whitney, and included Utah state Rep. Stephen Handy, Bryan Harris, Director of Development at Longroad Energy Partners, and Jack Morgan, Senior Program Manager of the National Association of Counties. There were between 50-60 people in attendance, almost all of whom were other elected county officials from the western U.S.

- A virtual geological tour of the Utah FORGE site and the surrounding area intended for the scientific community was produced and promoted.
- A short "fly over" video, which highlighted the current Utah FORGE infrastructure and the trajectory of 16A(78)-32 was produced and promoted
- Utah FORGE-generated lesson plans were incorporated into the Milford High School science class.
- Secured Enel as the sponsor for the pilot classroom contest, which was conducted in the Milford Middle School science class during the January – March academic year.

November 26-27, 2021
Members of the Utah FORGE Communication and Outreach team engaged with approximately eight individuals in an impromptu meeting. These individuals learned about the temperature and depth of the wells, that there are existing conventional geothermal plants in Utah, and the basics of EGS. They also asked about water requirements and electricity generation.

December 21, 2021
Utah FORGE team members attended quarterly public meetings in Beaver County to provide an update of the project, explain upcoming planned stimulation, discuss seismicity, introduce the possible continuation of the project beyond the current time frame, and answer any questions from elected officials and community members. The meeting and Utah FORGE update was included in the December 29, 2021 *The Beaver County Journal*.

Year 2022

January 2022
The Utah FORGE quarterly e-newsletter, *At the Core* was distributed through social media platforms and to the 500+ email distribution list.

Four lesson plans were completed. Through collaboration with our colleagues at the University of Utah College of Education, we incorporated the requirements needed to make the plans accessible to students of various learning abilities, including those in Special Education, those for whom English is not a native language, and those at risk for not achieving academic success.

February 2022
The geothermal song parody pilot contest was launched in Mr. Zac Taylor's 7th-9th grade science class at Milford High School. This included a field trip for the students to the Cove Fort geothermal power plant and a presentation by the Utah FORGE Outreach and Communication team members. Students also received handouts about geothermal energy, as well as Utah FORGE-branded promotional items. There were 37 students and 4 adults in attendance.

The Utah FORGE frequently asked questions (FAQ) were promoted through the social media platforms of Utah FORGE and the Outreach and Communication team personal sites. They proved to be very popular; the project's LinkedIn page received over 3,500 impressions for the FAQs, and a team member's personal page received an additional 1,000-plus impressions. A total of 13 FAQs were posted.

March 15, 2022
The Utah FORGE team provided an update on the project's timeline for stimulation, and also answered questions at the Beaver County Commission and Milford City Council meetings. In total, the meetings were attended by 24 people. Along with the Commissioners and Councilmembers, also attending the meetings were: Utah state Senator Evan Vickers, who represents Beaver County; Cindy Bulloch, Southern Utah Co-Director for U.S. Rep. Chris Stewart (in whose district the site is located); Beaver City Councilmembers Owen Spencer and Alison Webb; and Beaver City Manager Jason Brown.

March 30, 2022
The winners of the Enel-sponsored geothermal song parody contest, which was piloted in Mr. Zac Taylor's 7th through 9th grade science class at Milford High School, were selected and notified during class.

- Two short videos were produced and promoted. The first was an aerial overview of the Utah FORGE site and surrounding area, while the second was a 360-degree timelapse of activities at the site. Viewers are able to use their cursors to control a 360º view of the rig and site.

April 19, 2022
The Outreach and Communication team attended the song parody contest awards celebration at the Milford City Council. The winners and runner up of the contest were recognized during the council meeting, receiving their prizes – iPads for the members of the winning team and a $50 gift card for the runner up. Mayor Nolan Davis expressed his gratitude to Utah FORGE and Enel, who provided funding for the contest. He thanked the team for running the contest and always including the community in its outreach efforts. Additionally, he expressed his appreciation that the Utah FORGE team has made continuing efforts to involve the area's young people. A photo featuring the students, and a short narrative, were submitted to *The Beaver County Journal*. It ran in the April 27 edition.

April 19, 2022
Dr. Joseph Moore conducted a tour of the site for the members of the Beaver County Commission. The Commissioners learned about the stimulation and its role in the project. They expressed their continued support.

April 26, 2022
Dr. Joseph Moore provided a tour of the Utah FORGE site to a delegation of parliamentarians from Belgium, more than 20 people participated.

April 2022

- A new poster was created and posted in the display kiosk located in Milford's Caboose Park. The poster focuses on Utah FORGE's appreciation for the community's support.
- A short overview / recap view of the successful stimulation, and an accompanying brief video of activities around the rig, were created and pushed.
- A final fifth lesson plan, Explaining the Uneven Distribution of the Earth's Natural Resources was completed. Through our collaboration with the University of Utah College of Education, the lesson plans will be distributed to science leads throughout Utah in late July / early August when teachers are planning their curricula.

May 22, 2022
A wrap up piece about the successful stimulation for *Think Energy* and an interview with Dr. John McLennan were carried in the publication.

June 21, 2022
Dr. Joseph Moore presented at public meetings in Beaver County at which he provided an overview of the recent successful stimulation, discussed seismicity, outlined next steps, and – as Utah is in the midst of a drought – remined those in attendance that the water that will be used in future stimulations is non-potable. The first meeting was at the Beaver County Commission, approximately 13 people attended. The second meeting was with the Milford City Council, some 10 people participated.
An overview of the stakeholders and VIPs in Beaver County was provided to a representative from Fervo. The company has leased BLM land southwest of the Utah FORGE site, and requested assistance in learning more about the stakeholder landscape

July 11 and July 12, 2022
Dr. Joseph Moore met with members of Utah's Congressional delegation and their staff. He provided an update of the Utah FORGE project to Sen. Mitt Romney and Rep. Chris Stewart, as well as to the energy director for Sen. Mike Lee.

July 12, 2022
The Utah FORGE Outreach and Communications team traveled to Beaver County to provide an overview of the project to University of Utah President Taylor Randall, and 12 other officials from the university. Milford Mayor Nolan Davis and Councilman Les Whitney also joined the meeting.

July 13, 2022
Dr. John McLennan participated on the geothermal panel at the National Association of State Lands Summer Conference. He provided an overview of Utah FORGE and answered panel questions. Between 50-60 individuals from around the western U.S. attended.

August 6, 2022
Members of the Utah FORGE Outreach and Communication team staffed an informational booth at the annual Midvale (Utah) Harvest Days Festival. Over 160 people visited the booth.

August 16, 2022
Dr. Joseph Moore provided a tour of the Utah FORGE site in Beaver County to U.S. Sen. Mitt Romney, Chief of Staff Liz Johnson, Deputy Chief of Staff Kelsey Berg, Press Secretary Arielle Mueller, and Southern Director Kyle Wilson.
Dr. Moore introduced the Utah FORGE project to Commissioner-elect Brandon Yardley, who joined Sen. Romney.

August 22 – August 24, 2022
The Utah FORGE Outreach and Communication team, including student interns, staffed a table at the University of Utah's Welcome Week. The event introduces new and returning students to clubs and other groups associated with the University. Over the three days, more than 300 people stopped at the booth, including University of Utah President Taylor Randall.

August 26 – August 27, 2022
The Utah FORGE Outreach and Communication team staffed a booth at the Beaver County Fair in Minersville, Utah. The team provided visitors with information about the project and answered questions about geothermal energy in general and Utah FORGE specifically. To attract attention and invite people to come to the booth to chat, a thermal camera and a thermoelectric human power module were place at the table, both of which led to discussions about heat transfer. Additionally, core samples and a 3D printed replica of the drill bit were displayed. Young people were given their own rock kit packet, which included a piece of granite rock, an info sheet, and a magnifying glass. They could also "win" their choice of Utah FORGE branded beach balls or bubbles by answering geothermal questions (with help from the booth's staff.) Over 300 individuals stopped at the booth.

September 27 – September 28, 2022
Members of the Utah FORGE Outreach and Communication team, joined by a student intern and Chemical Engineering PhD candidate, hosted a booth during the two-day STEM Fest. The team used a thermal camera and hands-on modules to interact with students and discuss heat transfer, geothermal energy, and Utah FORGE. STEM Fest included two days of school groups and an evening for families. Organizers estimated the event saw over 13,000 participants.

October 11, 2022
The Utah FORGE Outreach and Communication team, met U.S. Representative John Curtis (Utah) and provided a tour of the site. Joining the Congressman were Lorie Fowlke, District Director; Larry Ellertson, Rural and Energy Advisor; Adrielle Herring, Outreach Advisor; and HD Sanderson, Health and Military Affairs Specialist. Additionally, Gordon Larsen, Senior Advisor for Federal Affairs to Utah Governor Spencer Cox, joined the tour. Along with the site, the

group visited the area around Mag Lee's bathhouse to see the steaming ground, and also toured the Blundell geothermal power plant. Rep. Curtis expressed his appreciation and continued support for the project.

October 18, 2022
Members of the Utah FORGE Outreach and Communication team presented an update of activities at the regularly scheduled Beaver County Commission, which is open to the public. The team discussed its outreach efforts and upcoming site operations, including the planned drilling of well 16B(78)-32. They also answered questions from the elected officials. A total of thirteen people attended the team's presentation, including members of the County Commission, administrators, Commissioner-nominee Brandon Yardley, and a representative from Cove Fort (Enel) geothermal power plant. The Commissioners again expressed their appreciation for the update and the ongoing outreach to the community, and reiterated their unwavering and continued support for the project.

November 22, 2022
The Utah FORGE team visited the 5th and 6th grade classes at Minersville Elementary School to provide an age-appropriate overview about geothermal energy. Additionally, the team led hands-on science activities, which proved to be very popular with the students. Based on what they learned during the classroom visit, the students created posters explaining and illustrating a geothermal concept. The posters, along with those created by students at the other Beaver County elementary schools, will be displayed in the local public libraries. A winner and runner-up from each school will receive an award courtesy of Enel Green Power in January 2023.

December 5, 2022
The Utah FORGE Outreach and Communication team visited the 5th and 6th grade classes at Milford and Belknap (Beaver City) Elementary Schools to provide an age-appropriate overview about geothermal energy. The team also led hands-on science activities, which were greatly enjoyed by the students. One of the teachers commented, "I've never seen these kids so engaged." Based on what they learned during the classroom visit, the students created posters explaining and illustrating a geothermal concept.

December 5, 2022
Members of the Outreach and Communication team met with Jen Wakeland, the new Strategic Development Director for Beaver County to provide an overview of Utah FORGE and our activities in the community. Ms. Wakeland expressed her support and offered to assist in any way the team needs. Commissioner Tammy Pearson also stopped by during the meeting and reiterated her support for the project.

December 6, 2022

The Outreach and Communication team attended the Beaver County Commission meeting and provided an update on the recent school visits and the poster contest. The Commissioners expressed their continued appreciation for the team's efforts to involve the County's students.

December 12 – December 15, 2023
Members of the Outreach and Communication team hosted a booth at the American Geophysical Union (AGU) Fall Meeting in Chicago. Between 300-400 attendees visited the booth.

January 2023
A new video highlighting the successful stimulation of well 16A(78)-32 in April 2022 and deployment of seismic monitoring tools at the Utah FORGE site was released.

Two new student interns were hired:

- Sarah Buening – environmental studies student / writer
- BJ Iturrieta – graphic design student

February 9, 2023
Utah FORGE Hosted Secretary Jennifer Granholm at the University of Utah. In addition to key Utah FORGE and EGI personnel, and several students, the Secretary was joined by:

- Utah Lt. Governor Deidre Henderson
- University of Utah Provost and Senior Vice President for Academic Affairs Dr. Mitzi Montoya
- Interim Vice President of Research Dr. Erin Rothwell
- Dean of the College of Mines and Earth Sciences Dr. Darryl Butt
- Associate Dean for Research at the John and Marcia Price College of Engineering Dr. Kevin Whitty
- University of Utah Vice President for Government Relations Jason Perry
- Utah Office of Energy Development Director of Communications Harry Hansen

Dr. Joseph Moore presented an overview and the goals of the Utah FORGE project. Then Secretary, Lt. Governor and Dr. Moore then toured the geothermal pump room of the Carolyn and Kem Gardner Commons building, and concluded the visit to the University with a press conference at the Hinckley Institute of Politics.

February 10, 2023
The Outreach and Communication team traveled to Beaver County to present prizes to the winners of the Utah FORGE / Enel geothermal poster contest held in the 5th and 6th grades at Belknap (Beaver), Milford and Minersville elementary schools.

February 21, 2023

Members of the Utah FORGE Outreach and Communication team met with Utah state Senators Nate Blouin, Kathleen Riebe and Stephanie Pitcher to provide an introductory overview of the Utah FORGE project to them.

February 22, 2023
Workshops for teachers who are being trained on Canvas by our partners at the University of Utah College of Education on incorporating the standards-based lesson plans the College developed in collaboration with Utah FORGE were held. To facilitate helping the teachers incorporate geothermal into their classrooms, Dr. Stuart Simmons provided a geoscience / Utah FORGE overview. Approximately 20 science teachers across the state participated.

March 21, 2023
Members of the Utah FORGE Outreach and Communication team updated the Beaver County Commission and members of the community ahead of the planned April drilling. Approximately fifteen people attended. Along with the members of the Commission, other attendees included state Sen. Evan Vickers, state Rep. Carl Albrecht, Beaver City Councilman Owen Spencer, Beaver City Councilman Hal Murdock, and *Beaver County Journal* publisher Mary Wignall. The Commissioners expressed their ongoing support for the project.

March 21, 2023
The Utah FORGE Outreach and Communication team provided an overview of the upcoming planned April drilling to the Milford City Council. Approximately 10 individuals attended. The Council again offered their thanks and support.

March 22 – March 23, 2023
In-person lectures to eighth grade students at Beaver and Milford High Schools in advance of the song parody contest were provided. The students learned about geothermal energy and its uses. In all, five classes were visited with a total of approximately 75 students.

A monthly geothermal-themed crossword puzzle was developed and launched.

ATTACHMENT 1:

PSHA

PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE FORGE SITE

University of Utah
Salt Lake City, Utah

Prepared for:

University of Utah
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May 2020

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PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE FORGE SITE

University of Utah
Salt Lake City, Utah

EXECUTIVE SUMMARY

This report presents an update of the probabilistic seismic hazard assessment (PSHA) conducted by Amec Foster Wheeler (2018) to obtain the mean annual frequency that specified levels of ground motion will be exceeded at four locations in the vicinity of the proposed FORGE (Frontier Observatory for Research in Geothermal Energy) site. The target sites are the FORGE drilling center, the town of Milford, UT, a central location in the adjacent windmills, and the Blundell geothermal plant.

The site lies within the Basin and Range province of North America, in an area characterized by the presence of numerous normal faults capable of generating large magnitude earthquakes. Most notably, the site is approximately 120 km from the closest segment of the Wasatch fault. The distribution of earthquakes in Utah is concentrated in the central part of the State, along the Wasatch range. Most of the earthquakes are small magnitude events, however the most recent estimate by the Working Group on Utah Earthquake Probabilities (WGUEP) is a probability of 43 percent that an earthquake with **M** ≥ 6.75 associated with ruptures along the Wasatch fault will occur in the next 50 years (WGUEP, 2016).

The main components of the PSHA are seismic source characterization and ground-motion characterization. The PSHA developed for FORGE specifically incorporated uncertainties in the models and model parameters that make up the seismic source and ground-motion characterization.

Seismic source characterization provides a probabilistic model for the rate of occurrence, spatial distribution, and size distribution of earthquakes within the region surrounding the site. Two types of seismic sources were included in the model: areal source zones, which are used to model the occurrence of distributed seismicity throughout the region; and local and regional faults, which are used to model the localized occurrence of larger magnitude earthquakes on mapped geologic features. The distributed seismicity source zones were developed based on interpretations of the regional geology, seismicity, and tectonics. Local and regional faults are characterized based on geological investigations conducted by the University of Utah (local faults) and using the Quaternary faults database compiled by USGS.

The PSHA was conducted using the ground motion predictive equations (GMPEs) developed in the NGA-West 2 Project (Bozorgnia et al., 2014). These models provide the necessary characterization of ground motions for the local site conditions encountered at the four sites analyzed in this study.

Several updates are included in this report. First, the location of the FORGE drilling center has been re-assigned to be the centroid of the area that will be stimulated. This location is approximately 500 m from the FORGE drilling center used in the 2018 calculations. Second, since the publication of the 2018 PSHA report, the University of Utah has collected site velocity data that allowed for a re-evaluation of the Vs30 and basin-depth parameters necessary to adjust the NGA-West 2 ground motion models to the site conditions at each site. Third, based on new research conducted on segments of the Wasatch fault and on the Negromag fault, changes were made to the earthquake recurrence model of each fault. The effect of these changes was found to be generally very small. In addition to these updates, the effect of adding 1.3 more years of observed seismicity to the earthquake catalog developed by Amec Foster Wheeler (2018) was evaluated by statistical testing. The test results indicated that there was no need to update the recurrence model of the zones based on the additional observed seismicity.

While updating the hazard calculations, an error was discovered in the earthquake recurrence parameters used for the source zones in the Amec Foster Wheeler (2018) PSHA. This report presents corrected results and supersedes Amec Foster Wheeler (2018). The corrected results are significantly lower than the 2018 PSHA results. The results of the PSHA indicate that for short return periods the high-frequency hazard is controlled by small nearby earthquakes associated with the host distributed seismicity zone (the Basin and Range zone), while the low-frequency hazard is affected by larger magnitude, more distant earthquakes, such as those occurring on the nearest segment of the Wasatch fault. For long return periods, the hazard is dominated by earthquakes occurring on the local faults. The hazard at the FORGE drilling center, Milford, and Blundell Geothermal Plant is comparable, while the hazard at the windmills is relatively lower, due to its greater distance from the local faults and from the Intermountain Seismic Belt.

PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR THE FORGE SITE

University of Utah
Salt Lake City, Utah

1.0 INTRODUCTION

This probabilistic seismic hazard assessment (PSHA) was performed to obtain the mean annual frequency that specified levels of ground motion will be exceeded at four locations near the proposed Frontier Observatory for Research in Geothermal Energy (FORGE) site in central Utah. The target sites are the FORGE drilling center, the town of Milford, UT, a central location in the adjacent windmills (referred to in the following as windmills), and the Blundell geothermal plant. Table 1-1 lists the coordinates of the four sites, which are shown in Figure 1-1. The location of the FORGE drilling center shown in Table 1-1 and Figure 1-1 is approximately 500 m away from the location of the FORGE drilling center used in Amec Foster Wheeler (2018). This location represents the possible centroid of the area that will be stimulated (Kris Pankow, email communication on April 10, 2020).

1.1 OBJECTIVES

The scope of work for this study involved developing a seismic hazard model that encompasses the region within approximately 300 km of the FORGE site. Due to attenuation of seismic wave with distances in the western US, earthquakes occurring at greater distances are not expected to contribute to the site hazard. The model includes regional and local earthquake sources, each characterized in terms of the recurrence rate of earthquakes as a function of magnitude. The sources were developed and characterized based on the observed seismicity and geologic data. A suite of ground motion prediction equations (GMPEs) applicable to Utah were selected for use to assess the ground motions that local and regional earthquakes may produce at the sites.

The project scope of work consisted of three tasks: 1) develop a seismic source characterization model; 2) select GMPEs appropriate for the tectonic characteristics of the earthquake sources and the local site conditions; and 3) calculate PSHA at the four locations. The hazard analysis was conducted using a probabilistic approach. Seismic hazard results are presented for peak ground acceleration and 5% damped response spectra ordinates for spectral periods of 0.02, 0.05, 0.075, 0.10, 0.20, 0.50, 1.0, 2.0, and 5.0 sec (frequencies of 50, 20, 13.3, 10, 5, 2, 1, 0.5 and 0.2 Hz). The hazard is computed for a broad period range in order to provide a more complete description of the site hazard and to provide results that can be used in analyses of various types of structures.

Following the publication of Amec Foster Wheeler (2018) PSHA report, Wood was retained to conduct a series of analysis to evaluate the need to update the FORGE Probabilistic Seismic Hazard model based on new information. Specifically, the Department of Energy (DOE) has indicated that the seismic hazard model should be updated based on 1) new information on the regional setting and structure; and 2) new data pertaining the velocity model at the site. This report and the results of the PSHA analyses presented herein include the new information that was evaluated. During these evaluations, an error was discovered in the 2018 Amec Foster Wheeler calculations. The hazard results presented in this report are obtained with the correct parameters and therefore supersede the 2018 PSHA presented in Amec Foster Wheeler (2018). The corrected results are significantly lower than the 2018 PSHA results for all sites.

1.2 DOCUMENT STRUCTURE

This report is organized into five parts:

Section 1 – Introduction

This section presents the objectives of the study and describes the document structure.

Section 2 – Earthquake Catalog

This section describes the compilation and analysis the earthquake catalog for the project region used in the development of the SSC model and its update.

Section 3 – Seismic Hazard Model

This section describes the seismic hazard model developed for the FORGE region and its update.

Section 4 – Probabilistic Seismic Hazard Analysis

This section describes the results of the PSHA conducted for the four sites of interest and the development of ground-motion response spectra.

Section 5– Conclusions

This section presents the study conclusions, based on the seismic hazard results at the four localities of interest.

2.0 EARTHQUAKE CATALOG

The primary source for the compilation of the earthquake catalog is the catalog of earthquakes for the "Utah Region" (lat. 36.75° to 42.50° N, long. 108.75° to 114.25° W) from 1850 through 2016, compiled by Arabasz et al. (2017). This compilation is termed the "Utah catalog" in the following. The catalog contains mostly "Best-Estimate Magnitudes", BEM in the following, which is either an observed moment magnitude **M**, value of **M** obtained by conversion using another magnitude type, or a magnitude assumed equivalent to **M** (Arabasz et al., 2016).

The spatial extension of the Utah catalog is not sufficient to cover the region of interest for the source characterization. The project catalog was expanded to the south and to the west by adding records from the catalog used in the National Seismic Hazard Map project of 2014 (Petersen et al., 2014). Six different catalogs were downloaded from the USGS website (https://github.com/usgs/nshmp-haz-catalogs). Three catalogs cover the Central and Eastern U.S. (CEUS) and three catalogs cover the Western U.S. (WUS). In the study region, the separation between CEUS and WUS catalog occurs at approximately longitude 113.8° W. Figure 2-1 reproduces a table from the USGS website that describes the characteristics of the six catalogs. The top three rows refer to the CEUS catalogs, the bottom three to the WUS catalogs. The three catalogs are described here for CEUS since it is the same for WUS. In all catalogs duplicated and non-tectonic events caused by mining and explosions have been removed. Catalog *c2 contains both dependent earthquakes (aftershocks and foreshocks) and events possibly related to fluid injection (PFI); catalog *.c3 does not contain dependent events but contains PFI; catalog *.c4 does not contain dependent events nor PFI. For the purpose of this study, we need to maintain dependent events in the catalog, but we need to remove PFI, therefore we have first compared catalogs *.c3 and *c4 to identify PFI, then removed the PFI from *.c2. The corrected CEUS and WUS *.c2 catalogs were merged, sorted in chronological order, and trimmed to the study region. This catalog is termed "NSHM catalog" in the following.

Two important issues need to be resolved for using the NSHM catalog: 1) the catalog only extends to the end of 2012; 2) the uniform moment magnitude is E[M] (EPRI/DOE/NRC, 2012) not BEM. The first issue is addressed by truncating the completeness of the NSHM catalog to the end of 2012 (see Section 3.3). The second issue is addressed in Section 2.1.

2.1 NSHM MAGNITUDES AND UTAH MAGNITUDES

Figure 2-2 shows the 2,129 earthquakes common to the Utah and NSHM catalog. For these earthquakes, we have compared the moment magnitude from the Utah catalog with the expected moment magnitude (E[**M**]) from the NSHM catalog (Figure 2-3). The plot on the left-hand side of Figure 2-3 shows the differences between NSHM E[**M**] and Utah Catalog BEM versus magnitude, while the plot on the right-hand side of Figure 2-3 shows the differences versus time. While the plots indicate a linear trend, they also show a wide dispersion of the data, which is greater for larger magnitudes and older events.

Using both catalogs, we collected the seismicity within an area of 50-km radius from the center of the FORGE site. For this analysis we assumed that the equivalent earthquake counts for the Utah catalogs are equal to 1 for each earthquake. We used the completeness time intervals from Arabasz et al. (2016) for the Utah region, and Mmax of 6.75 (Arabasz et al., 2016) for the recurrence calculations done using the Utah catalog, and Mmax of 8 (Petersen et al., 2014) for the recurrence calculations done using the NSHM catalog. Both catalogs are declustered using the method by Gardner and Knopoff (1974). It was noticed that the earthquake of November 14, 1901 (BEM 6.63, E[**M**] 6.5) has different epicentral coordinates in the Utah and NSHM catalogs, such that it falls inside the 50-km radius area in the Utah catalog, but not in NSHM. To be able to compare the recurrence from the two seismicity models, the earthquake was considered either inside the 50-km area for both catalogs, or outside for both catalogs. Figure 2-4 shows the comparison between the mean and fractile earthquake frequency distribution obtained from the Utah catalog (green) and the corresponding distributions obtained from the NSHM. The plot on the left-hand side of Figure 2-4 shows the recurrence comparisons assuming that the coordinates of the 1901/11/14 earthquake are as in the Utah catalog (i.e., the earthquake is inside the 50-km area); the plot on the right-hand side of Figure 2-4 shows the case where the coordinates of the 1901/11/14 earthquake are as in NSHM (i.e., the earthquake is outside the 50-km area). While the slope of the recurrence curves is slightly steeper for Utah, the difference is small enough that the two catalogs can be considered equivalent. Based on this comparison, and solely for the scope of this study, NSHM E[**M**] are used as is to extend the Utah catalog to the south and to the west to cover the study region.

2.2 CATALOG DECLUSTERING

The PSHA formulation developed by Cornell (1968, 1971) assumes that the occurrence of earthquakes is a Poisson process. Studies such as Gardner and Knopoff (1974) have shown that when foreshocks and aftershocks (dependent events) are removed from an earthquake catalog, the remaining (independent) events can be considered to conform to a Poisson process in time.

Dependent events have been removed from the updated earthquake catalog using multiple approaches. The criteria applied for this study are those of Grünthal (1985, updated by pers. comm., 2002), Gardner and Knopoff (1974), Uhrhammer (1986), and EPRI/SOG (1988). The EPRI/SOG (1988) model was originally developed by Veneziano and Van Dyke (1985), although details of the methodology were only available in form of a draft report. As discussed in EPRI/DOE/NRC (2012), the advantages of the EPRI/SOG (1988) approach are that it is insensitive to incompleteness because a homogeneous Poisson process is only assumed in proximity to the earthquake sequence being tested and that it does not assume a priori a shape for the clusters.

The first three methods address the uncertainty in the duration and extent of the time and space windows used to identify dependent events, while the fourth method is conceptually different. All together the four declustering algorithms address epistemic uncertainty in the identification of dependent events.

The results of the declustering are summarized in Table 2-1: the initial catalog contains 32,763 earthquakes, the declustered catalogs vary considerably in the overall number of earthquakes, with the larger differences observed in the smaller magnitude intervals.

2.3 ANALYSIS OF CATALOG COMPLETENESS

Arabasz et al. (2017) conducted an in-depth analysis of completeness for the region covered by the project catalog. Their estimates of completeness for the Utah Region (UTR) are used in this project without modification. The portion of the study region that falls within the WGUEP region uses the completeness interval obtained for that project (WGUEP, 2016). For the portion of the study area covered by the NSHM catalog, the completeness intervals for the UTR were applied, but time elapsed was calculated based on a catalog ending in 2012. The start of the completeness period for various magnitude intervals for UTR and WGUEP is shown in Table 2--2.

2.4 EVALUATE THE NEED TO UPDATE THE EARTHQUAKE CATALOG BASED ON RECENT OBSERVED SEISMICITY

In PSHA the earthquake catalog is used primarily to develop earthquake frequency relations for zones of distributed seismicity and to develop models that represent the spatial distribution of the seismicity within the zones. Observed seismicity is also used to guide the selection of appropriate maximum magnitude and focal depth distributions for source zones.

The latest available update of the earthquake catalog for the Utah region (Arabasz et al., 2017), includes updates and revisions to the historical seismicity prior to 1962 (Arabasz et al., 2019). The catalog used in NSHM14 was updated for the 2018 National Seismic Hazard Map (NSHM18 in the following, Petersen et al., 2019). It is important to note that the only the declustered catalog is available for download.

The FORGE catalog was compared to the NSHM18 catalog for the area and time period. All comparisons were made with the FORGE catalog declustered using the Gardner and Knopoff (1974) method. An initial comparison showed 36 events within the Utah region that were found in NSHM18 but not in FORGE. Using Arabasz et al. (2019) for the pre-1962 records, and notes by Dr. Arabasz (2020, written communication) for the remaining cases, all the discrepancies were reconciled.

The common events identified in the FORGE and NSHM18 catalog were compared in terms of location and magnitude. The location is generally consistent between the catalogs with a few outliers that appear caused by typos in the epicentral coordinates. The analysis of magnitudes shows that NSHM18 magnitude are generally lower than FORGE for small **M**, and higher for large **M**. When compared to the NSHM14, the magnitudes from NSHM18 are consistently higher.

The comparison between NSHM18 and FORGE catalogs identified 45 events from 2017 to April 9, 2018 that can be used to evaluate the need to update the FORGE model with regard to the prediction of future earthquakes within zones of distributed seismicity. The first observation is that the post-2016 seismicity is distributed where pre-2016 earthquakes have occurred; therefore, the pattern of observed seismicity does not suggest the need to update the spatial density distribution of seismicity. The second observation is that the largest events occurred after 2016 are well within the maximum magnitude range for the source zone, indicating that there is no need to update the maximum magnitude distributions.

To evaluate the need to update the recurrence rates, a statistical test was used. Under the null hypothesis, the number of earthquakes observed in the time elapsed since the end of the FORGE catalog is consistent with the number of earthquakes predicted by the long-term earthquake rates obtained using the FORGE catalog. The FORGE seismic hazard model (Amec Foster Wheeler, 2018) uses the Poisson recurrence model for the distributed seismicity sources. Given the frequency of earthquakes (λ) and the time interval of observation (t), the probability of observing exactly n earthquakes is given by:

$$P[N = n] = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \qquad (2\text{-}1)$$

An exact Poisson test (e.g., Fay, 2010) was performed to test the null hypothesis that the observed number of earthquakes in the time elapsed between the end of the Amec Foster Wheeler (2018) catalog (i.e., 12/31/2016) to the end of the updated NSHM18 catalog (i.e., 4/9/2018) has been generated by a natural process with true rate of earthquakes equal to the long-term earthquake rate of the hazard model. The time interval is equal to 1.3 years (t in Equation 1). Because the interest is in evaluating whether the true rate should be higher, a one-sided test is used. The test is performed by calculating the probability of observing a number n of earthquakes with **M** ≥ 3.0, or greater counts, given the true rate λ_i, where λ_i is one member of the uncertainty distribution for λ calculated from the FORGE model parameters. The test is defined by the following equation:

$$P[N \geq n_{obs} | \lambda_i] = 1 - \sum_{n=0}^{n-n_{obs}-1} P[N \geq n | \lambda_i] \qquad (2\text{-}2)$$

The equation is used to evaluate each term of the summation from n = 0 to n = $n_{obs\ -1}$. Probabilities smaller than 5% reject the null hypothesis (i.e., fail the test).

The mean rate (λ_i) of earthquakes with **M** ≥ 3 can be obtained from the recurrence curves developed for the FORGE study and is used to calculate the mean predicted number of earthquakes greater or equal than **M** 3 ($N \geq n | \lambda_i$), which is 11.87. During this time interval, the NSHM18 catalog shows 13 earthquakes (n_{obs}) with **M** greater or equal than 3 in zone BR (Basin and Range) and none in the other zones. From Equation 2, the probability is 77%. The process was repeated for **M** 3.55, resulting in a probability of 91% as shown in Table 2-3. In both cases, the probability is greater than 5% indicating that the predicted rates and the recent observed seismicity are not inconsistent.

3.0 SEISMIC HAZARD MODEL

This section describes the seismic hazard model developed for FORGE.

A PSHA incorporates both aleatory uncertainty and epistemic uncertainty. Aleatory uncertainty (or variability) is the natural randomness in a process, and epistemic uncertainty is the scientific uncertainty in characterizing the process due to limited data and knowledge. Examples of aleatory uncertainty are variation in the peak ground motion of individual recordings about a median ground-motion relationship, and the location and magnitude of the next earthquake. Examples of epistemic uncertainty are alternative models for ground motion estimation, the estimated long-term rate of slip on a particular fault, and the statistical uncertainty in quantifying the recurrence rate of earthquakes from a finite set of earthquake data. In this project uncertainties are addressed using logic trees. Methodologies for quantifying epistemic uncertainty include the development and weighting of alternative interpretations of seismic source characteristics to provide a structured characterization of epistemic uncertainty suitable for seismic hazard computation (Budnitz et al., 1997). The weighted alternative interpretations can be expressed by the use a sequenced series of nodes and branches on a logic tree (e.g., Kulkarni et al., 1984; EPRI-SOG, 1988).

The following sections contain descriptions of the logic tree framework for the FORGE seismic hazard model; descriptions of the distributed seismicity source zones and of the local and regional faults; and a description of the ground motion predictive equations implemented in the seismic hazard analysis.

3.1 SEISMIC SOURCE CHARACTERIZATION MODEL

The seismic source characterization model includes two types of seismogenic sources: areal source zones that model distributed seismicity throughout the region (Section 3.1.1), and fault sources that act as localizers of larger magnitude earthquakes. The fault sources are further divided between local faults (Section 3.1.2), which are located within approximately 50 km of the site, and regional faults (Section 3.1.3), that are located at greater distances from the site. The characterization of the local faults was based information gathered as part of this study. The characterization of the regional faults was based on the 2014 National Seismic Hazard Maps (NSHM) characterization developed by Petersen et al. (2014).

3.1.1 Areal Source Zones

The study area is covered by three areal source zones simplified from the zones from the NSHM (Petersen et al., 2014). Table 3-1 summarizes the characterization of the areal source zones, which are shown in Figure 3-1.

The spatial distribution of future earthquakes was modeled using kernel density estimation (e.g., Silverman, 1986). A Gaussian kernel was selected to model the spatial distribution. Selection of the kernel size parameter h controls the balance between accurately portraying the areas of high seismicity without introducing areas of unrealistically low seismicity in areas of sparse seismicity. This balance was achieved by using the adaptive kernel smoothing recommended by Stock and Smith (2002), in which the kernel size is adjusted throughout the study region, decreasing in size in areas of higher data (earthquake) density and increasing in size in areas of sparse data. The Stock and Smith (2002) adaptive kernel approach is similar in concept to the approach used by Petersen et al. (2014) in the NSHM. Adaptive kernel smoothing spatial density models were developed for each of the areal source zones using each of the four alternative declustered earthquake catalogs.

Earthquake recurrence rates for the areal source zones were modeled by a truncated exponential magnitude distribution with parameters determined using the maximum likelihood formulation of Weichart (1980). Epistemic uncertainty in the recurrence parameters was modeled by a joint distribution of earthquake rate and b-value calculated from the likelihood formulation. Twenty-five alternative pairs of earthquake rate and b-value were developed for each of the alternative maximum magnitudes listed in Table 3-1 and for each of the four alternative declustered earthquake catalogs.

The maximum magnitude distributions for the source zones developed by Petersen et al. (2014) were adopted for use in this study.

3.1.1.1 Rocky Mountain

The Rocky Mountain Areal Source Zone encompasses the northeast corner of the study area. The source area includes the north-south trending Rocky Mountain chain. The Rocky Mountains are a result of uplift during the Laramide orogeny and have had relatively low rates of historical seismicity.

The strike distribution for earthquakes in this zone was assumed to be random. Based on the style of faulting of mapped faults and available focal mechanisms, future earthquakes are assumed to be an equal mix of normal and strike-slip earthquakes. The assigned dip aleatory distribution was 35 (0.2), 50 (0.6), and 65 (0.2) degrees for normal ruptures and 90 degrees for strike-slip ruptures. The maximum depth of seismogenic rupture for this zone could not be directly assessed from the seismicity due to the limited number of earthquakes. Therefore, the epistemic distribution is assessed to be 8 km (0.2), 12 km (0.6), and 16 km (0.2), consistent with results obtained from the analysis of the seismicity of the entire region.

3.1.1.2 Basin and Range

The Basin and Range Areal Source Zone encompasses the majority of the study area including the FORGE site. The Basin and Range is defined by approximately north-south trending extensional valleys and mountain ranges. Most faults in the source zone are basin bounding normal faults.

Strike distribution for this study was assumed to be N30E. Based on the style of faulting of mapped faults and available focal mechanisms, future earthquakes are modeled as a mixture of 70 percent normal faulting and 30 percent strike slip faulting. The assessed aleatory distribution for rupture dip was 35 (0.2), 50 (0.6), and 65 (0.2) degrees for normal ruptures and 90 degrees for strike-slip ruptures. The epistemic distribution for maximum depth of seismogenic rupture assessed from analysis of the seismicity is 8 km (0.2), 12 km (0.6), and 16 km (0.2).

3.1.1.3 Colorado Plateau

The Colorado Plateau Areal Source Zone encompasses the southeastern portion of the study area. The Colorado Plateau is relatively undeformed and unfaulted in comparison to the Basin and Range and Rocky Mountains.

Strike distribution for this study was assumed to be random. Based on the style of faulting of mapped faults and available focal mechanisms, future earthquakes are assumed to be an equal mix of normal and strike-slip earthquakes. The assumed aleatory dip distribution was 35 (0.2), 50 (0.6), and 65 (0.2) degrees for normal ruptures and 90 for strike-slip ruptures. The f distribution for maximum depth of seismogenic rupture for this zone could not be directly assessed from the seismicity due to the limited number of earthquakes available. The epistemic distribution is assumed to be 8 km (0.2), 12 km (0.6), and 16 km (0.2), consistent with results obtained from the analysis of the seismicity of the entire region.

3.1.2 Local Faults

Three local faults within 50 km of the FORGE site were identified as potentially active (Figure 3-2 and Table 3-2). Because down dip geometry is poorly defined for these faults they are assigned an epistemic distribution for dip of 50 (0.6), 65 (0.2), and 35 (0.2) degrees. Earthquake recurrence for the faults was modeled using the Youngs and Coppersmith (1985) characteristic magnitude distribution. The characteristic magnitude is calculated from the rupture dimensions using alternative empirical models (Hanks and Bakun, 2008, Stirling et al., 2008; Wesnousky, 2008). The use of three alternative equations, combined with nine alternative rupture geometries (three dips x three seismogenic depths), creates an epistemic distribution for characteristic magnitude.

The age of deformation of the local faults is also poorly known. Based on the limited information gathered, they were assigned a common wide epistemic distribution for slip rate of 0.002 (0.125), 0.06 (0.75), and 0.2 (0.125) mm/yr.

3.1.2.1 Opal Mound

The Opal Mound fault runs northeast-southwest along the western flank of the Mineral Mountains for 7 km. It is an east-dipping normal fault with a surface trace defined by siliceous hydrothermal deposits. Along the trace of the fault there are discontinuous fault offsets of 5 to 33 cm in a 10-m wide zone. The surface expression of the fault may be mineralization due to hydrothermal fluids moving along the fault promoting differential erosion rather than tectonic movement on the fault (Kleber, 2017). The eastern dip into the range front is atypical for the Basin and Range province. Knudsen et al. (2019) concluded the most recent activity on the fault may be late Pleistocene in age.

3.1.2.2 Negromag Wash

The Negromag Wash fault strikes east-west for 10 km in the Mineral Mountains, dipping to the north. The geomorphic expression of the fault is an approximately 1 km long, 1 to 3 m scarp which offsets Pleistocene alluvial fans. Knudsen et al. (2019) completed a paleoseismological study of the region surrounding the FORGE site and concluded the Negromag Wash fault was most likely a pre-Quaternary feature. They conclude the fault scarp is the result of differential erosion rather than movement on the fault. Based on the results of this study, the likelihood of activity of the Negromag fault was lowered to 0.4 from 1.0.

3.1.2.3 Mineral Mountain West

The Mineral Mountain West fault zone runs northeast-southwest along the western flank of the Mineral Mountains and into the basin. The northern 8 km of the fault zone contain a graben with a mean scarp height of 3.5 m on internal horst and graben blocks. The highest slip rates are in the middle of the fault zone. The fault zone is 38 km long with an assigned maximum rupture length of 15 km. Knudsen et al. (2019) concluded the most recent activity on the fault may be late Pleistocene in age.

3.1.3 Regional Faults

Within the study area 52 individual faults and fault segments were identified based on the National Seismic Hazard map (NSHM) source faults (Table 3-2 and Figure 3-3; Petersen et al., 2014). Faults used in the NSHM are more than 50 km from the study sites. Of these, the Kane Spring Wash fault is strike-slip and the remainder are normal faults. All of the faults are with in the Basin and Range Areal Source Zone and have epistemic uncertainties in dip of 50 (0.6), 65 (0.2), and 35 (0.2) degrees for the normal faults and 90 for the strike slip fault. Earthquake recurrence rates are assessed using the slip rate distributions listed in Table 3-2 and the Youngs and Coppersmith (1985) characteristic magnitude distribution. The characteristic magnitude is calculated from the rupture dimensions using alternative empirical models (Hanks and Bakun, 2008, Stirling et al., 2008; Wesnousky, 2008). The use of three alternative equations, combined with nine alternative rupture geometries (three dips x three focal depths), creates an epistemic uncertainty distribution for the characteristic magnitude.

The Wasatch fault zone is the longest and most active of the faults included and its SSC model is further discussed in section 3.1.3.1.

3.1.3.1 Wasatch

The Wasatch fault zone is an approximately 200 km long normal fault that bounds the western edge of the Wasatch Mountains. It stretches from north of the Idaho border to south of Provo, UT. Although the fault zone has not generated a large earthquake during the historical period, paleoseismic evidence suggests large earthquakes occur on the fault. The Wasatch fault zone is more than 120 km to the northeast of the study sites.

The characterization of the Wasatch fault zone is adopted from Petersen et al. (2014). The fault zone is divided into seven individual segments that can break individually or as one fault that stretches the entire length of the fault zone (Table 3-3). The Wasatch fault zone is modelled in three alternative ways: 1) an unsegmented fault, generating a 127-km long rupture anywhere along its entire length; 2) a set of seven individual segments, each rupturing its full length; 3) an unsegmented fault that can generate earthquakes ruptures with lengths of 20 (0.3), 30 (0.3), 40 (0.3) and 50 (0.1) km. The characteristic magnitude is calculated from the rupture dimensions using alternative empirical models (Hanks and Bakun, 2008; Stirling et al., 2008; Wesnousky, 2008). The use of three alternative equations, combined with nine alternative rupture geometries (three dips x three focal depths), creates a characteristic magnitude distribution.

Two of the segments of the Wasatch fault, the Provo and Nephi segments have new reported slip rates based on recent trenching studies (Bennet et al., 2018 and Duross et al., 2017, respectively). These studies both concluded the slip rate was lower than the rate used by Petersen et al. (2014) and the slip rate distributions for these segments were adjusted to incorporate these lower rates for the individual segment portion of the Wasatch fault model.

3.1.4 Evaluate the Need to Update the Seismic Source Model

A review of literature published since the Amec Foster Wheeler (2018) report was conducted to identify new data or models that could be used to update elements of the source characterization models. Table 3-4 lists the articles that were evaluated during this review and summarizes their potential effect on the source model. As indicated in the previous sections, recent information was used to modify the slip rate distribution and probability of activity assessment of faults.

3.2 GROUND MOTION CHARACTERIZATION MODELS

In PSHA earthquake ground motions are typically specified in terms of alternative ground-motion-prediction equations (GMPEs). There are two necessary components of a GMPE: 1) a relationship for the median amplitude (mean log amplitude) of ground motions as a function of earthquake magnitude, source-to-site distance, and spectral frequency of interest, and other variables as appropriate; 2) a relationship for the aleatory variability of the ground motion about the median amplitude. To address uncertainty in the GMPEs, four alternative GMPEs were selected for the 2018 FORGE seismic hazard model (Amec Foster Wheeler, 2018). These are four of the NGA-West2 ground motion models: the Abrahamson et al. (2014); Boore et al. (2014); Campbell and Bozorgnia (2014); and Chiou and Youngs (2014). These are the GMPEs used in the NSHM for sites other than rock in the WUS (Petersen et al., 2014).

The four NGA West 2 GMPEs cover a wide spectral range and are defined for the ten spectral frequencies chosen for this analysis (see Section 1.1). The four models can be directly used to assess ground motions for site conditions specified in terms of VS30, the time-averaged shear wave velocity of the top 30 m. Figure 10 of Zhang et al. (2018) shows Vs profiles to a depth of 400 m for the FORGE drilling center and the town of Milford. Similar profiles were provided by Dr. Pankow (2020, written communication) for the center of the windmills and the Blundell plant. These profiles were used to obtain site-specific V_{S30}. The four NGA-West2 GMPEs also include parameterization for basin depth in terms of depth to a shear wave velocity of 1 km/s, $Z_{1.0}$, or depth to a shear wave velocity of 2.5 km/s, $Z_{2.5}$. Values of these parameters were obtained from the velocity profiles for each site and applied in the hazard calculations. Table 3-5 lists the V_{S30}, and parameters $Z_{1.0}$ and $Z_{2.5}$ obtained at each site.

A model for the epistemic uncertainty in median ground motions was developed by Al Atik and Youngs (2014) as part of the NGA-West2 project. The model provides values of the standard deviation in ln(median) motion as a function of magnitude and structural period. The epistemic uncertainty in the NGA-West2 median motions was represented in the GMC logic tree by the three-point discrete representation of a normal distribution developed by Keefer and Bodily (1983) in which the central estimate is given a weight of 0.63 and the 5th and 95th percentiles (located at ±1.645 sigma) are each given a weight of 0.185.

4.0 PROBABILISTIC SEISMIC HAZARD ANALYSIS

The development of design ground motions for the four locations near the proposed FORGE site involved performing a PSHA using the seismic sources and the ground-motion models described in Section 3.

The following sections illustrate the approach used to perform the analyses and the results of the PSHA for the reference site conditions.

4.1 PSHA ANALYSIS APPROACH

The mathematical formulation used in most PSHAs assumes that the occurrence of damaging earthquakes can be represented as a Poisson process. Under this assumption, the probability that a ground-motion parameter, Z, will exceed a specified value, z, in time period t is given by (e.g. Cornell, 1968, 1971).

$$P(Z > z \mid t) = 1 - e^{-\nu(z)\cdot t} \leq \nu(z)\cdot t \tag{4-1}$$

where ν(z) is the average frequency during time period t at which the level of ground-motion parameter Z exceeds value z at the site from all earthquakes occurring in all sources in the region. Equation (4-1) is valid provided that ν (z) is the appropriate average value for time period t. In this study, the hazard results are reported in terms of the frequency of exceedance ν(z).

The frequency of exceedance ν(z) is a function of the frequency of earthquake occurrence, the randomness of size and location of future earthquakes, and the randomness in the level of ground motion that future earthquakes may produce at the site. It is computed by the following expression:

$$\nu(z) = \sum_{n} \alpha_n(m^0) \int_{m^0}^{m^u} f(m) \left[\int_{0}^{\infty} f(r \mid m) \cdot P(Z > z \mid m, r) \cdot dr \right] \cdot dm \tag{4-2}$$

where $\alpha_n(m^0)$ is the frequency of earthquakes on source n above a minimum magnitude of engineering significance, m^0; f(m) is the probability density of earthquake size between m^0 and a maximum earthquake the source can produce, m^u; f(r|m) is the probability density function for distance to an earthquake of magnitude m occurring on source n; and P(Z>z|m,r) is the probability that, given an earthquake of magnitude m at distance r from the site, the peak ground motion will exceed level z. The frequency of earthquake occurrence, $\alpha_n(m^0)$, and the size distribution of earthquakes, f(m), were determined by the earthquake recurrence relationships. The distribution for the distance between the earthquake rupture and the site was determined by the geometry of the seismic sources. The conditional probability of exceedance, P(Z>z|m,r), was determined using the GMPEs described in Section 3.3. The GMPEs defined the level of ground motion in terms of a lognormal distribution. Based on the studies presented in EPRI (2006), the ground-motion distributions were not truncated in the PSHA calculation.

The seismic hazard model for the site region described in Section 3 treats all the parameters of Equation (4-2) as uncertain and specifies discrete probability functions for each one. The result is a large number of alternative parameter sets, each with a finite probability that it represents the "correct" parameter set. The computation of $\nu(z)$ is made for a particular parameter set, and the result is assigned the probability associated with that parameter set. The process is repeated over all parameter sets, producing a discrete probability density for the frequency of exceedance, $\nu(z)$. The probability density for $\nu(z)$ is then used to compute the mean or expected hazard and various percentiles of the distribution that define the uncertainty in the hazard given the uncertainty in the input parameters.

Wood E&IS's in-house set of seismic hazard software was used to perform the PSHA calculations. The computational scheme used to compute the hazard involves replacing the integrals of Equation (4-2) with summations over 0.1-unit magnitude and small distance intervals (e.g., 0.1 km for distances less than 10 km, 1 km for distances less than 100 km). The distance density function, $f(r|m)$, was computed numerically over each source region (assuming either a uniform density or a spatially varying density computed using a Gaussian kernel density estimator), assuming that each earthquake has a finite rupture area dependent on magnitude with the orientation of ruptures specified as described in Table 3-1. The fault sources are modeled as planar features with magnitude-dependent rupture areas located equally likely along the length of each fault. The probability function $P(Z>z|m,r)$ was computed assuming that peak ground motions are lognormally distributed about the specified median predictions from the GMPEs.

The hazard was computed using a fixed lower-bound magnitude (m^0 in Equation [3-2]) of **M** 4.0. The distance density functions were computed consistent with the distance measure used in the GMPEs.

Distributions for the annual frequency of exceeding various levels of peak ground acceleration and 5% damped response spectra were computed for spectral periods of 0.02, 0.05, 0.07, 0.10, 0.20, 0.50, 1.0, 2.0, and 5.0 s (frequencies of 50, 20, 13.3, 10, 5, 2, 1, 0.5 and 0.2 Hz). At each ground-motion level, the complete set of results forms a discrete distribution for frequency of exceedance, ν(z). The computed distributions were used to obtain the mean frequency of exceeding various levels of peak ground motion (mean hazard curve), as well as hazard curves representing various percentiles of the distributions. The logic trees represent a best judgment as to the uncertainty in defining the input parameters, and thus the computed distributions represent the implied confidence in the output, the estimated hazard.

4.2 EFFECT OF MODEL UPDATES ON PSHA

Figure 4-1 illustrates the effect of updating the slip rate of the Provo segment of the Wasatch fault, and the probability of activity of the Negromag fault. The Figure compares the hazard result at the FORGE drilling center for PGA, and spectral acceleration for periods of 0.2 s and 1 s. These changes produce a small reduction in seismic hazard because the slip rate and the probability of activity were lowered.

Similarly, Figure 4-2 shows the effect of using the updated site characterization parameters for the FORGE drilling center. This site is chosen as an example because it shows the largest difference in V_{S30} between 2018 PSHA and the update. Results vary depending on the site, but in general show small variations of the mean hazard.

4.3 RESULTS OF THE PSHA FOR FORGE DRILLING CENTER

Figures 4-3, 4-4, 4-5 and 4-6 show the hazard results for the FORGE drilling center respectively for PGA, and 5 Hz, 1 Hz and 0.2 Hz spectral acceleration (or spectral periods of 20, 1, and 5 s). These ground-motion measures span the frequency range of primary interest. The figures show in black the total mean hazard curve defining the mean frequency of exceeding specified ground-motion levels over all the sources of uncertainty defined in Section 3. The range in the results is shown by curves defining the 5th (black, dash-dotted curve) and 95th (black, dashed curve) percentiles of the distributions for frequency of exceedance computed from the logic tree. These percentile hazard curves define uncertainty in the hazard resulting from uncertainties in specifying the inputs to the analysis. The contribution to the total mean hazard from various elements of the source characterization model are also shown on the figures. The blue curve represents the contribution from the areal source zones, which is dominated by the Basin and Range zone. The host zone is the largest contributor to the hazard at exceedance frequencies greater than 10-4. Below that level (return period of 10,000 years and greater) the local faults (light blue curve) become the largest contributors. This curve represents the combined contribution of the Opal Mound, Negromag Wash and Mineral Mountain West faults. At 5 s (0.2 Hz), the Wasatch fault (orange curve) is the second largest contributor to the total hazard for short return periods (annual exceedance frequencies of 10^{-2} to 10^{-4}). The orange curves represent the overall Wasatch model obtained by combining the three modeling alternatives described in Section 3.1.3.1. In all figures, the green curve represents the aggregated contribution of all the regional faults (excluding Wasatch). Figure 4-5 shows the contribution of all the faults and fault segments to the total hazard at 1 Hz: aside from various segments of the Wasatch fault zone, and the three local sources, the regional fault that show the highest contribution is the Paragonah fault (PAR), which is located to the southeast of the FORGE drilling center.

A sensitivity test was conducted for the Mineral Mountain West fault to evaluate the sensitivity of the hazard to the mean slip rate. The test is conducted by assigning the highest weight to the lowest slip rate (0.002 mm/yr). Figure 4-7 shows that the hazard for this fault will be reduced by approximately 40%, which in turn will cause a reduction of the total hazard of approximately 10% for AFE of 10^{-4}.

Figure 4-8 shows the mean horizontal uniform hazard response spectra (UHRS) obtained by interpolation of the total mean hazard curves for the 10 spectral frequencies analyzed, at specified annual frequencies of 1/475 years, 1 /975 years, 1/2,475 years,1/5,000 years, and 1/10,000 years. The values are shown in Table 4-1.

Deaggregation of the seismic hazard is used to identify the mean M and mean distance of earthquakes contributing to the seismic hazard at a given spectral frequency and return period. The mean M and mean distance resulting from the deaggregation of the seismic hazard for PGA, 5 Hz, 1Hz, and 0.2 Hz (PGA, 20, 1, and 5 s) and for return periods of 475, 975, 2,475, 5,000 and 10,000 years are shown in Table 4-2.

4.4 RESULTS OF THE PSHA FOR THE WINDMILLS, MILFORD, AND BLUNDELL PLANT

The seismic hazard analyses were repeated for the windmills, the town of Milford, UT, and the Blundell Geothermal Plant using the appropriate site characterization. Seismic hazard curves for the windmills are shown in Figures 4-10 through 4-13, the UHRS is shown in Figure 4-14 and in Table 4-3. The deaggregation results for the windmills are shown in Table 4-4. The seismic hazard curves for the town of Milford, UT, are shown in Figures 4-15 through 4-18, the UHRS is shown in Figure 4-19 and in Table 4-5. The deaggregation results for Milford are shown in Table 4-6. The seismic hazard curves for the Blundell Geothermal plant are shown in Figures 4-20 through 4-23, the UHRS is shown in Figure 4-24 and in Table 4-7. The deaggregation results for the Blundell plant are shown in Table 4-8.

Figure 4-25 compares the 475 years return period UHRS for the four sites analyzed in this study. The results are comparable for FORGE, Blundell Plant and Milford due to their proximity to each other, with differences mostly due to the different V_{S30}. The hazard obtained for the windmills, which are located to the north of the FORGE drilling center, is lower because the location is further away from the local sources, the Paragonah fault and the observed seismicity belt.

5.0 CONCLUSIONS

This report updates the design ground motions for the FORGE drilling center, the town of Milford, UT, a central location in the adjacent windmills, and the Blundell geothermal plant. The seismic hazard was calculated for the local site condition in terms of Peak Ground Acceleration and nine spectral frequencies ranging from 0.2 Hz (5 s) to 50 Hz (0.02 s), and then interpolated to obtain spectral accelerations at annual frequencies of 1/475, 1/975, 1/2,475, 1/5,000 and 1/10,000 years. The results for the FORGE drilling center, Milford, and the Blundell Geothermal Plant are very similar due to the proximity of the three sites. The results for the windmills are slightly lower due to its increased distance from the main seismicity, which is concentrated along the Intermountain Seismic Belt, the local faults and the Paragonah fault.

Magnitude and distance deaggregation confirm that for short return periods the high-frequency hazard is controlled by relatively small nearby earthquakes associated with the background seismicity zone (Basin and Range zone), while the low-frequency hazard is affected by larger M, more distant earthquakes, such as those occurring on the nearest segment of the Wasatch fault. For long return periods, the hazard is dominated by earthquakes occurring on the local faults.

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TABLES

TABLE 1-1

COORDINATES OF THE SITES USED IN THE PSHA

University of Utah
Salt Lake City, Utah

Site	Latitude	Longitude
FORGE drill center	38°30'09.5"N	112°53'17.86"W
Milford, UT	38°23'49.43"N	113° 0'51.64"W
Blundell Geothermal Plant	38°29'20.06"N	112°51'10.70"W
Windmills	38°34'50.25"N	112°55'24.88"W

TABLE 2-1

EFFECT OF USING ALTERNATIVE CATALOG DECLUSTERING METHODS

University of Utah
Salt Lake City, Utah

Magnitude Interval	Original Catalog	Grünthal (1985)	Gardned and Knopoff (1974)	Urhammer (1983)	Veneziano and Van Dyke (1985)
2.0-2.3	28,358	13,410	16,372	21,757	10,709
2.3-2.6	1,108	544	636	779	462
2.6-2.9	1,006	472	538	670	425
2.9-3.2	882	458	530	626	369
3.2-3.5	653	324	368	443	291
3.5-3.8	363	222	239	278	206
3.8-4.1	207	131	135	147	114
4.1-4.4	70	53	53	57	37
4.4-4.7	41	25	25	26	17
4.7-5.0	38	21	23	25	23
5.0-5.3	17	9	10	11	7
5.3-5.6	13	10	10	10	10
5.6-5.9	2	1	1	1	1
5.9-6.2	2	2	2	2	0
6.2-6.5	1	1	1	1	1
6.5-6.8	2	2	2	2	2
6.8-7.1	0	0	0	0	0
Total	**32,763**	**15,685**	**18,945**	**24,835**	**12,674**

TABLE 2-2

COMPLETENESS INTERVALS
University of Utah
Salt Lake City, Utah

M interval	Beginning of Complete Period
WGUEP (2016)	
$2.9 \leq M < 3.6$	1986
$3.6 \leq M < 4.3$	1979
$4.3 \leq M < 5.0$	1963
$5.0 \leq M < 5.7$	1908
$5.7 \leq M < 6.4$	1880
$6.4 \leq M < 7.0$	1850
UTR (Arabasz et al., 2016)	
$2.9 \leq M < 3.6$	1986
$3.6 \leq M < 4.3$	1986
$4.3 \leq M < 5.0$	1963
$5.0 \leq M < 5.7$	1908
$5.7 \leq M < 6.4$	1880
$6.4 \leq M < 7.0$	1860

TABLE 2-3

RESULTS OF THE ONE-SIDED POISSON TEST FOR t=1.3
University of Utah
Salt Lake City, Utah

Magnitude	n_{obs}	$N>n\|\lambda_i$	$P[N>n_{obs}\| \lambda_i]$
$M>3$	13	11.87	77%
$M\geq3.55$	3	4.16	91%

TABLE 3-1

SOURCE PARAMETERS FOR AREAL SOURCE ZONES

University of Utah
Salt Lake City, Utah

Zone	Style of Faulting[1]	Average Fault Trend	Average Dip[1]	Dip Direction[1]	Top Depth of Rupture (km)	Maximum Depth of Seismogenic Rupture (km) [2]	Maximum Observed Earthquake	Maximum Magnitude Distribution[2]
Basin and Range	N (0.7) SS (0.3)	N30E	For Normal: 35 (0.2) 50 (0.6) 65 (0.2) For Strike-Slip: 90 (1.0)	Equally likely in both direction. Vertical	0	8 (0.2) 12 (0.6) 16 (0.2)	6.63 (1901/11/14)	6.75 (0.3) 7.00 (0.4) 7.25 (0.3)
Colorado Plateau	N (0.5) SS (0.5)	Random	For Normal: 35 (0.2) 50 (0.6) 65 (0.2) For Strike-Slip: 90 (1.0)	Equally likely in both direction. Vertical	0	8 (0.2) 12 (0.6) 16 (0.2)	5.02 (1988/8/14)	6.75 (0.3) 7.00 (0.4) 7.25 (0.3)
Rocky Mountains	N (0.5) SS (0.5)	Random	For Normal: 35 (0.2) 50 (0.6) 65 (0.2) For Strike-Slip: 90 (1.0)	Equally likely in both direction. Vertical	0	8 (0.2) 12 (0.6) 16 (0.2)	5.3 (1950/1/18)	6.75 (0.3) 7.00 (0.4) 7.25 (0.3)

Notes

1. Aleatory variability distribution.
2. Epistemic uncertainty distribution.

TABLE 3-2

SOURCE PARAMETERS FOR LOCAL AND REGIONAL FAULTS

University of Utah
Salt Lake City, Utah

Fault Name	Code	P_a[1]	Style of Faulting	Average Dip[2] (deg)	Dip Direction	Rupture Length (km)	Slip Rate[2] (mm/yr)
Opal Mound fault	OPM	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	5	0.002 (0.125) 0.060 (0.75) 0.200 (0.125)
Negro Mag Wash fault	NMW	0.4	Normal	35 (0.2) 50 (0.6) 65 (0.2)	N	10	0.002 (0.125) 0.060 (0.75) 0.200 (0.125)
Mineral Mountain West fault zone	MMW	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E and W	15	0.002 (0.125) 0.060 (0.75) 0.200 (0.125)
Antelope Range-Kingsley Mountains fault zone	ARK	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	69	0.013 (0.8) 0.300 (0.1) 0.020 (0.1)
Aubrey fault zone	AUB	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	63	0.023 (0.8) 0.030 (0.1) 0.040 (0.1)
Bear River fault zone	BRI	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	37	1.958 (0.8) 0.580 (0.1) 0.680 (0.1)
Black Hills fault	BLH	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	SE	9	0.131 (0.8) 0.170 (0.1) 0.110 (0.1)
Butte Mountains fault zone	BUM	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	61	0.013 (0.8) 0.220 (0.1) 0.010 (0.1)
California Wash fault	CAW	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	34	0.366 (0.8) 0.200 (0.1) 0.480 (0.1)

TABLE 3-2

SOURCE PARAMETERS FOR LOCAL AND REGIONAL FAULTS

University of Utah
Salt Lake City, Utah

Fault Name	Code	P_a[1]	Style of Faulting	Average Dip[2] (deg)	Dip Direction	Rupture Length (km)	Slip Rate[2] (mm/yr)
Coyote Spring fault	COS	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	15	0.013 (0.8) 0.230 (0.1) 0.010 (0.1)
Diamond Mountains fault	DIM	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	83	0.131 (0.8) 0.110 (0.1) 0.170 (0.1)
Dry Lake fault	DRL	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	47	0.010 (0.8) 0.080 (0.1) 0.010 (0.1)
Dutchman Draw fault	DUD	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	NW	16	0.098 (0.8) 0.100 (0.1) 0.130 (0.1)
East Cache fault zone	EAC	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	81	0.261 (0.8) 0.350 (0.1) 0.280 (0.1)
East Great Salt Lake fault zone, Antelope section	SLA	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	38	0.550 (0.5) 0.880 (0.5)
East Great Salt Lake fault zone, Fremont Island section	SLF	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	32	0.780 (0.8) 0.460 (0.1) 1.080 (0.1)
East Great Salt Lake fault zone, Promontory section	SLP	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	53	0.260 (0.5) 1.190 (0.5)
Eglington fault	EGL	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	SE	10	0.160 (0.5) 0.030 (0.5)

TABLE 3-2

SOURCE PARAMETERS FOR LOCAL AND REGIONAL FAULTS

University of Utah
Salt Lake City, Utah

Fault Name	Code	P_a[1]	Style of Faulting	Average Dip[2] (deg)	Dip Direction	Rupture Length (km)	Slip Rate[2] (mm/yr)
Frenchman Mountain fault	FRM	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	20	0.020 (0.8) 0.120 (0.1) 0.030 (0.1)
Golden Gate fault	GOG	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	36	0.013 (0.8) 0.130 (0.1) 0.010 (0.1)
Hiko fault zone	HIK	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	15	0.013 (0.8) 0.100 (0.1) 0.010 (0.1)
Hurricane fault zone (central)	HUC	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	NW	106	0.261 (0.8) 0.300 (0.1) 0.360 (0.1)
Hurricane fault zone (northern)	HUN	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	NW	47	0.261 (0.8) 0.620 (0.1) 0.330 (0.1)
Hurricane fault zone (southern)	HUS	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	NW	98	0.106 (0.8) 0.100 (0.1) 0.160 (0.1)
Independence Valley fault zone	IND	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	66	0.131 (0.8) 0.120 (0.1) 0.160 (0.1)
Jakes Valley fault zone	JAV	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	36	0.013 (0.8) 0.090 (0.1) 0.010 (0.1)
Joes Valley fault zone east fault	JOV	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	47	0.261 (0.8) 0.230 (0.1) 0.290 (0.1)

TABLE 3-2

SOURCE PARAMETERS FOR LOCAL AND REGIONAL FAULTS

University of Utah
Salt Lake City, Utah

Fault Name	Code	P_a[1]	Style of Faulting	Average Dip[2] (deg)	Dip Direction	Rupture Length (km)	Slip Rate[2] (mm/yr)
Kane Spring Wash fault	KSW	1	Strike Slip	90 (1.0)	n/a	43	0.010 (0.8) 0.050 (0.1) 0.010 (0.1)
Morgan fault	MOR	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	17	0.026 (0.8) 0.030 (0.1) 0.040 (0.1)
Mount Irish Range fault	MIR	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	12	0.013 (0.8) 0.040 (0.1) 0.010 (0.1)
Northern Butte Valley fault	NBV	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	13	0.131 (0.8) 0.100 (0.1) 0.130 (0.1)
Northern Huntington Valley fault zone	NHV	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	39	0.131 (0.8) 0.170 (0.1) 0.120 (0.1)
Oquirrh-Southern Oquirrrh Mountains fault zone	OSM	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	61	0.261 (0.8) 0.260 (0.1) 0.330 (0.1)
Paragonah fault	PAR	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	NW	27	0.600 (0.8) 0.550 (0.1) 0.550 (0.1)
Penoyer fault	PEN	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	54	0.021 (0.8) 0.030 (0.1) 0.030 (0.1)
Railroad Valley fault zone	RRV	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	152	0.091 (0.8) 0.120 (0.1) 0.120 (0.1)

TABLE 3-2

SOURCE PARAMETERS FOR LOCAL AND REGIONAL FAULTS

University of Utah
Salt Lake City, Utah

Fault Name	Code	P_a[1]	Style of Faulting	Average Dip[2] (deg)	Dip Direction	Rupture Length (km)	Slip Rate[2] (mm/yr)
Ruby Mountains fault zone	RMT	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	73	0.366 (0.8) 0.180 (0.1) 0.330 (0.1)
Ruby Valley fault zone	RVL	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	78	0.131 (0.8) 0.190 (0.1) 0.190 (0.1)
Schell Creek Range fault system	SCR	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	101	0.131 (0.8) 0.280 (0.1) 0.190 (0.1)
Sevier/Toroweap fault zone (northern)	STN	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	87	0.052 (0.8) 0.440 (0.1) 0.500 (0.1)
Sevier/Toroweap fault zone (southern)	STS	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	168	0.144 (0.8) 0.120 (0.1) 0.190 (0.1)
Sheep Basin fault	SHB	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	22	0.057 (0.8) 0.070 (0.1) 0.080 (0.1)
Spruce Mountain Ridge fault zone	SMR	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	32	0.131 (0.8) 0.050 (0.1) 0.160 (0.1)
Stansbury fault zone	STA	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	54	0.522 (0.8) 0.510 (0.1) 0.590 (0.1)
Strawberry fault	STR	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	37	0.131 (0.8) 0.230 (0.1) 0.130 (0.1)

TABLE 3-2

SOURCE PARAMETERS FOR LOCAL AND REGIONAL FAULTS

University of Utah
Salt Lake City, Utah

Fault Name	**Code**	**P_a[1]**	**Style of Faulting**	**Average Dip[2] (deg)**	**Dip Direction**	**Rupture Length (km)**	**Slip Rate[2] (mm/yr)**
West Spring Mountains fault	WSM	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	49	0.059 (0.8) 0.090 (0.1) 0.090 (0.1)
West Valley fault	WEV	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	E	17	0.522 (0.8) 0.315 (0.1) 0.440 (0.1)
Western Diamond Mountains fault zone	WDM	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	64	0.131 (0.8) 0.080 (0.1) 0.160 (0.1)
White River Valley fault zone	WRV	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	102	0.059 (0.8) 0.020 (0.1) 0.080 (0.1)

Notes
1. Probability fault is seismogenic.
2. Epistemic uncertainty distribution.

TABLE 3-3

SOURCE PARAMETERS FOR THE WASATCH FAULT

University of Utah
Salt Lake City, Utah

Fault Name	Code	P_a[1]	Style of Faulting	Average Dip[2] (deg)	Dip Direction	Rupture Length [2] (km)	Slip Rate [2] (mm/yr)
Wasatch fault floating M~7.4	WAF	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	127	1.2 (1.0)
Wasatch fault partial segment rutpures	WFS	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	20 (0.3) 30 (0.3) 40 (0.3) 50 (0.1)	Slip rate of each segment
Wasatch fault Salt Lake City section	WAS	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	52	1.697 (0.8) 1.030 (0.1) 1.080 (0.1)
Wasatch fault, Brigham City section	WAB	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	41	2.089 (0.8) 0.700 (0.1) 1.190 (0.1)
Wasatch fault, Levan section	WAL	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	32	2.480 (0.8) 1.450 (0.1) 1.270 (0.1)
Wasatch fault, Nephi section	WAN	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	46	2.219 (0.4) 1.00 (0.4) 0.500 (0.2)
Wasatch fault, Provo section	WAP	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	77	2.611 (0.4) 1.500 (0.4) 0.700 (0.2)
Wasatch fault, Weber section	WAW	1	Normal	35 (0.2) 50 (0.6) 65 (0.2)	W	63	2.480 (0.8) 1.450 (0.1) 1.270 (0.1)

Notes

1. Probability fault is seismogenic.
2. Epistemic uncertainty distribution.

TABLE 3-4

LITERATURE REVIEW

University of Utah
Salt Lake City, Utah

Author	Year	Notes	Revise Model?
Duross et al.	2017	This report discusses paleoseismic trenches across the Nephi segment of the Wasatch fault. The authors conclude a mean recurrence of ~1.2–1.5 kyr and vertical slip rate of ~0.5–0.8 mm/yr. They also find that the northern and southern strands can and do rupture at the same time.	Yes. The interpreted slip rates are lower than the range of 2.219-0.610 mm/yr used in the model. The slip rates and weights were updated to 2.219 (0.4), 1.0 (0.4), and 0.5 (0.2)
Hecker et al.	2019	This pamphlet and three maps document paleoseismic trenches across the Bear River fault zone. They find evidence for three ruptures, one of which is younger and was not interpreted in earlier studies.	No. The study is not yet completed and analysis of ages and offset per event on the fault has not been completed.
McDonald et al.	2018	This technical report is a preliminary report of LiDAR mapping of the Wasatch fault.	No. This is a preliminary report and does not contain the finalized updated map of the Wasatch fault
Brumbaugh	2019	This article discuses a 2016 swarm of earthquakes that occurred in the Grand Wash basin, northwestern Arizona.	No. The focal mechanisms of the events were determined to be normal which is consistent with the characterization of the Basin and Range areal source zone
Duross et al.	2017	This book chapter discusses the Holocene earthquake history of the Wasatch fault. They conclude a mean vertical slip rate of 1.3-2.0 mm/yr for the central segments of the fault.	No. The slip rates for the fault are consistent with the distribution of rates from the model.
Bruno et al.,	2017	This article examines scarps related to the 1934 Ms 6.6 Hansel Valley earthquake. They interpret evidence for both	No. The Basin and Range areal source zone accounts for booth normal (0.7) and strike-slip (0.3) faulting. The 1934 event is included in the earthquake catalog.
Bagge et al.	2019	This article uses three-dimensional forward modeling of the Wasatch fault to determine how earthquakes change the Coulomb stress. They conclude the Brigham City, Salt Lake City, and Provo segments are most prone to failure in a Mw ≥ 6.8 earthquake.	No. The magnitude and paleoseismic data used in this study were used in the development of this model. The authors conclude that the results of this study indicate that “forward modeling of earthquake sequences may ultimately contribute to improved seismic hazard estimates.”
DuRoss et al.	2019	This abstract discusses modeling of the complexity of the Wasatch fault and the ability of barriers along the fault to limit rupture length. They conclude ruptures can likely across proposed barriers on the Wasatch fault.	No. The ability of ruptures to continue through barriers is accounted for in the two branches for unsegmented rupture on the Wasatch fault.
Bennett et al.	2018	This article discusses a paeloseismic trench from the north end of the Provo segment of the Wasatch fault. The study concludes a recurrence interval of 0.2-1.8 kyr, with earthquakes as large as Mw 7.0 and a late Holocene vertical slip rate of 0.9 mm/yr (0.7–1.2 mm/yr).	Yes. The slip rate from this study is slightly lower than the slip rate used in the model (2.611-1.670) based on Petersen et al. (2014). The slip rates and weights were updated to 2.611 (0 .4), 1.5 (0.4), and 0.7 (0.2).
Howe et al.	2019	This article is the follow up to Howe (2017). It uses the same information and conclusions.	No.
Howe	2017	This Master’s thesis looked at the elevation of paleolake shorelines and determined that there did not seem to be a barrier to rupture between the Brigham City and Weber segments of the Wasatch fault.	No. The ability of ruptures to continue through barriers is accounted for in the two branches for unsegmented rupture on the Wasatch fault.
Peck	2018	This Master’s thesis studied the Maynard fault, a transfer fault in the Basin and Range region of Nevada. It concluded the fault offsets Quaternary and possibly Holocene sediments.	No. The thesis refines the mapping and structure of the Maynard and other faults but does not refine the slip rate, recurrence or other information necessary for addition to the model.
Zhang et al.	2019	This study uses a Bayesian model and data from seismic arrays in the near the FORGE sites to update the near-surface Vs profiles.	
Knudsen et al.	2019	This article discusses the three faults ones neat the Utah FORGE site—The Negro Mag fault, the Opal Mound fault and the Mineral Mountains West fault zone. The article concludes the Negro Mag fault may be pre-Quaternary. They conclude the most recent movement on the Opal Mound fault and the Mineral Mountains West fault is likely late Pleistocene age.	Yes. Based on the new information regarding the likely inactivity of the Negro Mag fault, the likelihood of activity of the fault is lowered to 0.4.

TABLE 3-4

LITERATURE REVIEW

University of Utah
Salt Lake City, Utah

Author	Year	Notes	Revise Model?
Petersen et al.	2019	This article summarizes the updates to the 2018 National Seismic Hazard Map. Updates include new ground motion models, an updated seismicity catalog, and for several deep sedimentary basins including the Salt Lake City region amplified shaking estimates of long period ground motions were incorporated. The individual fault sources were not updated.	No. The fault sources were not updated for the model. Section 1.1 discusses the need to update the model for source zones.
Valentini et al.	2019	This article uses UCERF3 methodology and applies it to the Wasatch fault to determine the variation in ground motion hazard from modeling a segmented vs unsegmented fault. They conclude the segmented model increases hazard by increasing the rate of M 6.2-6.8 events. The Unsegmented model allows larger (M 6.9-7.9), less frequent earthquakes. They conclude segmentation rather than slip rate or scaling relations had the largest control on seismic hazard.	No. Segmented and unsegmented variations of the Wasatch fault are included in the model.

TABLE 3-5

SITE-SPECIFIC NGA-WEST 2 PARAMETERS

University of Utah
Salt Lake City, Utah

Site	**V_{S30} (m/s)**	**$Z_{1.0}$ (m)**	**$Z_{2.5}$ (km)**
FORGE drill center	448	293	1.00
Blundell Plant	401	80	1.08
Milford	315	246	1.246
Wind Farm	422	325	1.95

TABLE 4-1

MEAN HORIZONTAL UNIFORM HAZARD RESPONSE SPECTRA FOR THE FORGE DRILLING CENTER

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	0.1144	0.1774	0.3028	0.4268	0.5659
0.02	50	0.1162	0.1807	0.3087	0.4360	0.5780
0.05	20	0.1591	0.2468	0.4157	0.5783	0.7758
0.075	13.33	0.2060	0.3170	0.5256	0.7337	0.9745
0.1	10	0.2400	0.3673	0.6079	0.8475	1.1249
0.2	5	0.2715	0.4226	0.7244	1.0312	1.3900
0.5	2	0.1543	0.2439	0.4424	0.6672	0.9537
1	1	0.0733	0.1165	0.2151	0.3378	0.5013
2	0.5	0.0309	0.0482	0.0859	0.1313	0.1980
5	0.2	0.0083	0.0129	0.0222	0.0328	0.0461

TABLE 4-2

MEAN M AND MEAN DISTANCE (R) DEAGGREGATION FOR FORGE DRILLING CENTER

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	M 4.9, R 10 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.7, R 5 km	M 6.7, R 5 km
0.2	5	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.7, R 5 km
1	1	M 6.7, R 75 km	M 6.1, R 5 km	M 6.2, R 5 km	M 6.7, R 5 km	M 6.7, R 5 km
5	0.2	M7.1, R 200 km	M 7.3, R 200 km	M 6.7, R 5 km	M 6.7, R 5 km	M 6.7, R 5 km

TABLE 4-3

MEAN HORIZONTAL UNIFORM HAZARD RESPONSE SPECTRA FOR THE WINDMILLS

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	0.0970	0.1427	0.2292	0.3142	0.4138
0.02	50	0.0984	0.1449	0.2329	0.3195	0.4210
0.05	20	0.1319	0.1986	0.3152	0.4292	0.5611
0.075	13.33	0.1707	0.2545	0.4046	0.5463	0.7175
0.1	10	0.2022	0.3006	0.4731	0.6387	0.8379
0.2	5	0.2340	0.3502	0.5645	0.7786	1.0298
0.5	2	0.1407	0.2127	0.3523	0.5023	0.6868
1	1	0.0689	0.1053	0.1753	0.2535	0.3563
2	0.5	0.0305	0.0444	0.0725	0.1044	0.1446
5	0.2	0.0083	0.0124	0.0196	0.0279	0.0376

TABLE 4-4

MEAN M AND MEAN DISTANCE (R) DEAGGREGATION FOR WINDMILLS

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	M 5.8, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km
0.2	5	M 5.8, R 15 km	M 5.9, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km
1	1	M 6.9, R 150 km	M 6.6, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km
5	0.2	M 6.9, R 150 km	M 7.0, R 150 km	M 6.7, R 15 km	M 6.7, R 15 km	M 6.7, R 15 km

TABLE 4-5

MEAN HORIZONTAL UNIFORM HAZARD RESPONSE SPECTRA FOR MILFORD, UT

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	0.1279	0.1955	0.3172	0.4356	0.5683
0.02	50	0.1291	0.1979	0.3210	0.4410	0.5750
0.05	20	0.1688	0.2554	0.4101	0.5538	0.7263
0.075	13.33	0.2173	0.3249	0.5129	0.6890	0.8960
0.1	10	0.2569	0.3796	0.5955	0.8018	1.0372
0.2	5	0.3142	0.4720	0.7557	1.0240	1.3302
0.5	2	0.1977	0.3046	0.5201	0.7582	1.0547
1	1	0.0933	0.1448	0.2539	0.3835	0.5557
2	0.5	0.0372	0.0569	0.0986	0.1477	0.2176
5	0.2	0.0093	0.0141	0.0239	0.0347	0.0484

TABLE 4-6

MEAN M AND MEAN DISTANCE (R) DEAGGREGATION FOR MILFORD, UT

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	M 4.8, R 10 km	M 5.0, R 10 km	M 6.6, R 10 km	M 6.6, R 10 km	M 6.6, R 10 km
0.2	5	M 4.9, R 10 km	M 6.4, R 10 km	M 6.4, R 10 km	M 6.6, R 10 km	M 6.6, R 10 km
1	1	M 6.6, R 50 km	M 6.4, R 10 km	M 6.6, R 10 km	M 6.6, R 10 km	M 6.6, R 10 km
5	0.2	M 7.2, R 300 km	M 7.3, R 300 km	M 6.6, R 10 km	M 6.6, R 10 km	M 6.6, R 10 km

TABLE 4-7

MEAN HORIZONTAL UNIFORM HAZARD RESPONSE SPECTRA FOR THE BLUNDELL GEOTHERMAL PLANT

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	0.1262	0.1958	0.3322	0.4704	0.6233
0.02	50	0.1281	0.1991	0.3384	0.4801	0.6360
0.05	20	0.1730	0.2668	0.4461	0.6194	0.8278
0.075	13.33	0.2230	0.3408	0.5590	0.7786	1.0308
0.1	10	0.2615	0.3968	0.6503	0.9005	1.1913
0.2	5	0.3040	0.4698	0.7942	1.1218	1.5085
0.5	2	0.1710	0.2711	0.4945	0.7531	1.0708
1	1	0.0770	0.1235	0.2309	0.3673	0.5464
2	0.5	0.0293	0.0464	0.0840	0.1296	0.1968
5	0.2	0.0072	0.0114	0.0199	0.0302	0.0421

TABLE 4-8

MEAN M AND MEAN DISTANCE (R) DEAGGREGATION FOR BLUNDELL GEOTHERMAL PLANT

University of Utah
Salt Lake City, Utah

Period (s)	Frequency (Hz)	475 years Return Period	975 years Return Period	2,475 years Return Period	5,000 years Return Period	10,000 years Return Period
0.01	100	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km
0.2	5	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.1, R 5 km
1	1	M 6.6, R 75 km	M 6.1, R 5 km	M 6.1, R 5 km	M 6.2, R 5 km	M 6.2, R 5 km
5	0.2	M 7.1, R 200 km	M 6.8, R 75 km	M 6.2, R 5 km	M 6.7, R 5 km	M 6.7, R 5 km

FIGURES

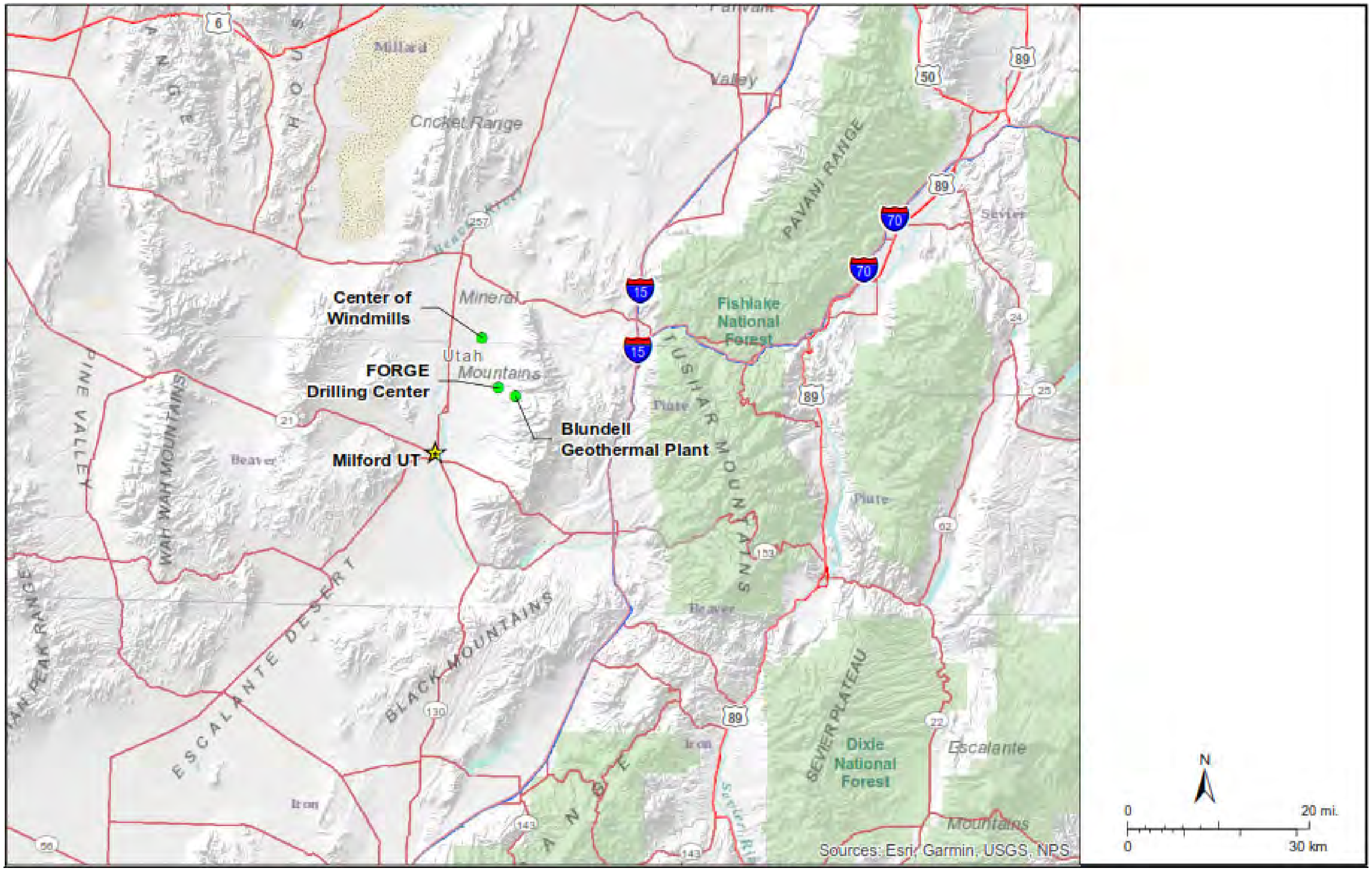
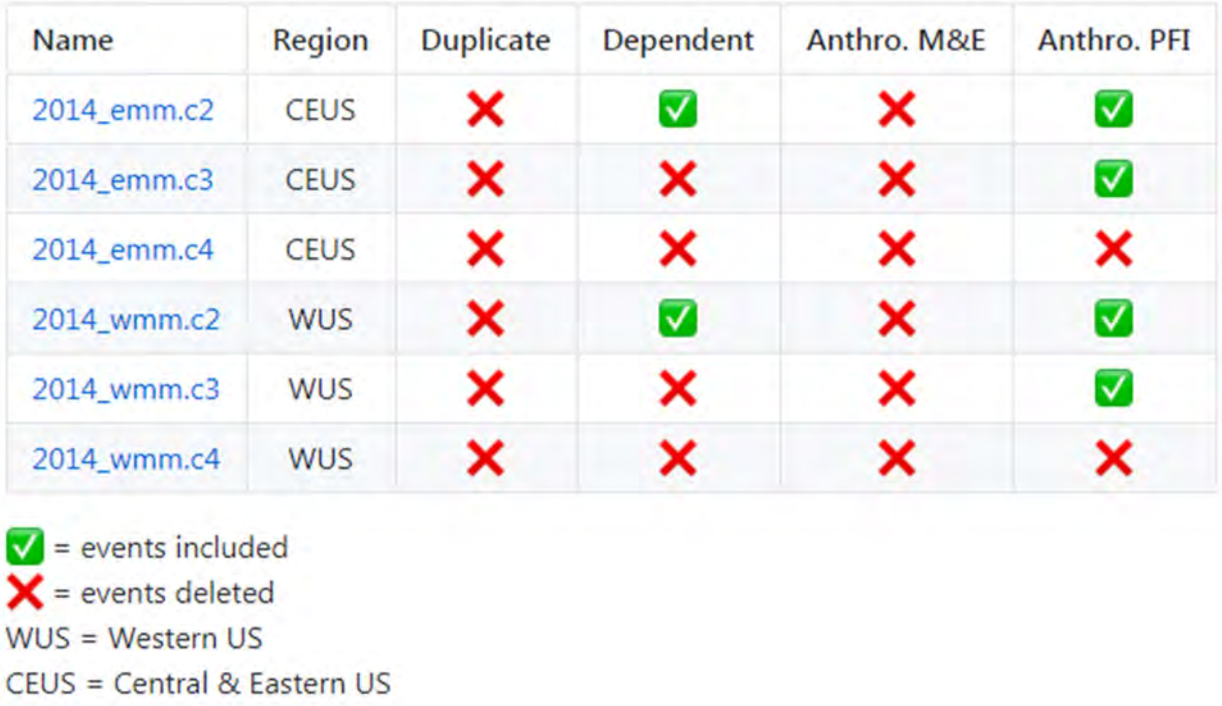


Figure 1-1: Site Location



Name	Region	Duplicate	Dependent	Anthro. M&E	Anthro. PFI
2014_emm.c2	CEUS	❌	✅	❌	✅
2014_emm.c3	CEUS	❌	❌	❌	✅
2014_emm.c4	CEUS	❌	❌	❌	❌
2014_wmm.c2	WUS	❌	✅	❌	✅
2014_wmm.c3	WUS	❌	❌	❌	✅
2014_wmm.c4	WUS	❌	❌	❌	❌

✅ = events included

❌ = events deleted

WUS = Western US

CEUS = Central & Eastern US

Figure 2-1: Characteristics of the Six NSHM Catalogs (Source: https://github.com/usgs/nshmp-haz-catalogs, accessed July 6, 2017)

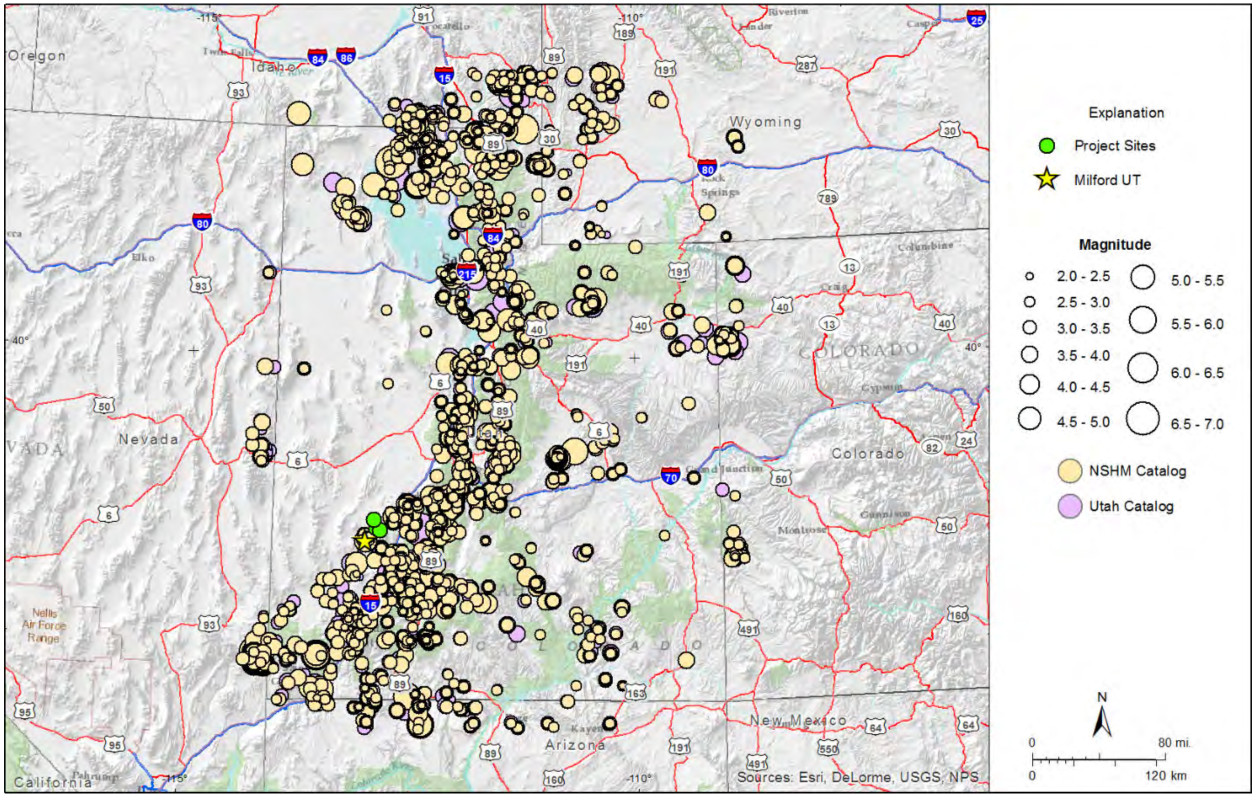


Figure 2-2: Earthquakes Common to the Utah (Black Circles) and NSHM (Green Circles) Catalogs

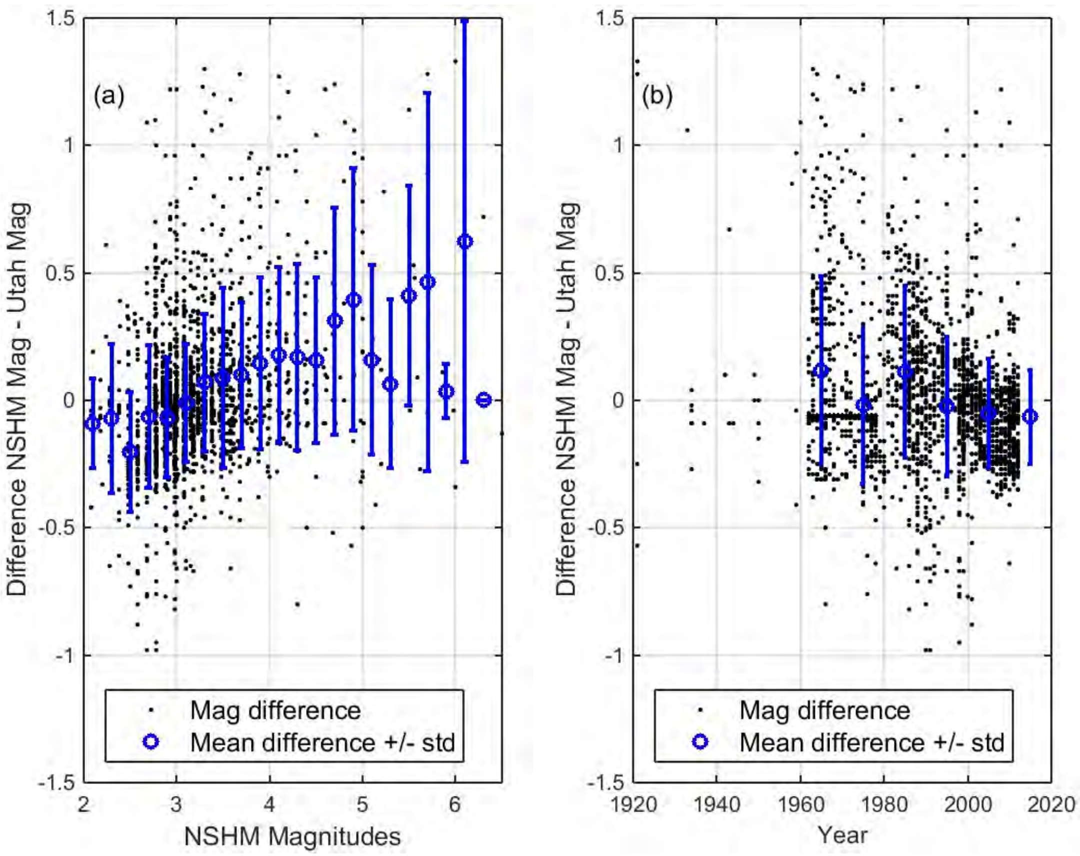


Figure 2-3: Difference in Magnitude Between Earthquakes in NSHM and Utah Catalog as a Function of Magnitude and Time

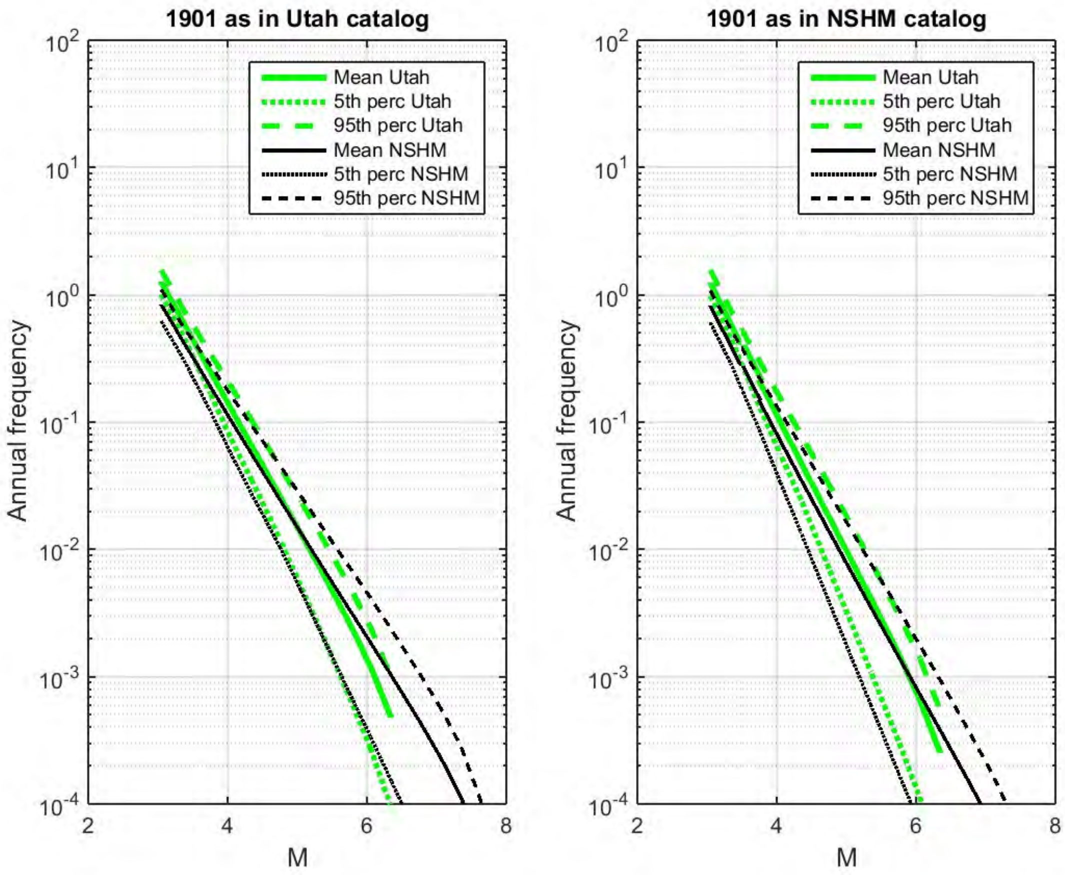


Figure 2-4: Comparison Between the Recurrence Within an Area of 50-km Radius Around FORGE Calculated from the NSHM Catalog (Black) and the Utah Catalog (Green)

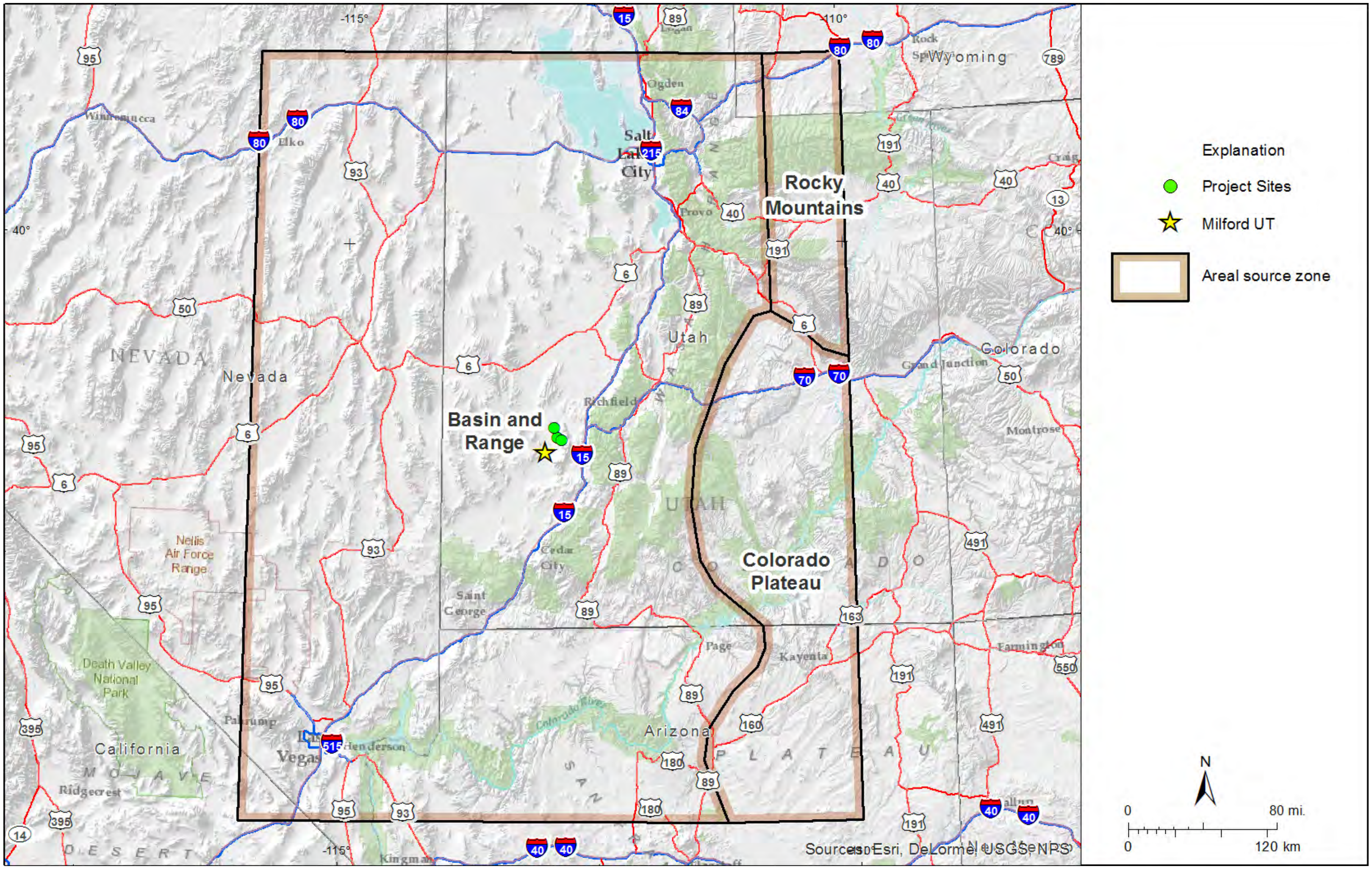


Figure 3-1: Areal Source Zones

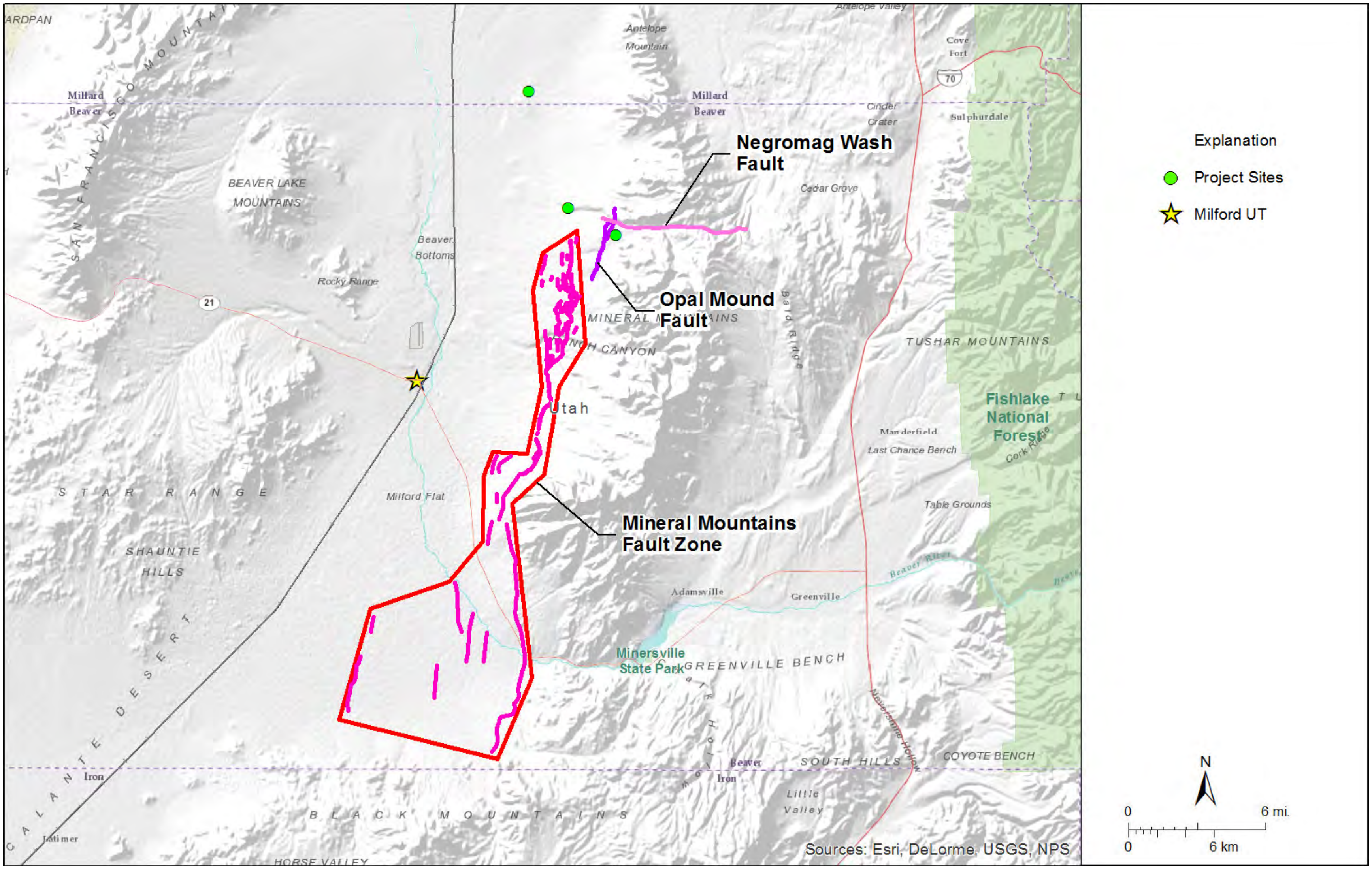


Figure 3-2: Local Faults

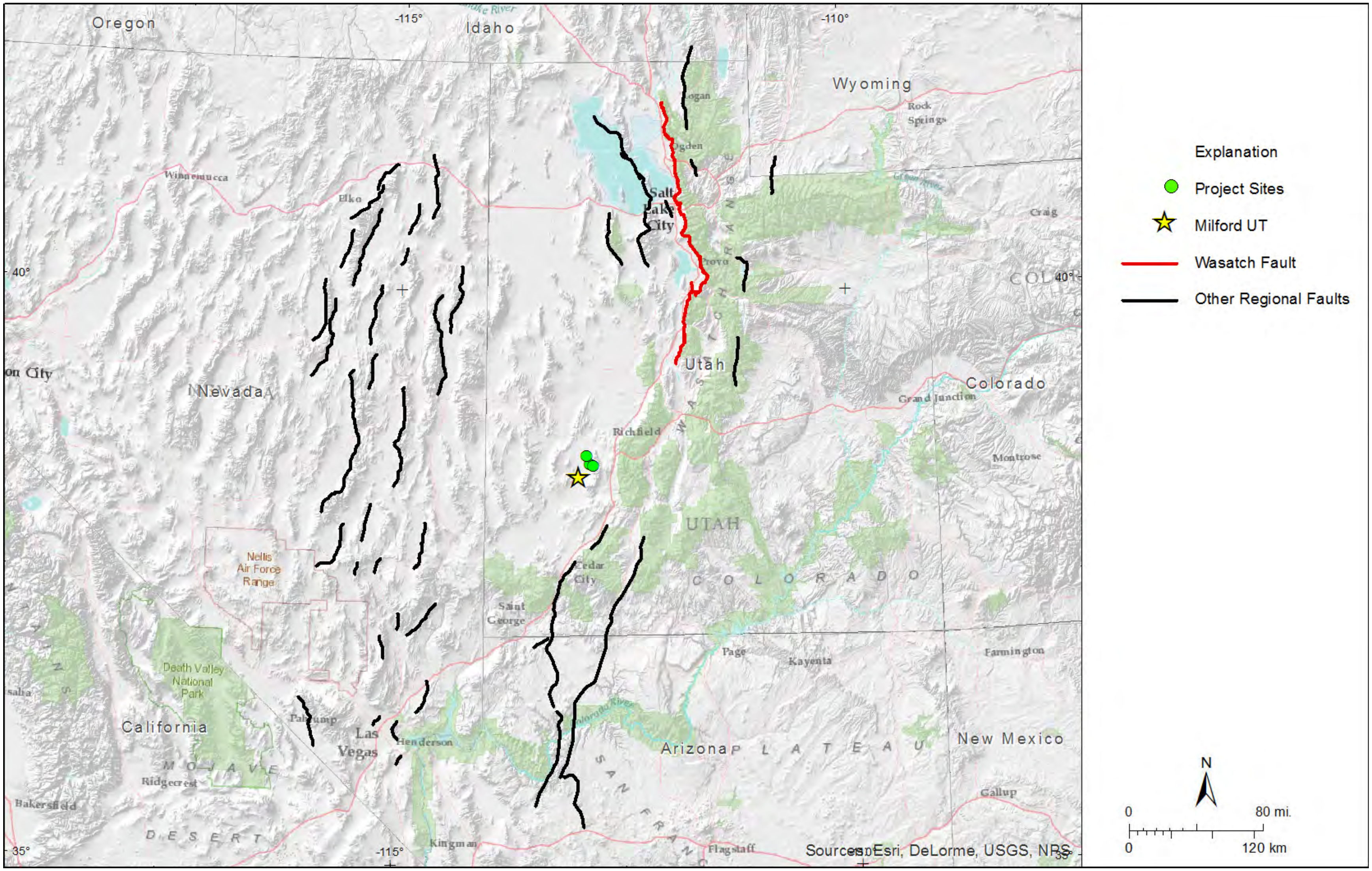


Figure 3-3: Regional Faults

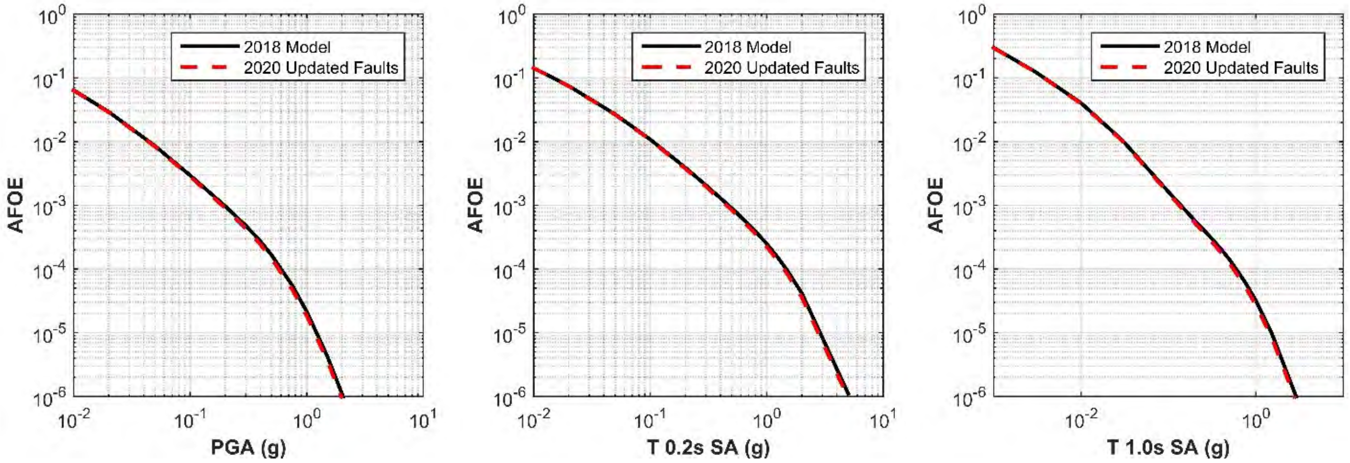


Figure 4-1: Effect of Updates in the Characterization of the Negromag and Wasatch Fault on the Seismic Hazard at the FORGE Drilling Center

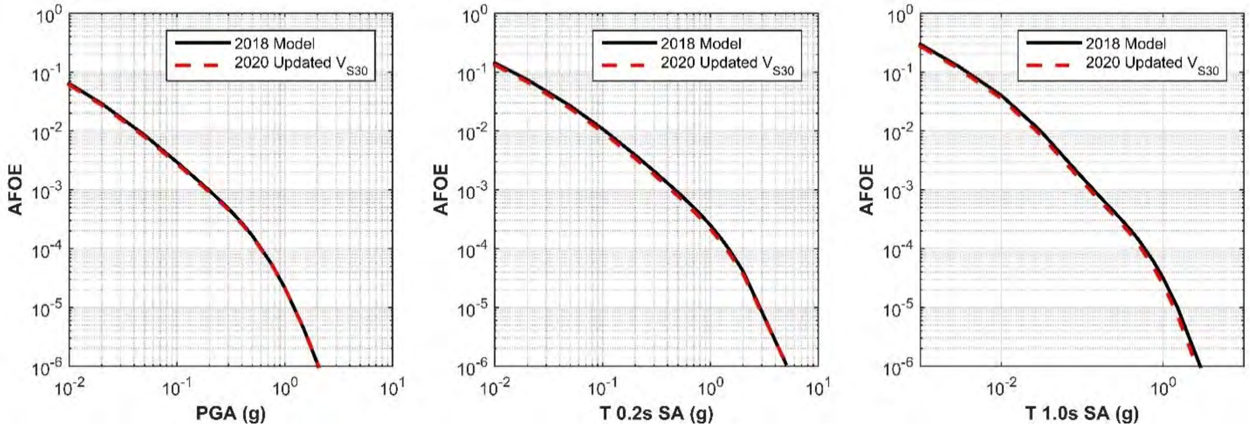


Figure 4-2: Effect of the updated site-specific adjustment of the NGA-West 2 models

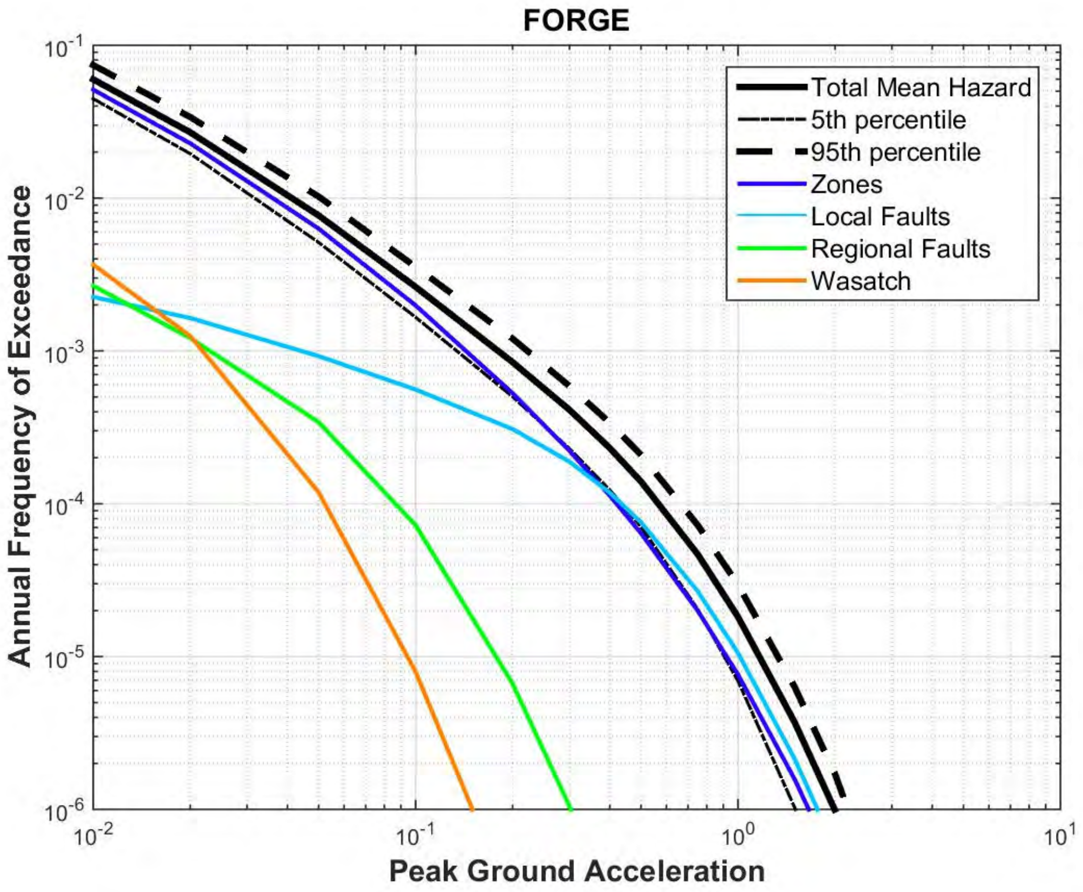


Figure 4-3: Total Mean Hazard for PGA and Grouped Source Contribution for the FORGE Drilling Center

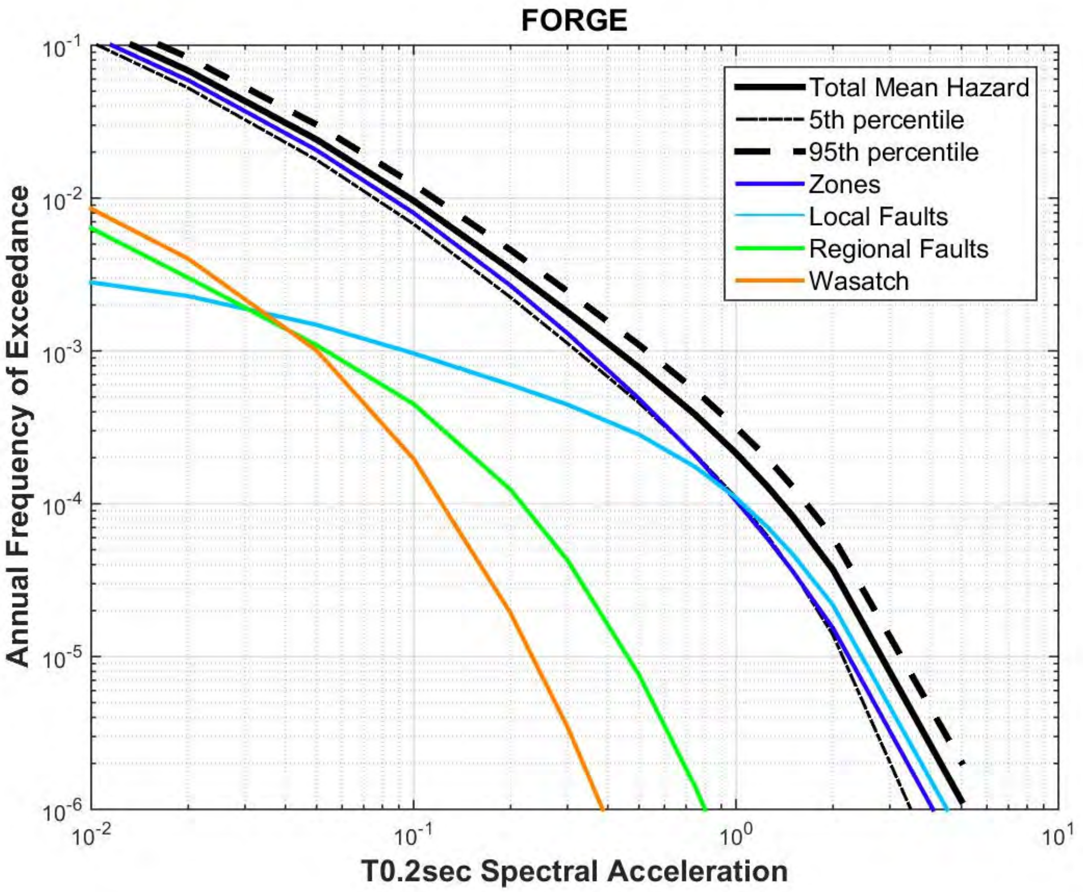


Figure 4-4: Total Mean Hazard for 0.2 s Spectral Acceleration and Grouped Source Contribution for the FORGE Drilling Center

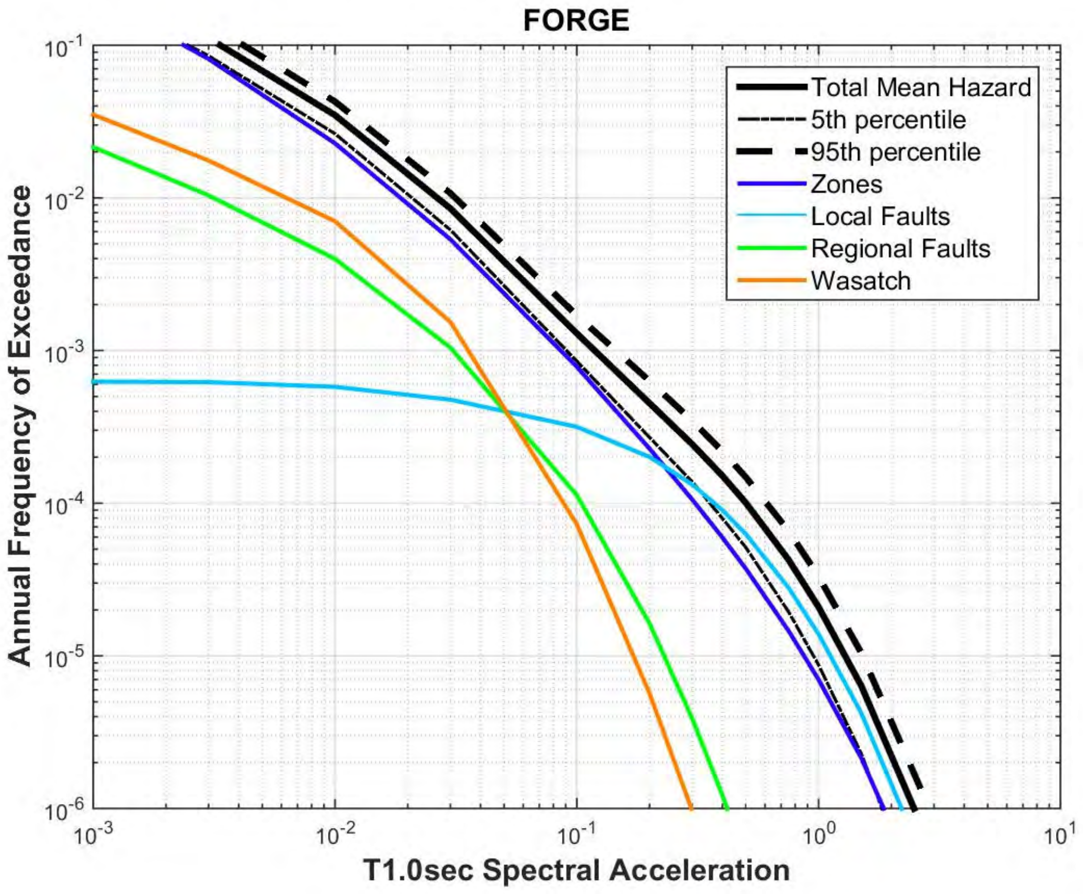


Figure 4-5: Total Mean Hazard for 1 s Spectral Acceleration and Grouped Source Contribution for the FORGE Drilling Center

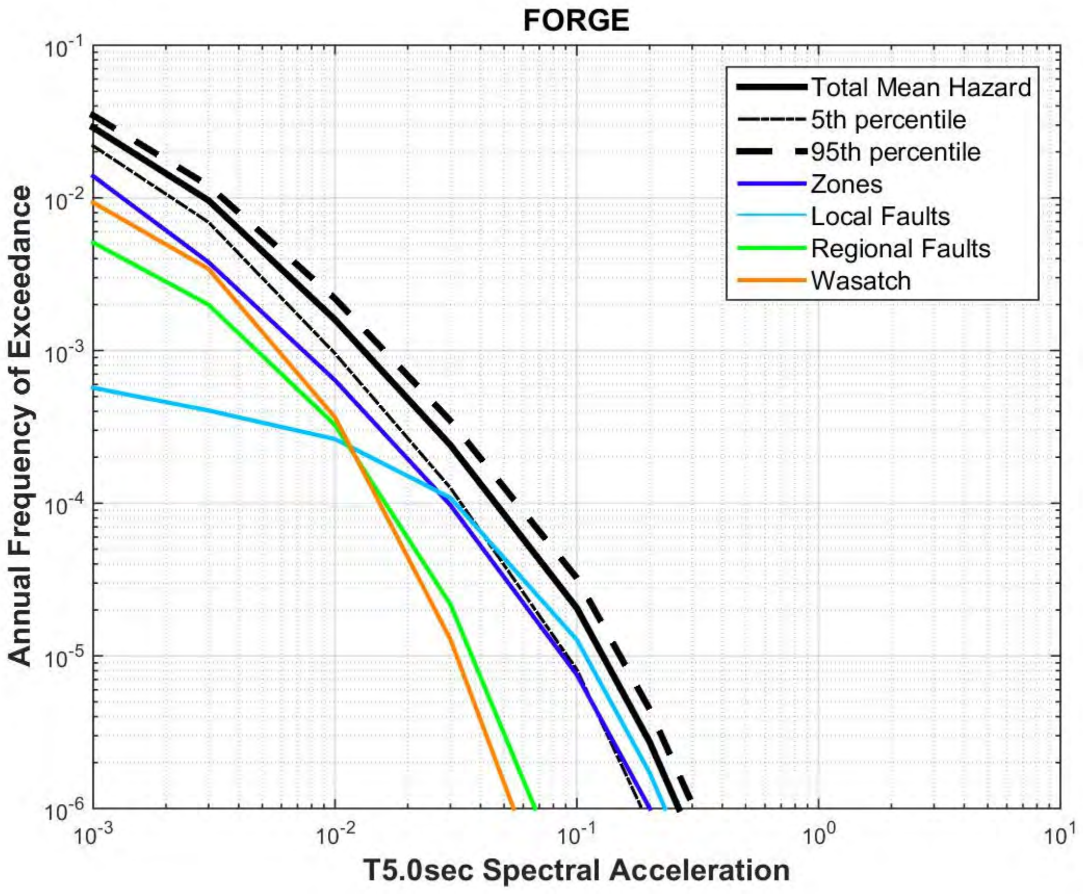


Figure 4-6: Total Mean Hazard for 5 s Spectral Acceleration and Grouped Source Contribution for the FORGE Drilling Center

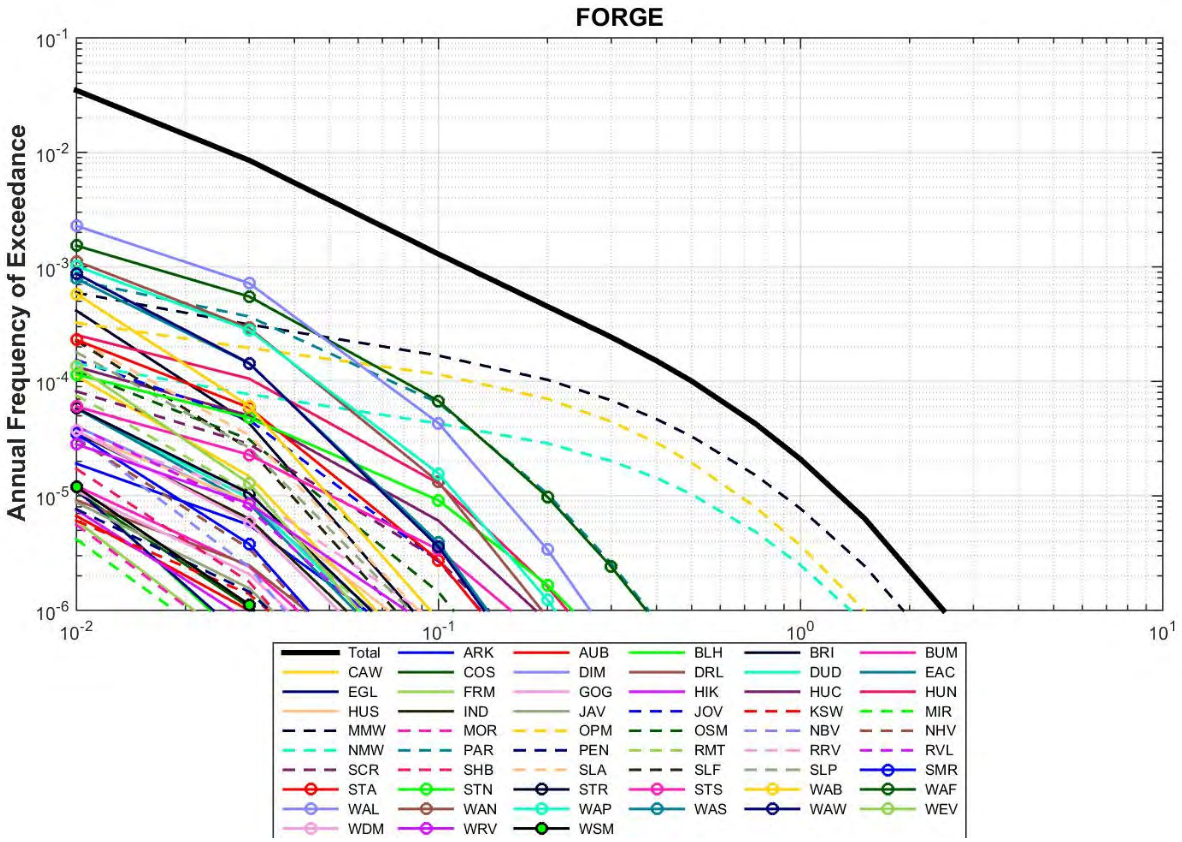


Figure 4-7: Seismic Hazard Curves for Local and Regional Faults for 1 s Spectral Acceleration at the FORGE Drilling Center

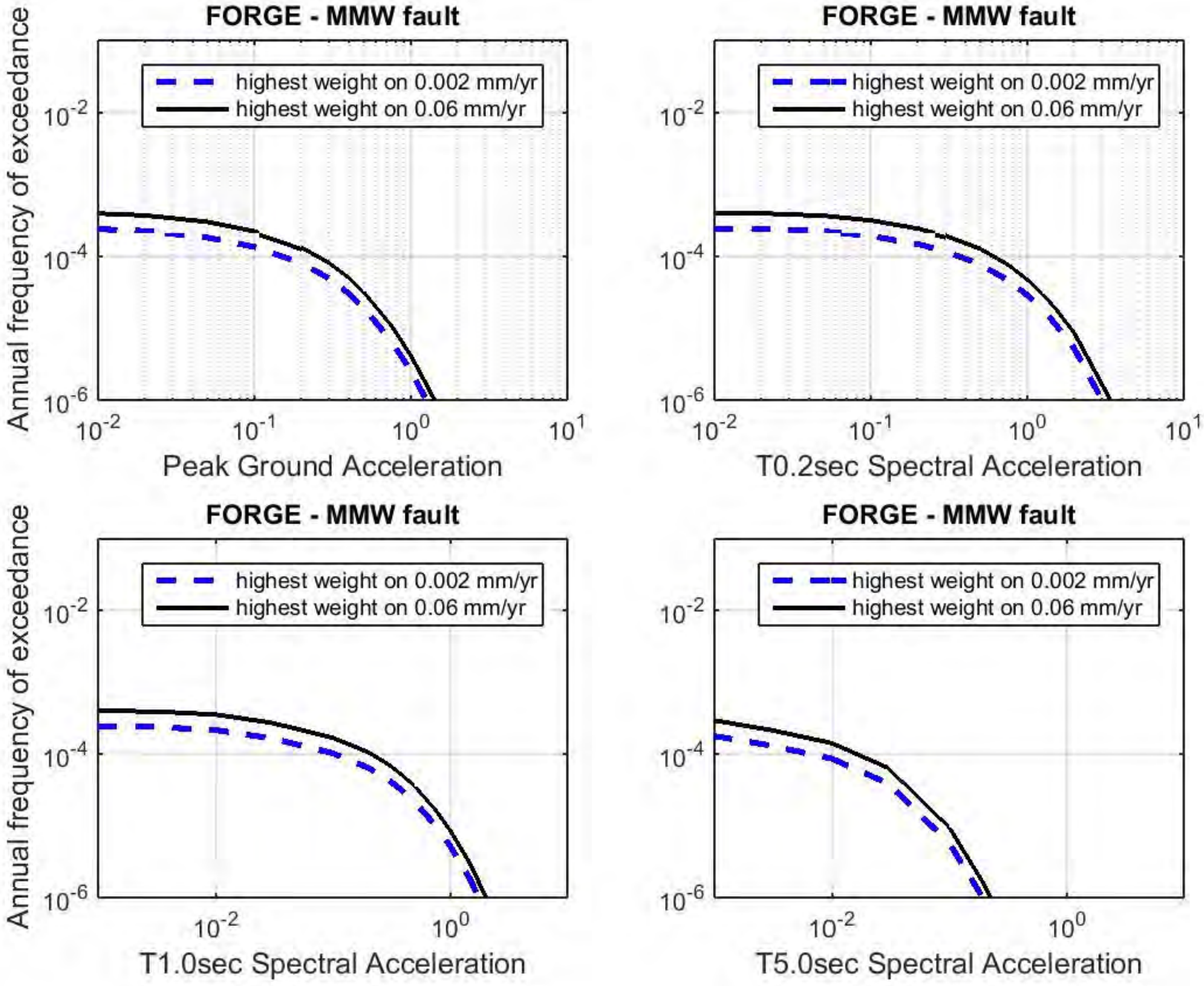


Figure 4-8: Sensitivity of the Mineral Mountain West Fault Hazard Curves to Changes in the Mean Slip Rate

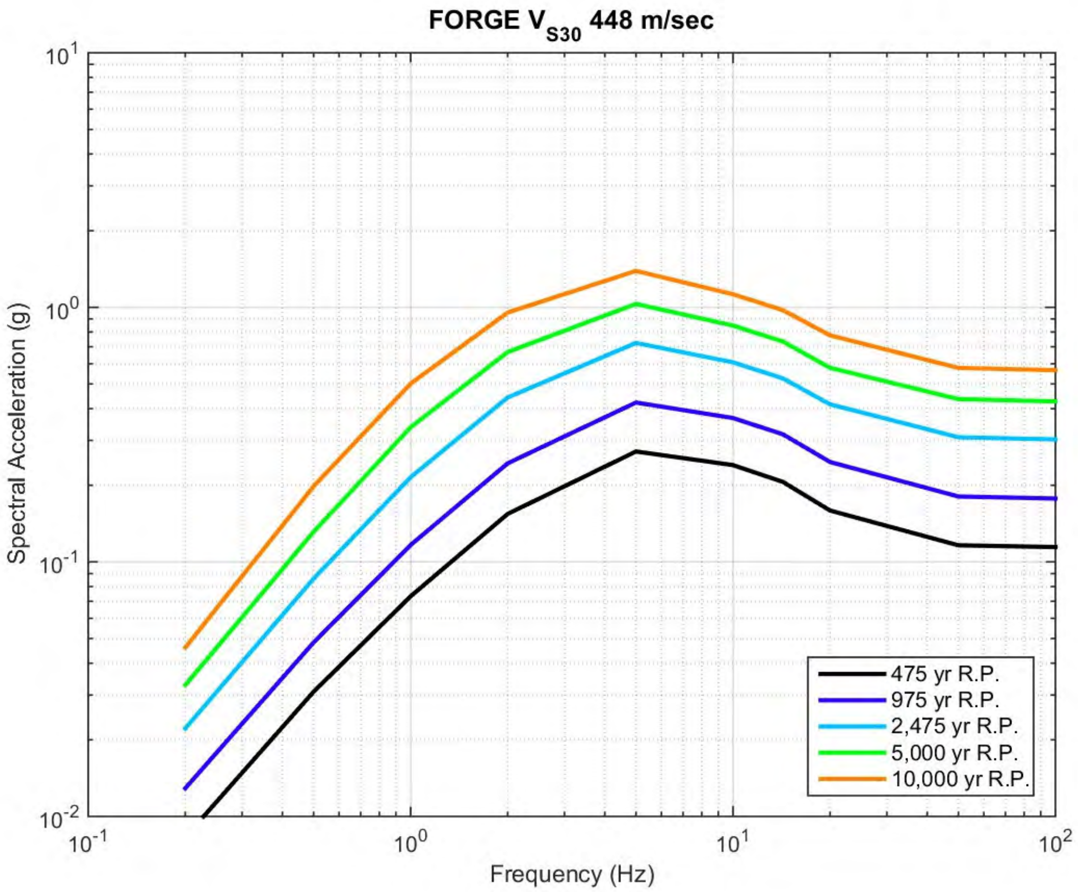


Figure 4-9: Mean Horizontal Uniform Hazard Response Spectra for the FORGE drilling Center

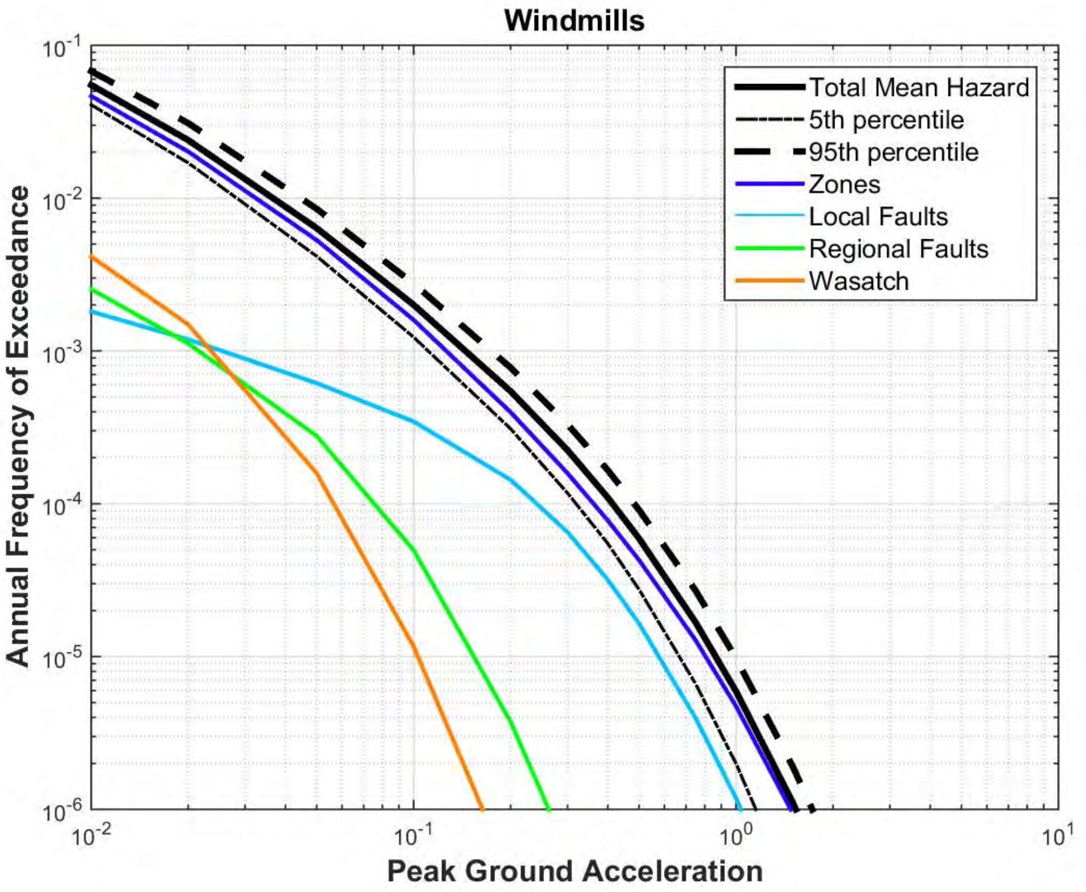


Figure 4-10: Total Mean Hazard for PGA and Grouped Source Contribution for the Windmills

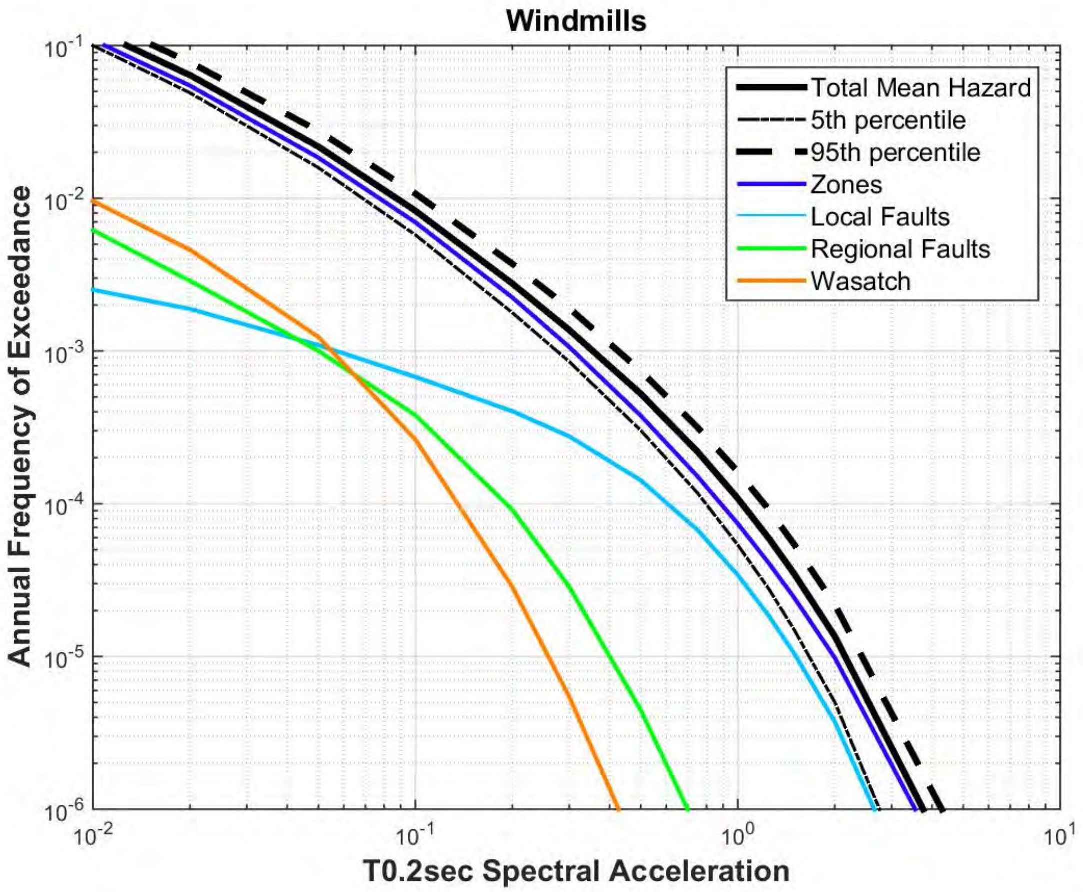


Figure 4-11: Total mean Hazard for 0.2 s Spectral Acceleration and Grouped Source Contribution for the Windmills

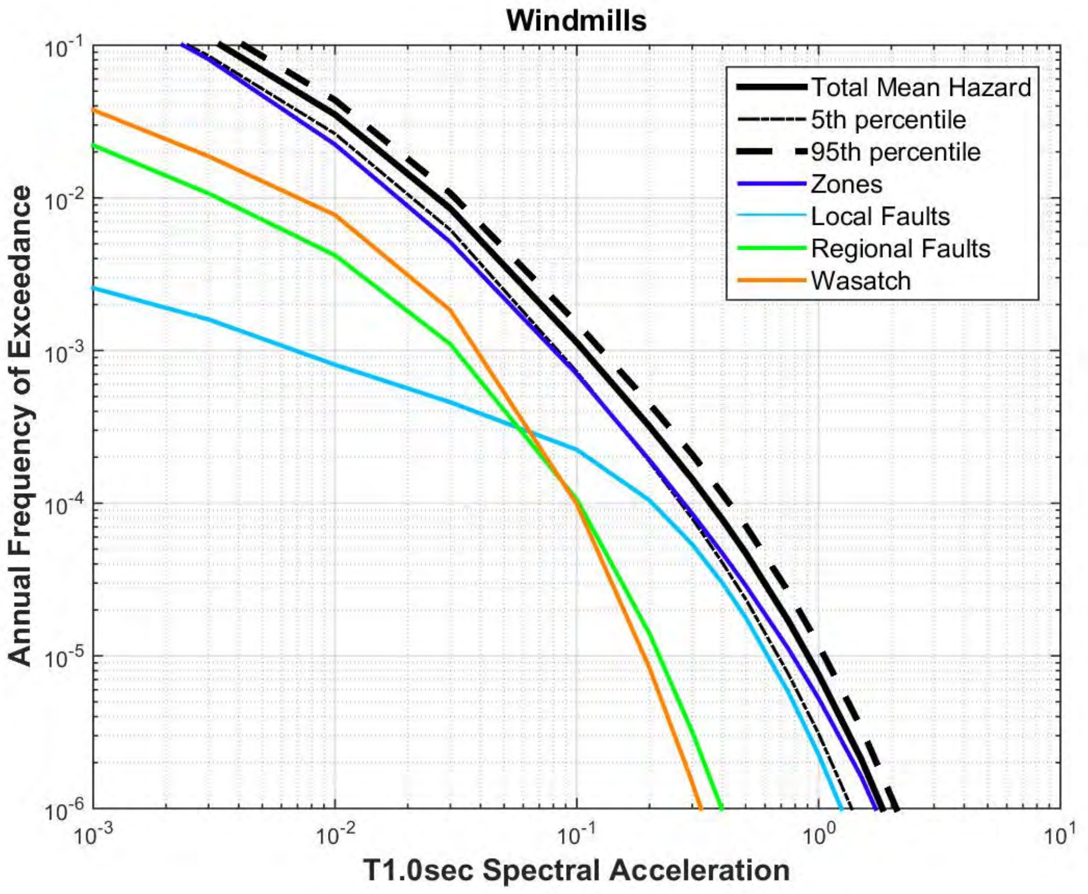


Figure 4-12: Total Mean Hazard for 1 s Spectral Acceleration and Grouped Source Contribution for the Windmills

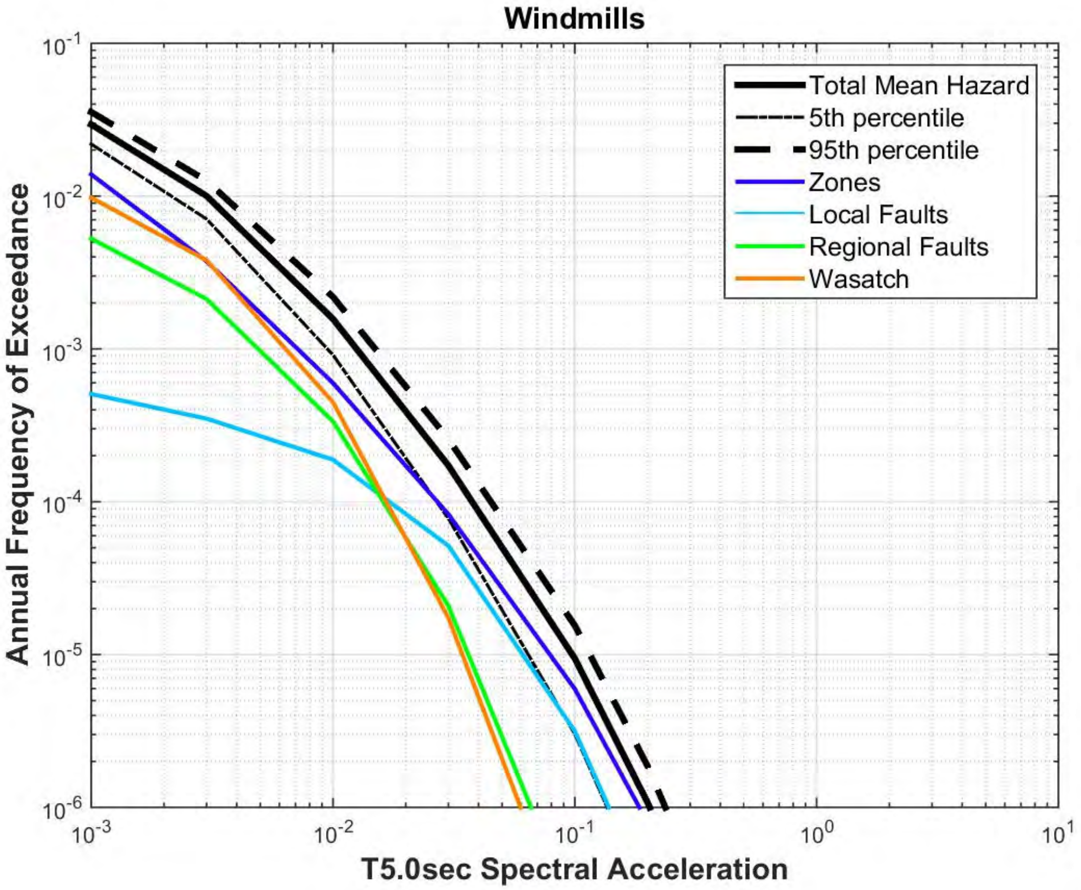


Figure 4-13: Total Mean Hazard for 5 s Spectral Acceleration and Grouped Source Contribution for the Windmills

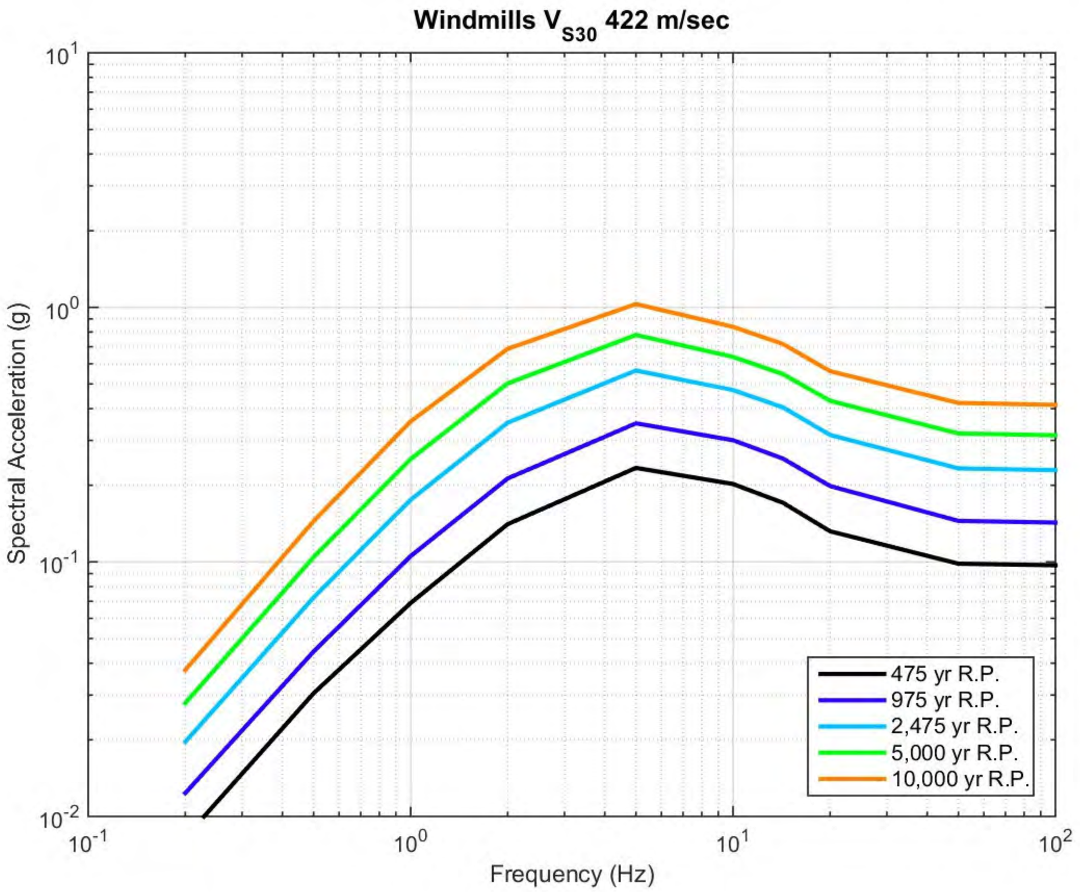


Figure 4-14: Mean Horizontal Uniform Hazard Response Spectra for the Windmills

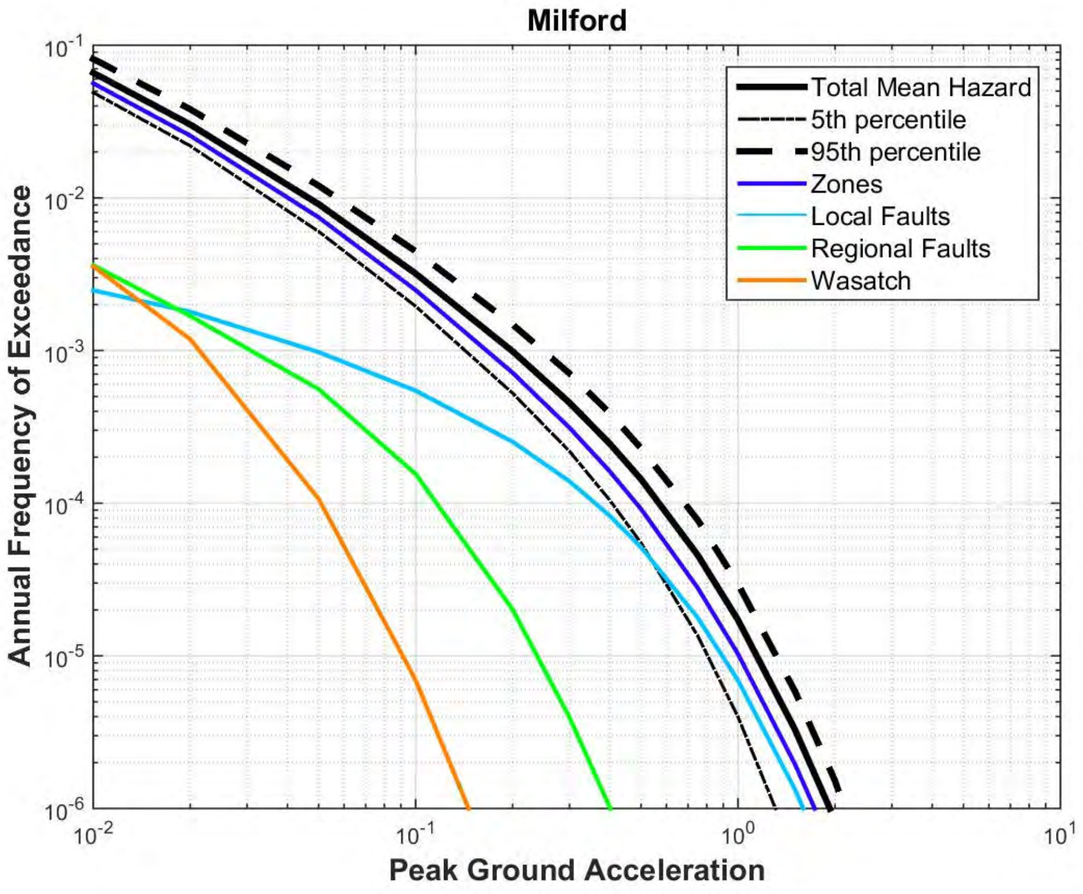


Figure 4-15: Total Mean Hazard for PGA and Grouped Source Contribution for Milford, UT

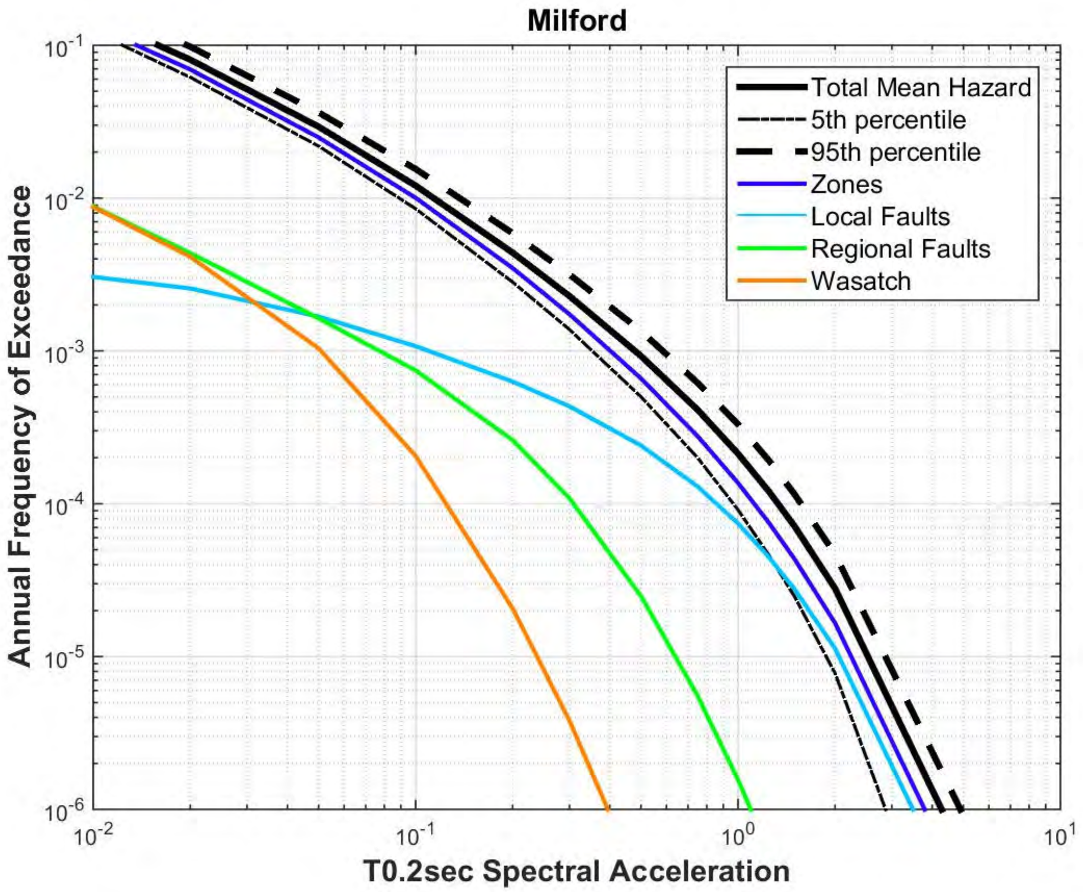


Figure 4-16: Total Mean Hazard for 0.2 s Spectral Acceleration and Grouped Source Contribution for Milford, UT

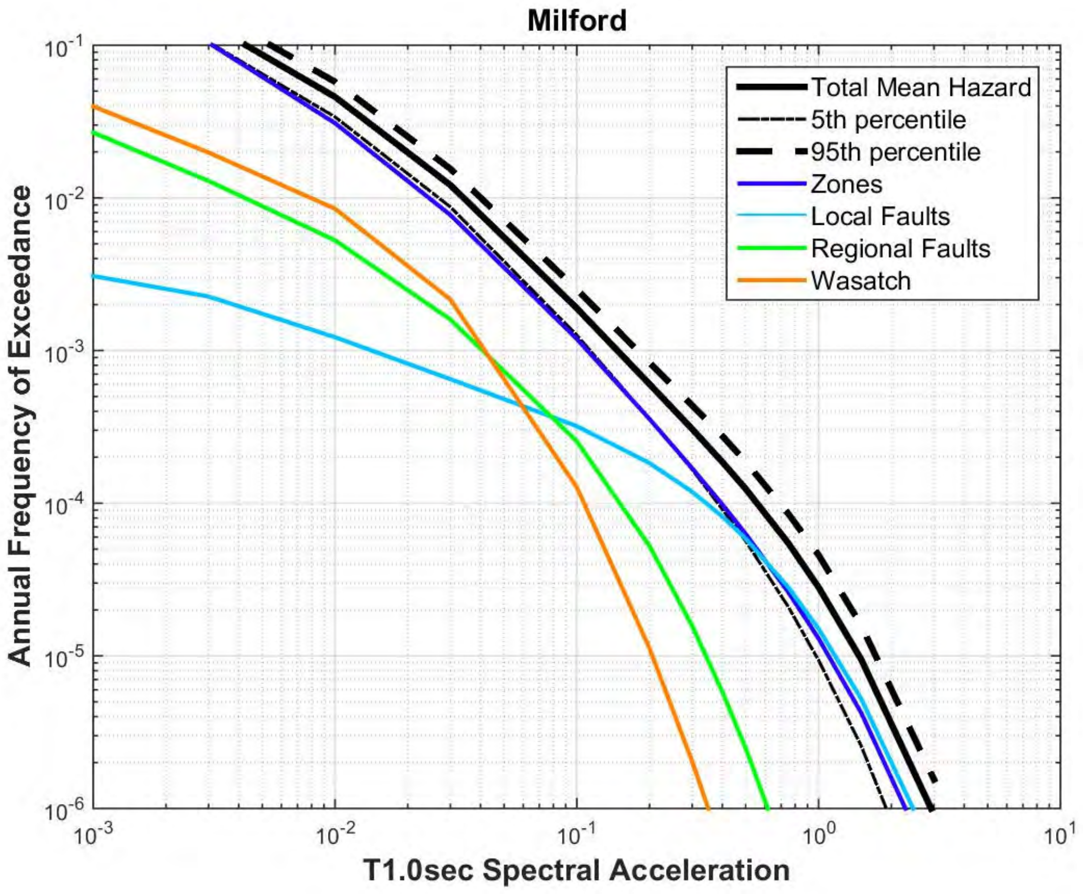


Figure 4-17: Total Mean Hazard for 1 s Spectral Acceleration and Grouped Source Contribution for Milford, UT

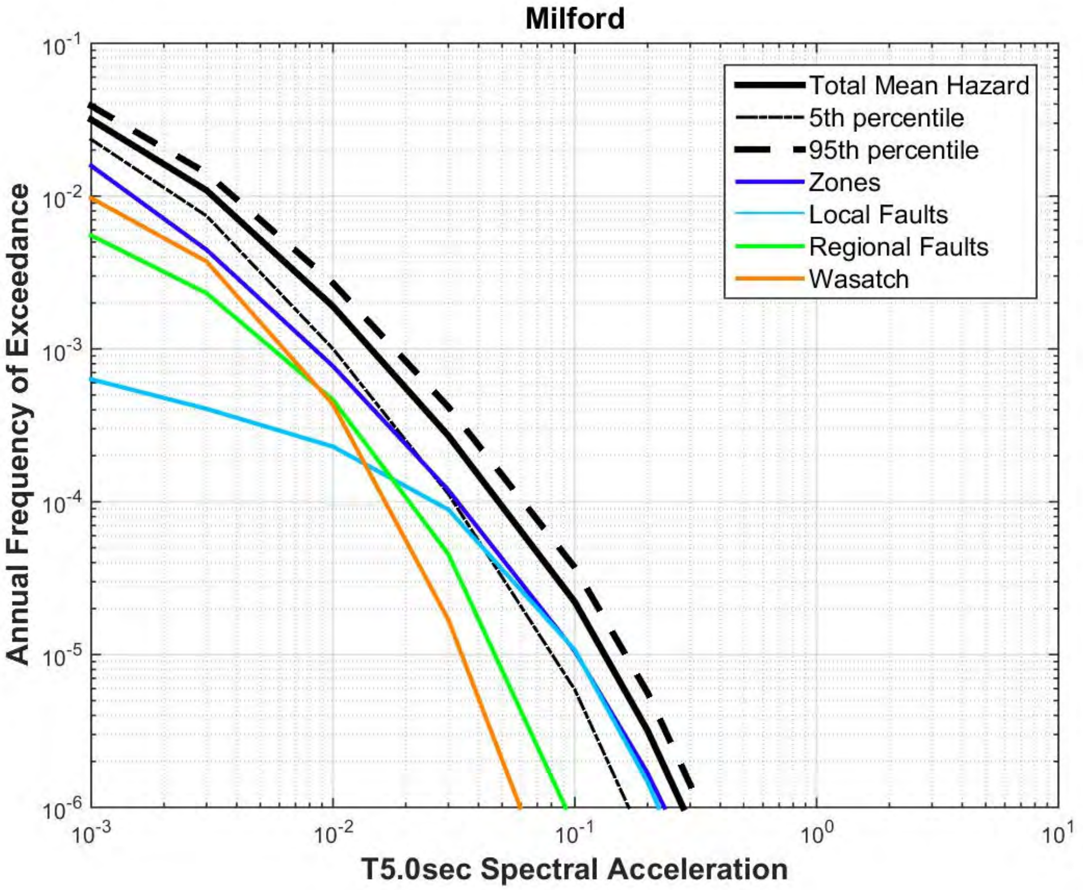


Figure 4-18: Total Mean Hazard for 5 s Spectral Acceleration and Grouped Source Contribution for Milford, UT

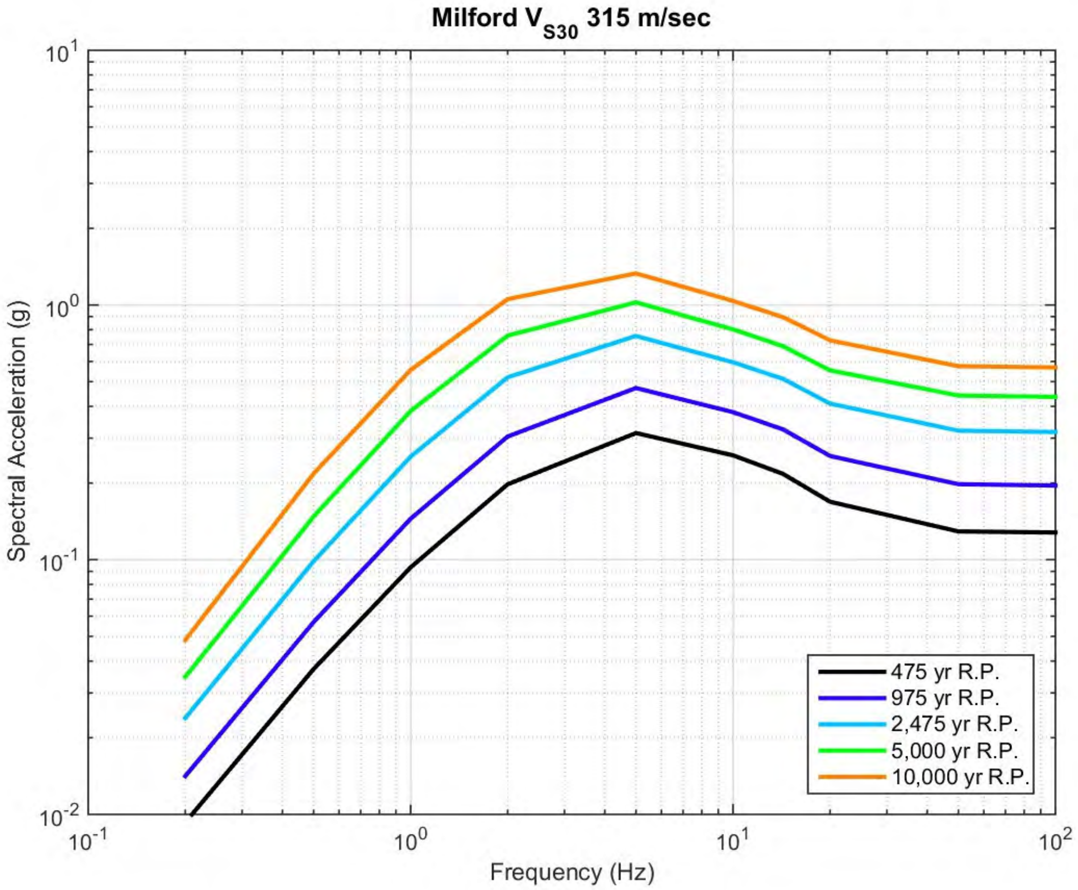


Figure 4-19: Mean Horizontal Uniform Hazard Response Spectra for Milford, UT

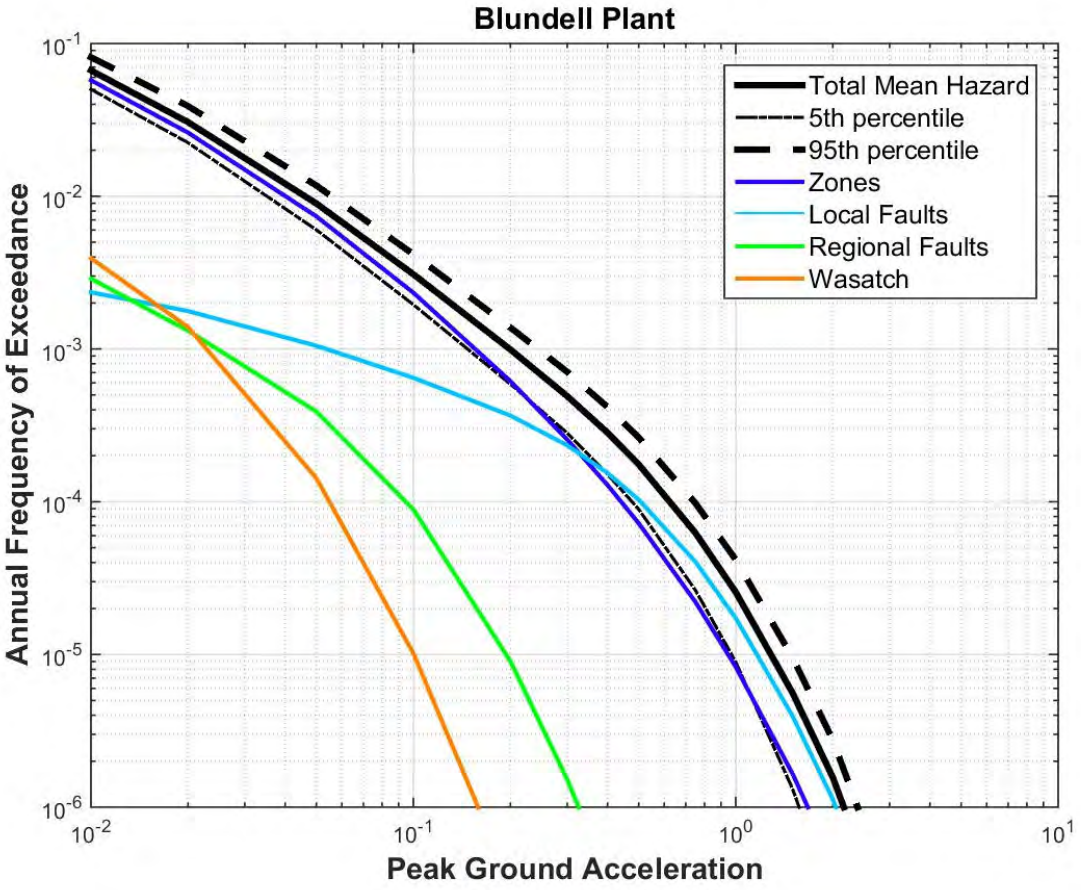


Figure 4-20: Total Mean Hazard for PGA and Grouped Source Contribution for the Blundell Geothermal Plant

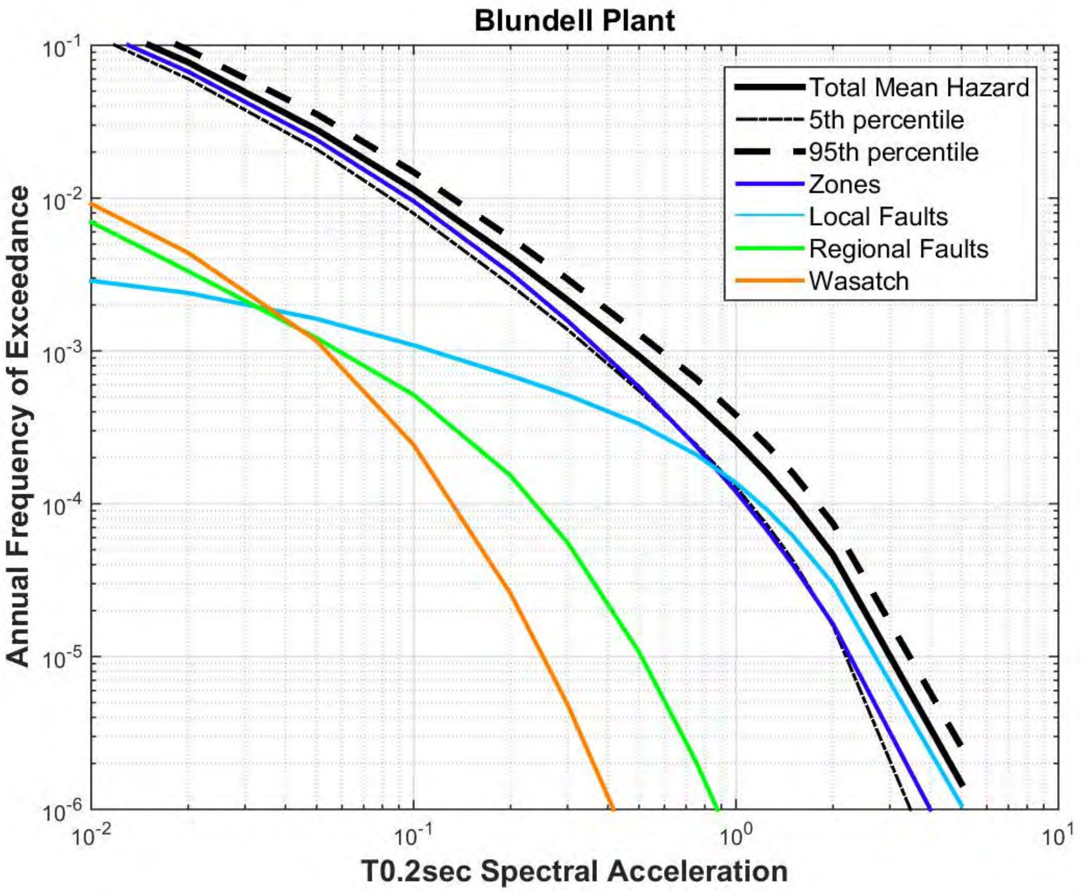


Figure 4-21: Total Mean Hazard for 0.2 s Spectral Acceleration and Grouped Source Contribution for the Blundell Geothermal Plant

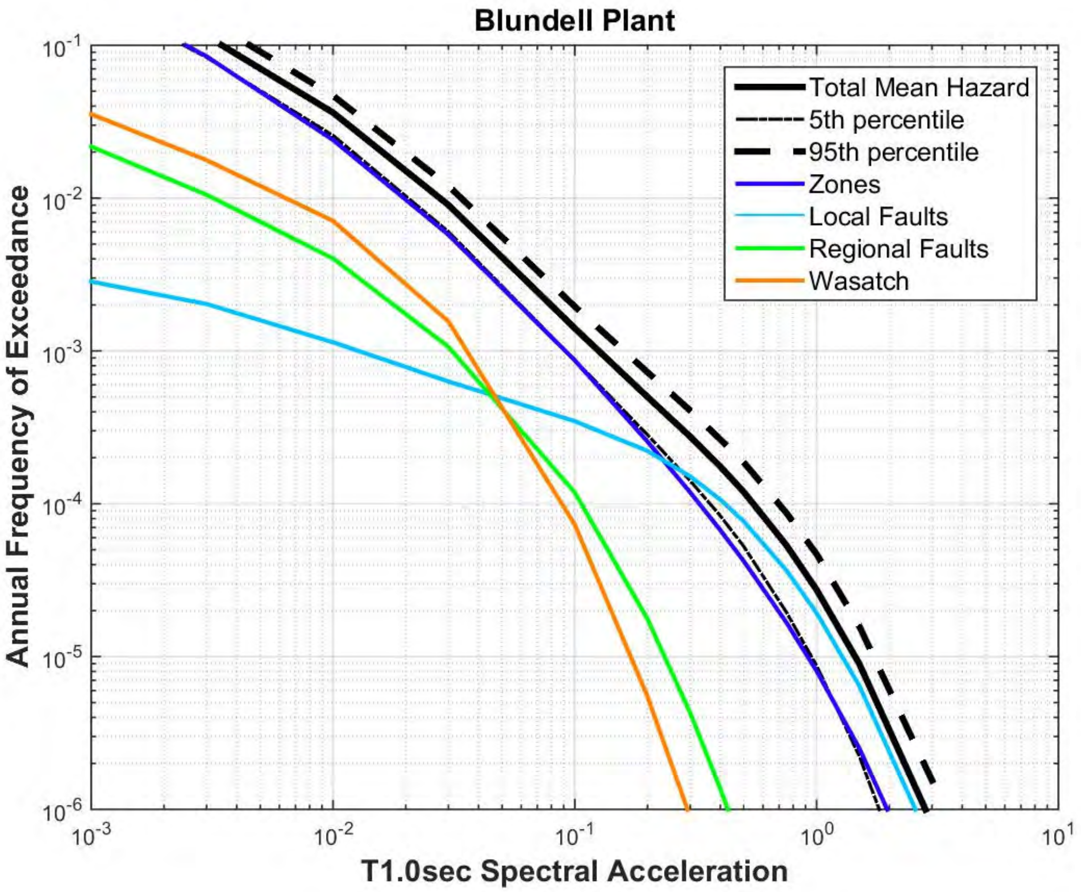


Figure 4-22: Total Mean Hazard for 1 s Spectral Acceleration and Grouped Source Contribution for the Blundell Geothermal Plant

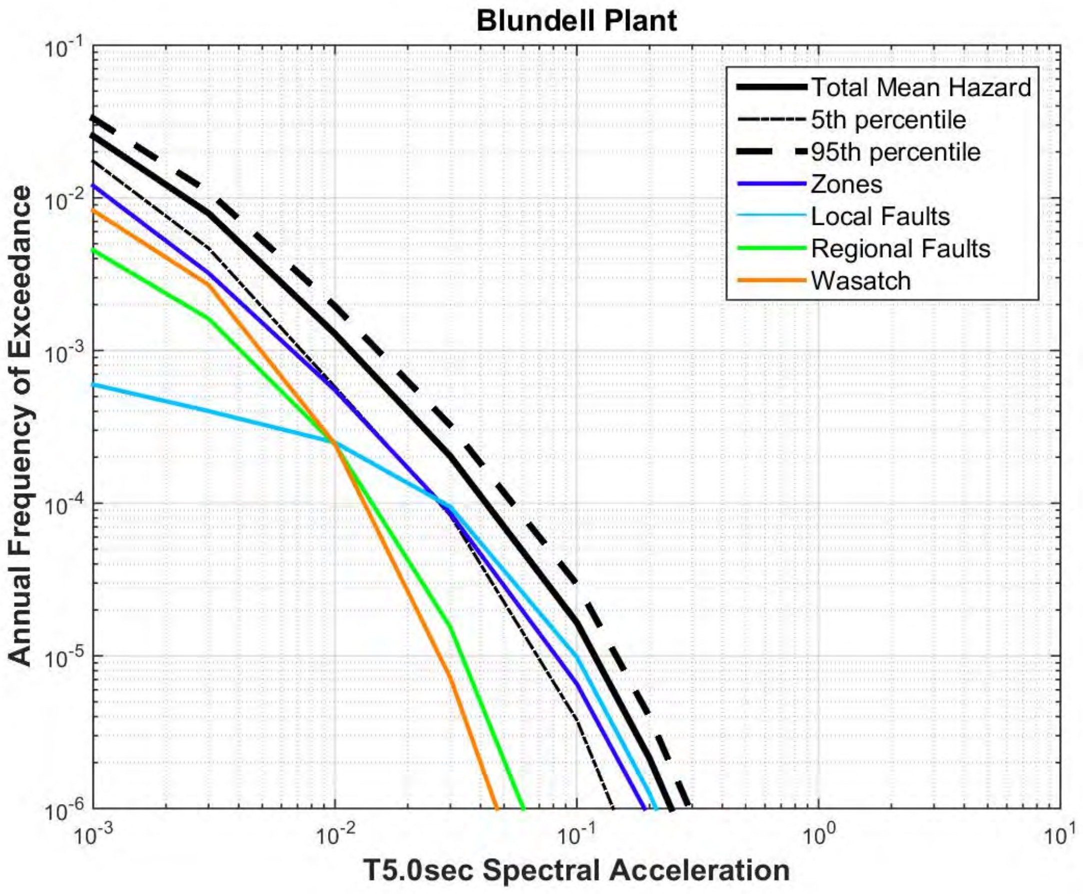


Figure 4-23: Total Mean Hazard for 5 s Spectral Acceleration and Grouped Source Contribution for the Blundell Geothermal Plant

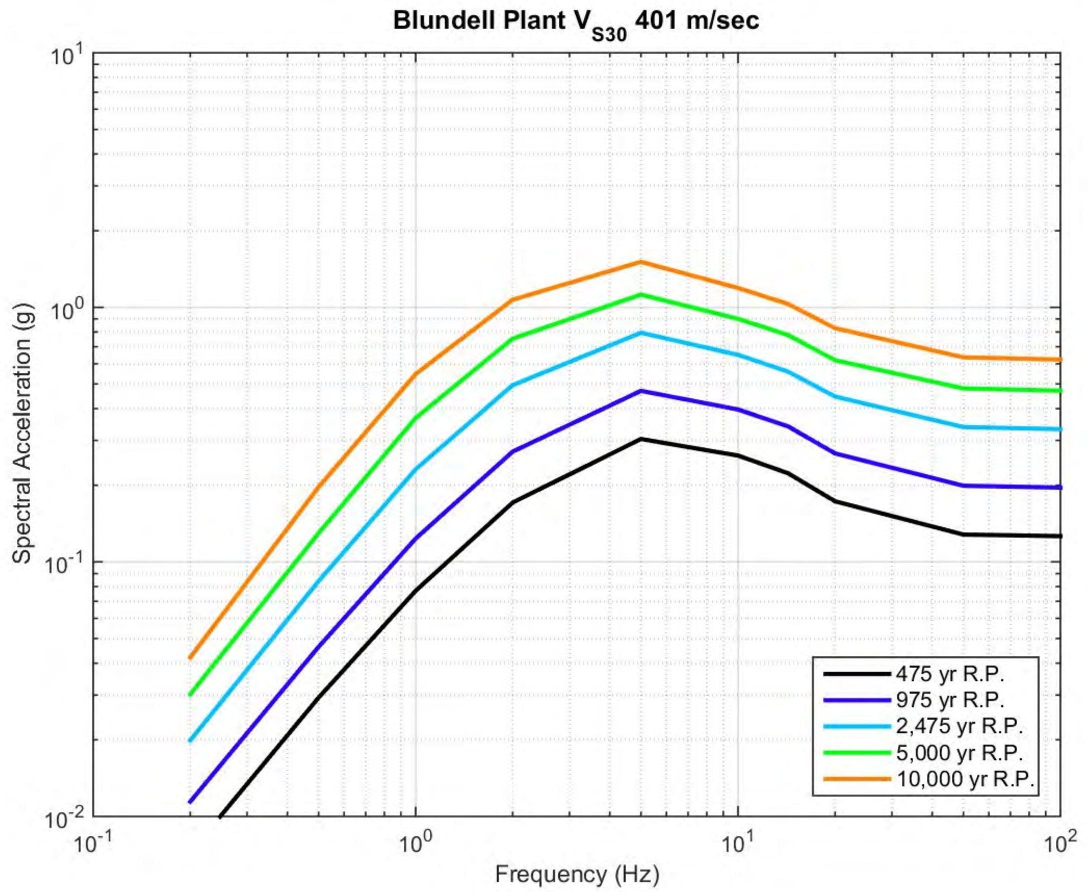


Figure 4-24: Mean Horizontal Uniform Hazard Response Spectra for the Blundell Geothermal Plant

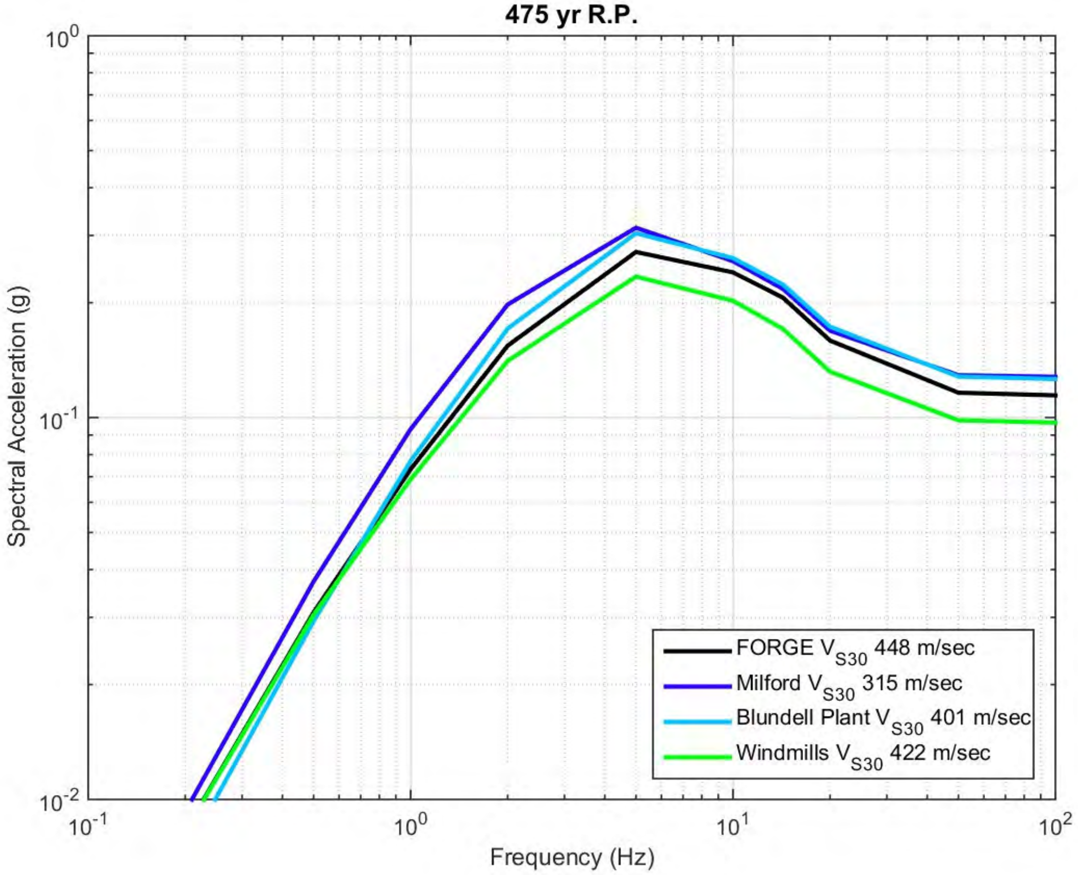


Figure 4-25: Comparison of the 475 Years Return Period Uniform Hazard Response Spectra for the Four Sites

ATTACHMENT 2:

RECOMMENDATION by WSP USA Environment & Infrastructure Inc.

WSP USA Environment & Infrastructure Inc.
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Oakland, California 94607
USA

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F: 1-833-778-3465

www.wsp.com

November 28, 2022

Project 8622201420

Dr. Kristine Pankow
University of Utah
115 S 1460 E
Salt Lake City, UT 84112

Subject: **Letter Report: Evaluate the Need to Update of the FORGE PSHA**
Milford, UT

Dear Dr. Pankow:

WSP USA Environment & Infrastructure Inc. (formerly Wood Environment and Infrastructure Solutions, Inc.) has evaluated new data and models published after completion of the FORGE seismic hazard study in 2018, to assess whether the seismic hazard model and calculations need to be updated.

The purpose of the FORGE PSHA completed in 2018 was to obtain the mean annual frequency of exceedance of specified levels of ground motions at four locations in the vicinity of the proposed FORGE site. The time-averaged shear wave velocity of the top 30, V_{S30}, was specified by the University of Utah for each site and ranged between approximately 300 and 400 m/s. Amec Foster Wheeler (2018) developed a source characterization model that included areal source zone where the seismicity is diffuse, regional faults, and local faults. Wood (2020) evaluated the Amec Foster Wheeler (2018) model focusing on two aspects specifically identified by DOE: 1) new information on the regional setting and structure; and 2) new data pertaining to the velocity model at the site. Consequently, Wood (2020) implemented changes to the earthquake recurrence model of the Wasatch and Mag Lee faults and changes to the V_{S30} and basin-depth parameters necessary to adjust the NGA-West 2 ground motion models to the site conditions at each site. The effect of adding 1.3 years of observed seismicity to the earthquake catalog developed by Amec Foster Wheeler (2018) was evaluated by statistical testing and the conclusion was that the additional earthquakes did not warrant an update of the seismicity rates. Additionally, it was noted that future updates should include the development of amplification functions at each site to permit the use of the Southwestern U.S. Ground Motion models (SWUS, GeoPentec, 2015) for the Basin and Range province, but this change was not implemented.

This letter report documents our evaluation of data and models that became available after the original FORGE model and after the 2020 model update that could produce changes to the baseline seismic hazard.

EVALUATION OF NEW DATA AND MODELS

Following our proposed scope of work, activities have focused primarily on a review of recent literature and additional earthquake records to evaluate the need to update: 1) the earthquake catalog; 2) the seismic source model; 3) the ground motion models. Our assessments and recommendations are described in the following.

Evaluation of Seismicity post-2018

The earthquake catalog developed by Amec Foster Wheeler (2018) for FORGE (the FORGE catalog in the following) was composed of two sources: the Utah Region catalog of Arabasz et al. (2017), which extends to the end of 2016, and the 2014 National Seismic Hazard Map catalog (in the following NSHM14, Petersen et al., 2014), which only extends to 2012, but covers a wider area. In the FORGE PSHA, the earthquake catalog is used primarily to develop earthquake frequency relations for zones of distributed seismicity and to develop models that represent the spatial distribution of the seismicity within the zones. Observed seismicity is also used to guide the selection of appropriate maximum magnitude and focal depth distributions for source zones. Wood (2020) updated the FORGE catalog introducing revisions to the historical seismicity (prior to 1962) from Arabasz et al. (2019). The catalog was extended to April 9, 2018 using records from the earthquake catalog developed for the 2018 National Seismic Hazard Map (NSHM18, Petersen et al., 2019).

For the 2022 update, the FORGE catalog was extended from 2018 to October 9, 2022, using earthquake records from the University of Utah catalog, and from the USGS National Earthquake Information Center (NEIC). Earthquake records were combined, and duplicates were removed. Then using relations from Arabasz et al. (2016) the magnitudes were converted to "best estimate magnitudes" consistent with the catalog for the Utah region.

To evaluate the need to update the recurrence rates, a statistical test was used. Under the null hypothesis, the number of earthquakes observed between January 1, 2018, to October 9, 2022 is consistent with the number of earthquakes predicted by the long-term earthquake rates obtained using the FORGE catalog updated to the end of 2017. The FORGE seismic hazard model (Amec Foster Wheeler, 2018; Wood, 2020) uses the Poisson recurrence model for the distributed seismicity sources. Given the frequency of earthquakes (λ) and the time interval of observation (t), the probability of observing exactly n earthquakes is given by:

$$P[N = n] = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{1}$$

An exact Poisson test (e.g., Fay, 2010) was performed to test the null hypothesis that the observed number of earthquakes in the 2018-10/9/2022 time period has been generated by a natural process with true rate of earthquakes equal to the long-term earthquake rate of the hazard model. The time interval is equal to 4.8 years (*t* in Equation 1). Because the interest is in evaluating whether the true rate should be higher, a one-sided test is used. The test is performed by calculating the probability of observing a number *n* of earthquakes with $M \geq m_i$, or greater counts, given the true rate λ_i, where λ_i is one member of the uncertainty distribution for *λ* calculated from the FORGE model parameters. The test is defined by the following equation:

$$P[N \geq n_{obs} | \lambda_i] = 1 - \sum_{n=0}^{n-n_{obs}-1} P[N \geq n | \lambda_i] \tag{2}$$

The equation is used to evaluate each term of the summation from $n = 0$ to $n = n_{obs} - 1$. Probabilities smaller than 5% reject the null hypothesis (i.e., fail the test).

The mean rate *(λ_i)* of earthquakes with M ≥ m_i can be obtained from recurrence curves and is used to calculate the mean predicted number of earthquakes greater or equal than m_i ($N \geq n|\lambda_i$). The test is conducted for the host source zone (Basin and Range, BR) for m_i equal to 2.85, 3.55, 4.25, and 4.95, which correspond to completeness magnitude intervals for which there are earthquakes. The table below shows the number of earthquakes in each interval, the corresponding number of earthquakes predicted by the mean long-term rates, and the probability computed according to Equation 2. The probability is 0% for the smallest magnitude, meaning that the null hypothesis is rejected. For larger magnitudes the test indicates that the observed events are consistent with the long-term rate computed from recurrence curves.

Table 1 – Results of the one-sided Poisson test for t=4.8 in zone BR

Magnitude	**n_{obs}**	**Mean $N \geq n\|\lambda_i$**	**$P[N \geq n_{obs}\|\lambda_i]$**
M≥2.85	143	70	0%
M≥3.55	25	19	12%
M≥4.25	4	4	52%
M≥4.95	1	1	52%

The larger number of **M**≥2.85 earthquakes could be caused by the different magnitude threshold used in compiling the catalog as well as different processing compared to the FORGE catalog. Figure 1 shows the recurrence curve obtained for zone BR using the FORGE catalog extended to 2017 (blue) and the recurrence curve obtained with the FORGE catalog extended to October 9, 2022 (red) and shows that the additional earthquakes produce only a small reduction in the recurrence rates for magnitudes greater than 3. This is because adding many small magnitude events produce a larger b-value, and a steeper curve: the rate of larger magnitude events becomes smaller.

Similarly, the one-sided Poisson test was conducted for zones RM and CP and the computed probabilities confirm that the observed earthquake counts are not inconsistent with the long-term rates predicted by the seismic hazard model.

Figure 2 shows the spatial distribution of small and large earthquakes over the years. Each plot represents a single year from 2016 to 2022. On each map, earthquakes with **M**≥4 are shown in yellow; the location of the FORGE sites is indicated by red stars. The spatial distribution of seismicity follows trends of natural seismicity that are consistent with the modeled spatial distribution of earthquakes. Two moderate events near the FORGE sites (September 12, 2018 **M** 3.87 and April 14, 2019 **M** 4.06) are interpreted to be related to fluid movement in the Black Rock Volcanic Center (Mesimeri et al., 2021).

While the number of small magnitude earthquakes is greater than predicted by the long-term seismicity rates, analysis of the seismicity that occurred between 2018 and 10/9/2022 does not warrant an update of the recurrence parameters of the distributed seismicity zones (BR, RM, CP) because the observed number of events in the last 4.8 years for magnitudes greater than 3.55 is consistent with the long-term rates predicted by the hazard model.

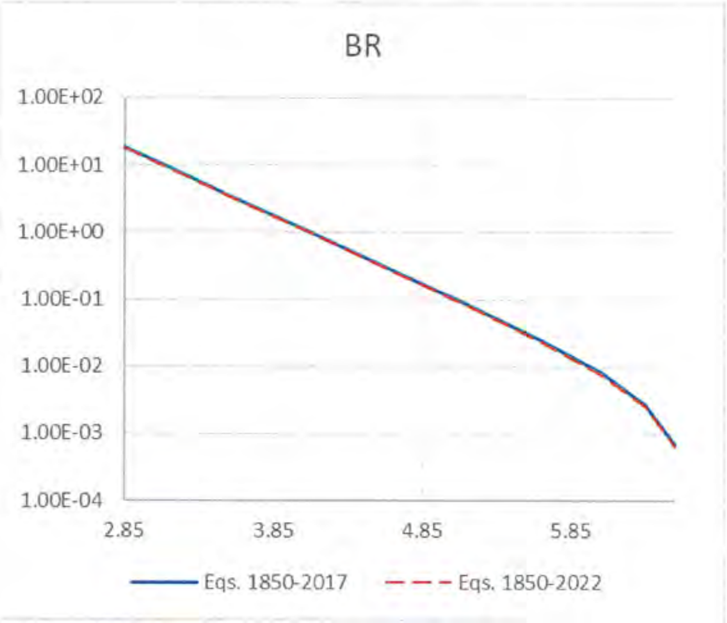
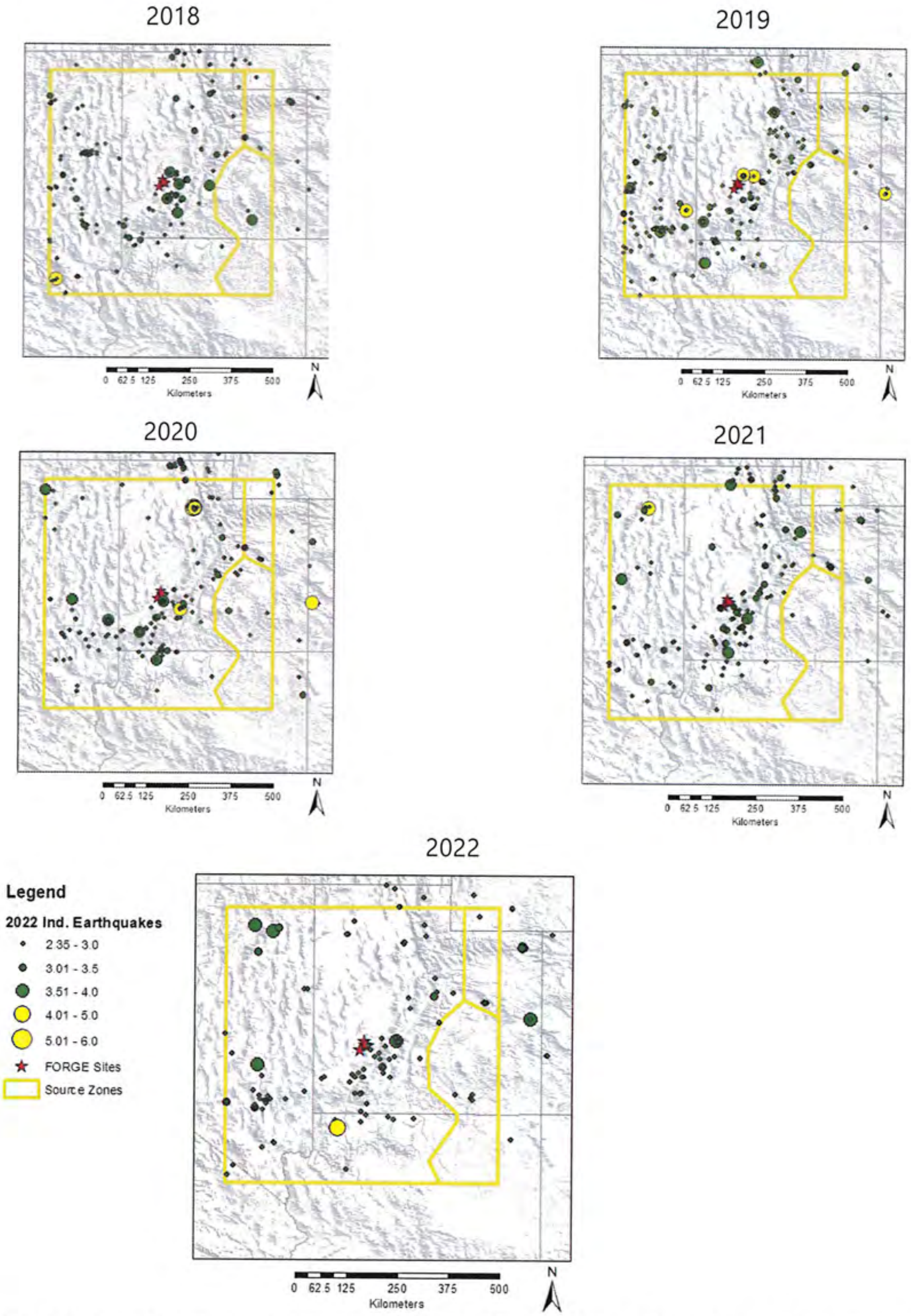


Figure 1: Recurrence for the BR zone obtained from the FORGE 2020 catalog (blue) compared to the recurrence obtained with the FORGE catalog extended to 10/9/2022.



2018

2019

2020

2021

2022

Figure 2: Maps of annual observed seismicity from 2018 to 2022. Earthquakes with M≥4 are plotted in yellow

Evaluation of New Research

WSP conducted a review of scientific publications since the 2020 PSHA to identify new data or models that could be used to update elements of the source characterization models. Appendix A lists the articles that were evaluated during this review and summarizes their potential effect on the source model. The most significant development since 2020 is publications developed in support of the 2023 USGS NSHM (Hatem et al., 2022a and Hatem et al., 2022b). The map and its inputs have not yet been finalized, however, currently 114 new faults have been added to the FORGE study region as 2023 NSHM sources (Figure 3). The principal reason for the addition of the faults is a change in the criteria the USGS uses to determine which faults will be included as sources. In the 2014 NSHM faults were only included if there was an associated slip rate. The 2018 NSHM used the same faults as the 2014 NSHM. For the 2023 NSHM, any fault with evidence for Quaternary activity was included. Other criteria used for the selection of fault sources for the 2023 NSHM included fault length of at least 7 km and evidence used for the determination of fault parameters must be available in a peer-reviewed, publicly available format.

The new fault sources in the FORGE study area were all previously evaluated in the USGS Quaternary fault and fold database (QFFD). When slip rates for faults are not known, the QFFD places them into slip categories (e.g., less than 0.2 mm/yr, between 0.2 and 1.0 mm/yr, etc.). To convert these broad ranges to slip rates for NSHM sources, the USGS applied different PDFs based on the region where the fault is located to get a slip rate distribution (Hatem et al., 2022a and 2022b). Geodetic slip rates are not yet included in the rates we used for slip in this model. They are expected to be released for the NSHM 2023 model when it is finalized.

The Mineral Mountains fault, one of the closest faults to the FORGE sites, was included in the NSHM 2023 fault sources. It had not previously been included as a fault source. The slip rate distribution for the NSHM source is 0 (0.1), 0.099 (0.8), and 0.26 (0.1) mm/yr which is the generic distribution in the region for QFFD faults with the classification of less than 0.2 mm/yr slip. The slip rate distribution previously applied in the FORGE Project is similar (0.002 (0.125), 0.060 (0.75), and 0.200 (0.125) mm/yr).

The effect of adding 113 fault sources from NSHM 2023 to the FORGE PSHA model was evaluated for the Milford site by computing seismic hazard for PGA, 0.2 s and 1.0 s. The Mineral Mountains source was not added as it was already included in the FORGE model. Figures 4 through 6 compare the mean Annual Frequency of Exceedance (AFE) for PGA, 0.2-s SA and 1.0-s SA from different sources. The solid black curve represents the total mean hazard from all crustal sources, i.e., faults and areal source zones from the FORGE 2020 study. The sum of the 2020 total mean hazard with the 113 faults from NSHM 2023 is shown by the dashed, black curve labeled "Total 2022". Individual hazard curves for NSHM 2023 faults are shows by various colors: these represent a subset of the 113 faults included in the sensitivity test, consisting of faults that are capable of larger earthquakes (**M** 7+) and faults close to the FORGE sites. Faults in the Bever Basin group have the highest contribution to hazard among the new NSHM 2023 faults. The surface traces of the faults are approximately 20-40 km from the Milford site. The base of west dipping Beaver Basin (intrabasin, central) fault extends nearly to the Milford site with the 35° dip alternative.

The results show a small to moderate increase in hazard for the 2022 results compared to the 2020 results. Table 2 shows the ground motion values for return periods of 475, 975, 2475, 5000, and 10,000 years for the 2020 FORGE model and the 2022 sensitivity test. As indicated in Table 2, there is a small increase (<10%) for PGA and T 0.2 s, while for T 1.0 s the increase is >15% for return periods shorter than 1000 years. This is consistent with the effect of including faults with large characteristic magnitudes and suggests that the hazard may need to be updated.

Table 2 – Comparison between ground motion calculated for the Milford site at various return periods using the 2020 FORGE model versus the 2022 hazard sensitivity results

<table>
<tr><td colspan="6">2020 FORGE - Milford site</td></tr>
<tr><td>Spectral Period</td><td>475 years</td><td>975 years</td><td>2475 years</td><td>5000 years</td><td>10000 years</td></tr>
<tr><td>PGA</td><td>1.28E-01</td><td>1.96E-01</td><td>3.17E-01</td><td>4.36E-01</td><td>5.68E-01</td></tr>
<tr><td>T 0.2s</td><td>3.14E-01</td><td>4.72E-01</td><td>7.56E-01</td><td>1.02E+00</td><td>1.33E+00</td></tr>
<tr><td>T 1.0s</td><td>9.33E-02</td><td>1.45E-01</td><td>2.54E-01</td><td>3.83E-01</td><td>5.56E-01</td></tr>
<tr><td colspan="6">2022 Hazard Sensitivity to addition of Faults – Milford site</td></tr>
<tr><td>Spectral Period</td><td>475 years</td><td>975 years</td><td>2475 years</td><td>5000 years</td><td>10000 years</td></tr>
<tr><td>PGA</td><td>1.37E-01</td><td>2.07E-01</td><td>3.28E-01</td><td>4.44E-01</td><td>5.75E-01</td></tr>
<tr><td>T 0.2s</td><td>3.40E-01</td><td>5.07E-01</td><td>7.88E-01</td><td>1.05E+00</td><td>1.36E+00</td></tr>
<tr><td>T 1.0s</td><td>1.09E-01</td><td>1.67E-01</td><td>2.85E-01</td><td>4.16E-01</td><td>5.83E-01</td></tr>
<tr><td colspan="6">% differences (2022 vs 2020)</td></tr>
<tr><td>Spectral Period</td><td>475 years</td><td>975 years</td><td>2475 years</td><td>5000 years</td><td>10000 years</td></tr>
<tr><td>PGA</td><td>7.3%</td><td>6.0%</td><td>3.3%</td><td>2.0%</td><td>1.1%</td></tr>
<tr><td>T 0.2s</td><td>8.1%</td><td>7.3%</td><td>4.3%</td><td>2.8%</td><td>1.9%</td></tr>
<tr><td>T 1.0s</td><td>16.5%</td><td>15.4%</td><td>12.4%</td><td>8.4%</td><td>5.0%</td></tr>
</table>

Much of the other new research listed in Appendix A relates to the 2020 Magna earthquake and possible interpretations of the Wasatch fault based on the occurrence of this event. The Wasatch fault system is more than 100 km away from the site and changes in the fault geometry, such as making the fault listric, would not have a large impact on the hazard at the FORGE sites.

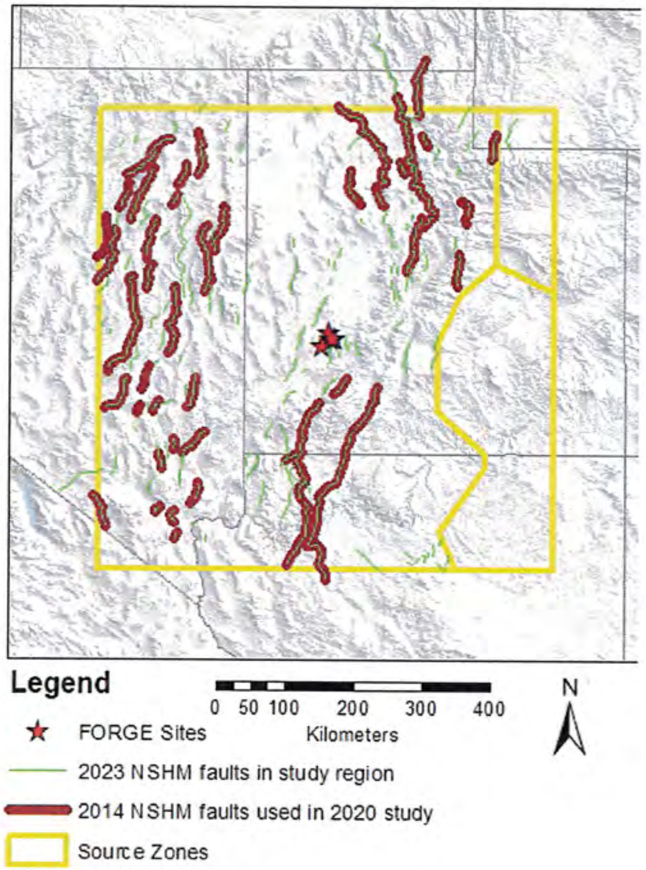


Figure 3: Comparison of the 2014 NSHM fault sources used in the FORGE model and the 2023 NSHM fault sources in the study region.

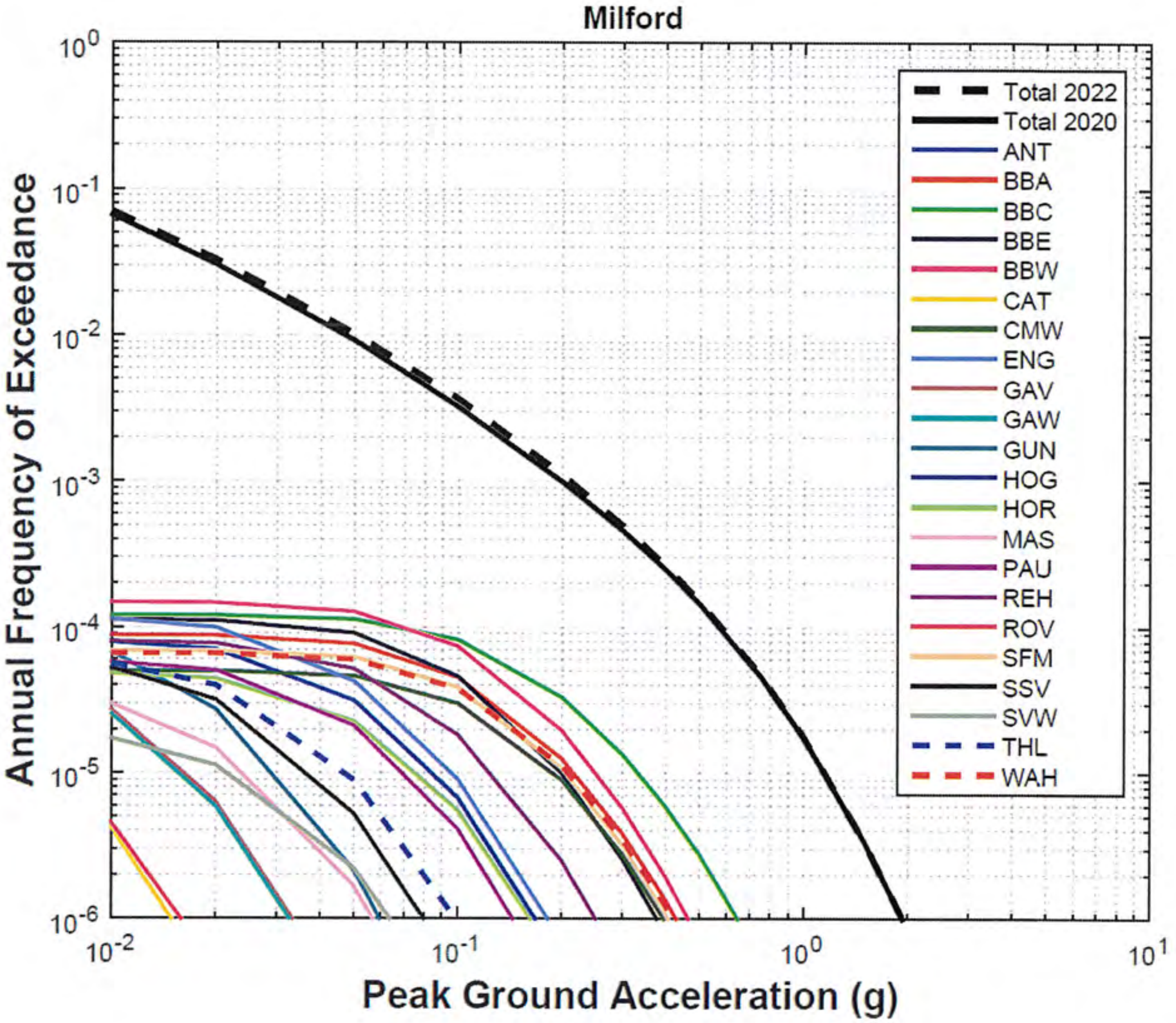


Figure 4: Mean hazard for PGA. See Appendix B for corresponding fault codes and names.

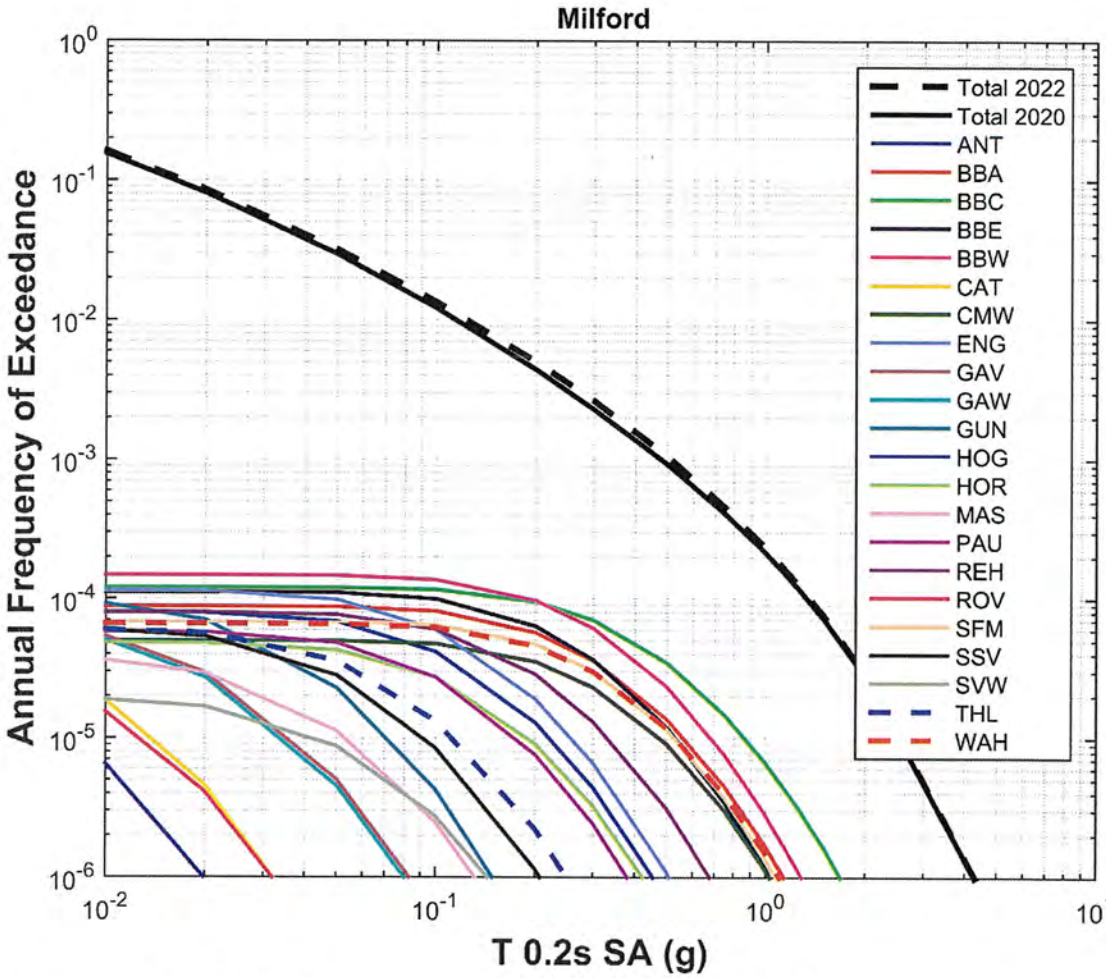


Figure 5: Mean hazard for T 0.2 s spectral acceleration. See Appendix B for corresponding fault codes and names.

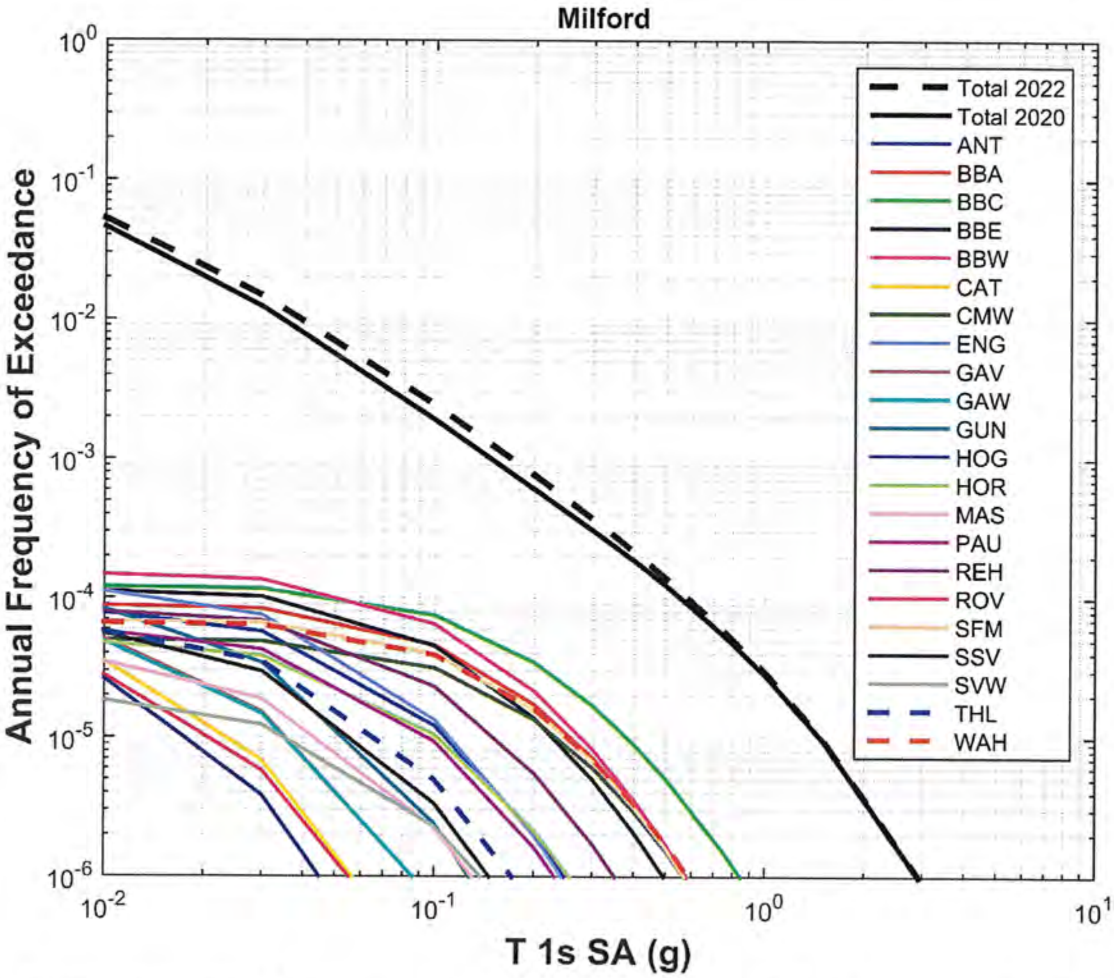


Figure 6: Mean hazard for T 1.0 s spectral acceleration. See Appendix B for corresponding fault codes and names.

Evaluate the need to update the ground motion model

In the 2018 and 2020 FORGE PSHAs, four NGA-West2 ground motion models were used to capture the epistemic uncertainty in ground motion predictions. All four models have generic site terms that estimate local site effects based on one or two proxy parameters such as V_{S30} and Z_1. Since the generic site terms are based on a global database, the accuracy of the estimated site effects can be improved by replacing the generic site effects with analytical estimates that are based on site specific response analysis and the subsurface properties. FORGE is in the extensional Basin and Range province and developing site-specific site terms would allow the use of the Southwest US (SWUS) ground motion model. The SWUS ground motion project was a SSHAC Level 3 study that developed ground motion characterizations for active tectonic regions in coastal California and western Arizona (GeoPentech, 2015). The SWUS coastal California model was developed for seismic sources located in the compressional tectonic regime in the vicinity of the Diablo Canyon nuclear power plant, and the SWUS Greater Arizona model was developed for the extensional tectonic regime in the southern Basin and

Range. The Greater Arizona model could be applied to the FORGE region. However, SWUS has a different reference site condition (V_{S30} 760 m/s) than FORGE (V_{S30} approximately 400 m/s).

Figures 7 and 8 compare the distribution of median ground motions predicted by the SWUS models to those based on the NGA West2 models. Each plot show values for **M** 5, 6, 7, and 8 earthquakes for a V_{S30} of 760 m/s. Plots are provided for peak ground acceleration (PGA – Figures 7a and 8a) and for pseudo-spectral accelerations (PSA) at periods of 0.2 (Figures 7b and 8b) and 1.0 s (Figures 7c and 8c). Figure 7 shows plots for strike-slip earthquakes in an extensional environment, and Figure 8 shows plots for normal slip earthquakes in an extensional environment. Each plot shows the mean, 5th percentile, and 95th percentile from the distribution of ground motion models. Two cases are shown for the NGA West2 models. The case labeled "USGS" uses the Petersen et al. (2014) weights of [0.22, 0.22, 0.22, 0.22, 0.12] on the GMPEs of Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014), and Idriss (2014), respectively, and applies the Petersen et al. (2014) epistemic uncertainty factors. The case labeled "NGA West2" uses the Petersen et al. (2014) weights on the GMPEs but applies the Al Atik and Youngs (2014) epistemic uncertainty factors. For normal slip earthquakes (Figure 8), the Idriss (2014) model is not used in developing the NGA West2 and USGS predictions, as Idriss (2014) does not specifically address normal faulting earthquakes.

In general, the SWUS mean predictions are similar to the NGA West2 and USGS predictions for **M** 5, 6, and 7 earthquakes and are generally higher than the other two for **M** 8 earthquakes. This indicates that the SWUS models have somewhat stronger magnitude scaling, particularly at large magnitudes and longer spectral periods. The SWUS uncertainty bands are generally similar to or slightly wider than the Al Atik and Youngs (2014) uncertainty bands for **M** 5, 6, and 7, and are wider than both the Al Atik and Youngs (2014) and USGS uncertainty bands for **M** 8.

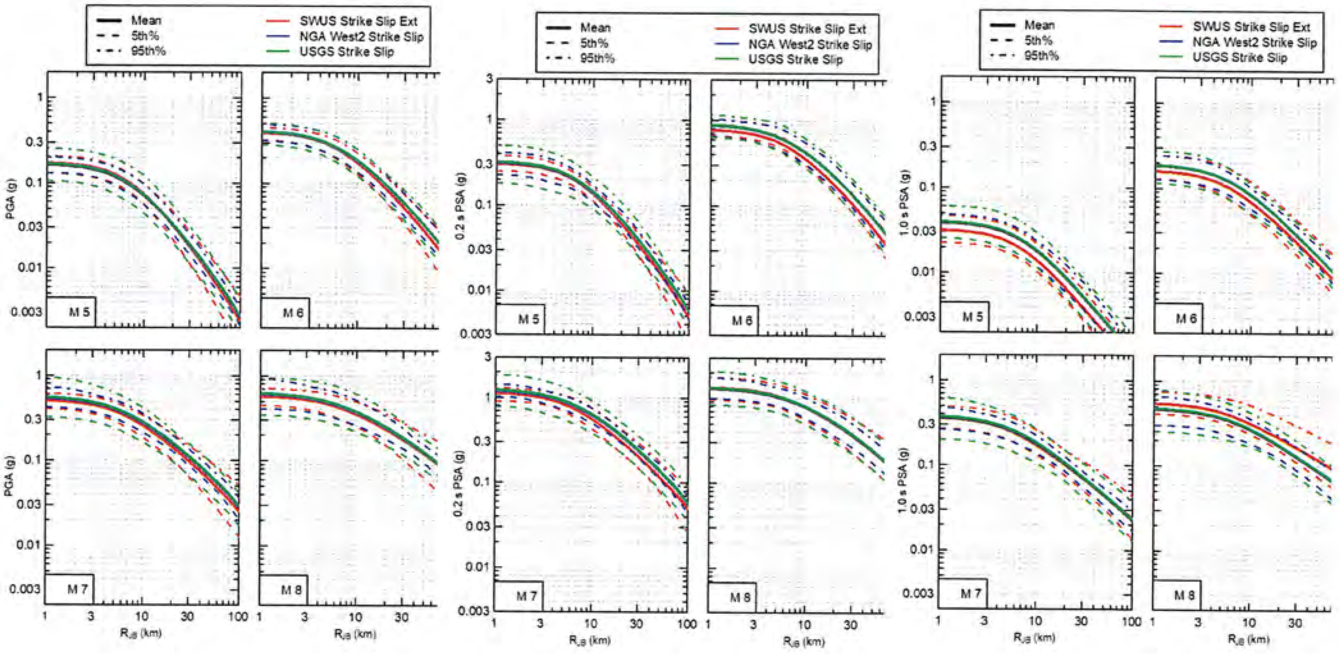
We reviewed recent publications on geophysical studies in FORGE to determine if there is enough data to conduct site response analysis. Zhang and Pankow (2021) developed subsurface velocity models using Geophone arrays recordings of the ambient noise. They validated the model by comparing it to shear wave velocity profiles estimated based on distributed acoustic data in one borehole. Additionally, Wells et al. (2022) obtained subsurface profiles using geophone arrays and regional broadband data. Our assessment is that it is feasible to replace the generic site terms with site-specific estimates based on 1-D site response analysis to more accurately capture site effects at the Forge locations.

RECOMMENDATIONS

WSP conducted a review of data and publications that became available after the latest update of the FORGE hazard model conducted in 2020 (Wood, 2020) to evaluate the need to further update the model. Our review focused on three aspects: 1) evaluating the need to update earthquake recurrence parameters based on seismicity observed in the last 4 years; 2) evaluating the need to update the seismic source model based on recent studies; 3) evaluating the need to update the ground motion characterization model based on recent models and available data.

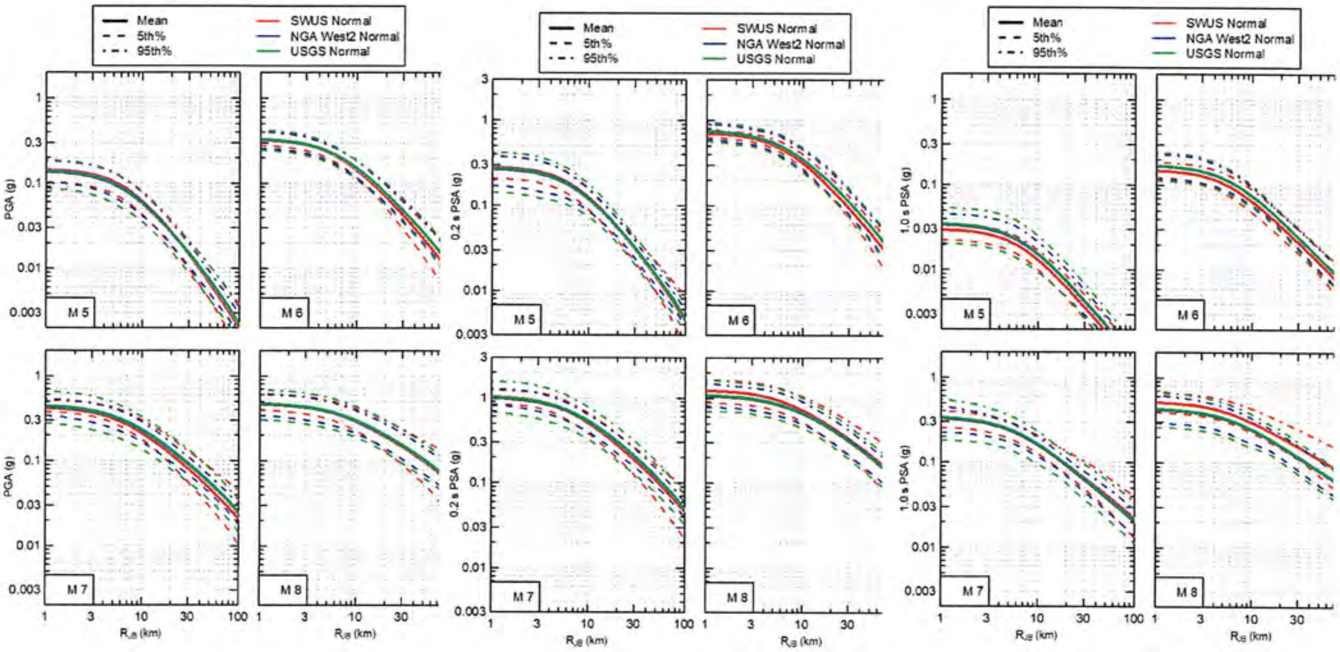
Our conclusions and recommendations are as follows:

- Recent seismicity does not warrant an update of earthquake recurrence parameters for distributed seismicity sources.
- The addition of 113 faults from the NSHM 2023 model produces a small to moderate increase in seismic hazard, particularly for T 1.0 s (1 Hz) at return periods shorter than 1000 years. Consider including some of these faults (namely those within 50 km of the sites, or with large characteristic magnitude) in the seismic hazard model.
- Available subsurface velocity models could be used to derive site-specific estimates based on 1-D site response analysis to use in combination with SWUS Greater Arizona ground motion models. However, the recommendation is to re-evaluate the ground motion characterization for the FORGE site once the USGS releases their 2023 NSHM approach for the western US.



(a) (b) (c)

Figure 7 Comparison of median predictions for strike slip earthquakes in an extensional environment: a) PGA; b) T 0.2s spectral acceleration; c) T 1s spectral acceleration.



(a) (b) (c)

Figure 8 Comparison of median predictions for normal slip earthquakes in an extensional environment: a) PGA; b) T 0.2s spectral acceleration; c) T 1s spectral acceleration.

Sincerely,
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vmf/ba/sc
https://woodplc.sharepoint.com/teams/oaklanddecisionanalysis/shared documents/general/201420_forge_2022_update/03 docctrl/draft report/draft-forge_2022.docx

Attachments: Appendix A: Review of literature from 2020-October 2022
Appendix B: 2023 USGS faults in study region.

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Appendix A:
Review of literature from 2020-October 2022

Author	Year	Summary	Change model?
Crowell	2021	This article reports on strong motion data from GPS stations related to the two M 6.5 events in Challis, Idaho, and Monte Cristo Range, Nevada; an M 5.7 in Magna, Utah, within the Salt Lake City metropolitan area; and an M 5.8 in the Owens Valley of California earthquakes in 2020.	No. All of the measurements analyzed are close to the earthquake sources and not near the FORGE site.
Evans	2022	This study develops the densest and most complete block model of the western continental United States to date. The model includes 853 blocks bounded by 1017 geologically identified fault sections from the USGS NSHM Fault Sections database. Microplate rotations and fault slip rates are constrained by 4979 GNSS velocities and 1243 geologic slip rates. This block model includes slip on faults that are not included in the USGS NSHM Fault sections database (but are required to form closed blocks) for an estimate of "off-fault" deformation The largest normal slip rates occur on a fault system including the Toiyabe range fault (0.5–2 mm/yr, FID: 1117) between 118° and 116° W, a fault system extending south from the Wasatch fault (FID: 2761) to the Maple Grove (FID: 2762) and Paragonah (FID: 2710) faults (around 113° W, 1–5 mm/yr). The easternmost faults in this system (including Joe's Valley fault, FID: 2709; Hogsback fault, FID: 2921; and Bear river fault, FID: 2900) have the highest normal slip rates of up to 6 mm/yr. We note, however, that this region of the model is especially poorly constrained (Fig. 4a), and these rates may be more representative of total regional deformation rather than truly concentrated on the structures described here.	No. The results of this study are not available yet.
Frietsch et al.	2021	This article uses Teleseismic and geodetic data to characterize the faults involved with the 2008 Wells Nevada Mw 6.0 earthquakes. They conclude the fault is listric and prefer a 2 fault model.	No. These faults are more than 100 km from the FORGE sites and alternative geometries such as listric faults would not have a significant impact on the hazard in this study.
Gold et al.	2021	Summarizes the 18 March 2020 Mw 5.7 Magna, Utah earthquake parameters and effects. In the summary it describes how the event likely resulted	No.

Author	Year	Summary	Change model?
		from blind slip on the shallowly west-dipping Wasatch fault system (Salt Lake City section)	The Wasatch fault is at a sufficient distance from the sites that variations in dip have little influence. The model does have a 35° dip alternative.
Hatem et al.	2022	The average fault length of added faults is 27 km, compared to the average fault length of 43 km across the entire NSHM23 FSD. Likewise, ~90% of the added faults fall within the 0–0.2mm/yr QFFD slip rate category. In turn, the geodetic strain rate field (determined by Zeng, 2022) is used as a benchmark when determining the preferred slip rate values within a QFFD bin. Therefore, we use the QFFD slip rate category and various PDFs within the range of these categories to establish slip rates for faults without published slip rates. Preferred geologic slip rates here https://www.sciencebase.gov/catalog/item/612d61abd34e40dd9c08c7d6	Yes. The new geologic slip rates were tested.
Hatem et al.	2023 c	Simplifying complex fault data for systems-level analysis: Earthquake geology inputs for U.S. NSHM 2023 1. Definitive evidence of Quaternary tectonic deformation. 2. Fault length must exceed 7 km. 3. Evidence of faulting and associated geometry must be available in a peer-reviewed, publicly available publication. 69 faults from NSHM18 were not included in NSHM23. Most represent the removal of alternative fault representations used in California. No alternative fault model in NSHM23 like in UCERF3. A few faults (n = 25) were excluded from NSHM23 FSD due to a lack of unequivocal tectonic deformation during the Quaternary. Some fault sections included as single faults in NSHM18 FSD are now segmented	Yes. These new faults were tested for their effect on the model

Author	**Year**	**Summary**	**Change model?**
Hecker et al.,	2021	This article uses paleoseismic and geomorphic data to conclude the Bear River fault has ruptured three times in the last 4,500 years. The first two earthquakes on the BRF occurred during the same period of time as a regional cluster of earthquakes in the Middle Rocky Mountains, suggesting that isolated faults in this slowly extending region interact through widespread changes in stress conditions. GPS data indicates a horizontal slip rate of less than 0.04-0.06 mm/yr and recurrence rate of 25-36 ky for the assumed single event offset of 2.5 m. The interpreted paleosismic recurrence is 1 kyr and 3 kyr indicating clustering or geologic or glacial allowing for the build up of strain	Maybe. The Bear River fault currently has slip alternatives of 1.958 (0.8), 0.580 (0.1), and 0.680 (0.1). This does not accommodate the lower slip rate interpreted from GPS
Kleber et al.	2021	Based on geologic and geophysical data (seismic and gravity), we interpret the mainshock of the Magna earthquake as having occurred on a relatively gently dipping part of the Salt Lake City segment, with aftershocks concentrated in the Saltair graben and West Valley fault zone.	No The Wasatch fault has an alternative of 35° with a weight of 0.2
Koehler and Vlcan	2020	This report summarizes the State of Nevada's project to make their own Quaternary fault Database. As of 2020 they had only updated the area near Las Vegas, Reno and Walker Lane. GIS files at: https://gisweb.unr.edu/nbmg/rest/services/Geology/Faults/MapServer	No. The faults in the region near the FORGE site are in the USGS Quaternary fault and fold database and were considered in the development of the model.
Li et al.	2022	This article uses seismic and tomographic data to create a sedimentary and crustal structure model of the Western US. Across the Basin and Range, the resolved crust has an average thickness of 38 km in the southern half of the northern Basin and Range, about 5 km thicker than neighboring regions. The thickened crust overlaps with major volcanic centers of the mid-Cenozoic ignimbrite flare-up. Overall, the new model is consistent with active source studies in the region but provides a more comprehensive view of shallow and deep structures across this large and tectonically complex region.	
Liberty et al.	2021	This article uses seismic data coupled with previous geological excavations to interpret a link between the East Bench and Warm Springs faults. This indicates stronger fault connectivity and the	No.

Author	Year	Summary	Change model?
		possibility of surface deformation and lateral spreading in Salt Lake City.	The model currently allows interconnectivity between segments of the Wasatch fault.
McDonald et al.	2020	This study used Lidar and aerial photo data to produce more detailed maps of the Wasatch fault. It also summarizes the state of the science for each segment of the Wasatch fault and identifies future sites for research.	No. The report does not update the location of the Wasatch fault to the extent that it would be significant for hazard assessment.
Mesimeri et al.	2021	This study identified over 1,000 -2<M<2 earthquakes near Milford through the deployment of new seismometers. They interpret 15 periods of swarm like activity between 2016 and 2019. They hypothesize the swarms are related to fluid migration related to the Roosevelt hydrothermal system. Seismicity locates on a 1 km long east-west striking narrow zone, east of the Roosevelt Hot Springs, with a scattered depth distribution due to the suboptimal station distribution. Composite focal mechanisms of highly similar earthquakes show two possible fault orientations, north-south and east-west parallel to the two closest mapped faults, Opal Mound and Mag Lee, respectively	No. There is currently insufficient information to estimate a slip distribution or geometry for a new fault source
Mesimeri et al.,	2021	This article examines two the September 12, 2018 and April 14, 2019 shallow earthquakes in the Black Rock volcanic field and concludes they are related to the volcanic field based on their rapidly decaying aftershocks, and low frequency energy.	No. For the current evaluation the events were left in the catalog. The PSHA does not have a separate volcanic source at this time.
Pang et al.	2020	This article uses the Magna 2020 earthquake sequence to conclude that near Salt Lake City the Wasatch fault is likely listric based on surface observations of the fault with a dip of 70 and aftershocks indicating a dip of 30-35 degrees.	No. The Wasatch fault has an alternative of 35° with a weight of 0.2
Politz	2022	This article describes a fault-based model that permits estimation of long-term slip rates on discrete faults and the distribution of off-fault moment release. It is based on quantification of the earthquake cycle on a viscoelastic model of the seismogenic upper crust and ductile lower crust and mantle. I apply it to a large dataset of horizontal and vertical Global Positioning System (GPS) interseismic	No. The results of this study are not available yet.

Author	Year	Summary	Change model?
		velocities in the western United States, resulting in long-term slip rates on more than 1000 active faults defined for the NSHM.	
Pollitz et al.	2022	Key innovations in the 2023 NSHM relative to past practice include (1) the addition of two new (in addition to two existing) deformation models, (2) the revision and expansion of the geologic slip rate database, (3) accounting for fault creep through development of a creep-rate model that is employed by the four deformation models, and (4) accounting for time-dependent earthquake-cycle effects through development of viscoelastic models of the earthquake cycle along the San Andreas fault and the Cascadia subduction zone. The four models are : (1) the viscoelastic fault-based model, which uses viscoelastic relaxation from idealized past events on NSHM faults to characterize interseismic deformation; (2) the deep-dislocation-driven fault-based model, which employs dislocations below the locking depth of NSHM faults; (3) Neokinema (Shen-Bird), which uses both the GPS data and crustal stress information to constrain long-term fault slip rates on NSHM faults; and (4) the block model (Eans) It says, which divides the crustal volume of the western United States into numerous fault-bounded blocks, with block boundaries closely aligned with the NSHM faults. For 2023 all faults with evidence of movement in the last 2.58 Ma are included. Previously the faults had to have a known slip rate. Approximately 500 faults are only constrained by QFFD slip rate bins. About 80% of the newly added faults are in the lowest (0–0.2 mm/yr) slip rate bin; hence, new faults are a large contributor to the total ~600 faults in the lowest slip rate bin. Vertical GPS rates are not included The four deformation models have the option to account for earthquake-cycle effects by correcting observed GPS velocities for the ghost transient It says Tabulations of results are in "Geodetic deformation model ingredients and results for use	No. The database of these results has not been released yet so the effect of using the geodetic modeling fault slip rates could not be tested.

Author	Year	Summary	Change model?
		in U.S. National Seismic Hazard Model 2023" but link does not work	
Shen and Bird	2022	The kinematic finite-element code NeoKinema is used to describe crustal deformation for the 2023 update of the NSHM. Three different data sets—Global Positioning System (GPS) velocities, geological fault offset rates, and crustal stress orientations—are used to constrain the model. Four corrections: Correction for ghost transient deformation due to past earthquakes. Large earthquakes induce transient visco-elastic deformation of the lower crust and upper mantle, which can last for decades or even centuries. Sounds like mainly used on San Andreas. Correction for fault creep effect. The crustal deformation models often assume that interseismic fault slip is only below the locking depth, which defines the base of seismic ruptures; if so, corrections are required for GPS data collected near to faults with shallow creep Correction for Cascadia mega thrust locking effect. The elastic deformation due to megathrust fault locking, however, has imprints across the surface of the continent, and the effect needs to be corrected for the GPS data to be used in deformation models not including the megathrust as a deformation source. Correction for GPS estimate of uncertainties. we impose an ad hoc minimum uncertainty σm=0.3 mm/yr and replace all the uncertainties σi for the GPS horizontal components with σi←(σm2+σi2)1/2.	No. The results of this study are not available yet.
Simmons et al.	2021	This extended abstract covers the geology and site conditions for FORGE.	No. This is a review article.
Voyles et al.	2020	This article develops a catalog of events from explosions in Utah and define 26 event clusters	No.
Wells et al.	2022	This article uses geophone arrays and regional broadband data to interpret crustal structure in south central Utah. They find correlation between low velocity anomalies and high surface heat flux and geothermal activity. Additionally, we find a laterally continuous low-velocity anomaly between 5 and 15 km depth, which may represent elevated	Maybe. The deep shear wave velocity profiles provided in the paper can be used in site response analysis.

Author	Year	Summary	Change model?
		temperature of hundreds of degrees Celsius, partial melt, and/or the presence of water, and a common heat source across the region which likely originates from the mantle.	
Wong et al.	2021	The 2020 M5.7 Magna earthquake strong motion data compared favorably with NGA-West2 GMMs, PGAs exceed the GMM predictions at the closest distances for the source model that we used. Alternative interpretations of the Magna earthquake are that it occurred (1) on an auxiliary fault within the Wasatch fault zone or (2) on a listric section of the northern Salt Lake City segment that is not representative of the geometry of the whole fault segment. (3) the Wasatch fault is listric	No. The shallower dip of a listric fault is accommodated by the dip alternatives (65, 50, 65) on the Wasatch fault
Zeng	2022	New WUS GPS velocities solutions are compiled from seven data processing centers for the deformation modeling project in support of the 2023 NSHM update. The data are processed using the procedure for UCERF3 and the 2014 NSHM. Velocities related to volcanism and uncertainties greater than 2 mm/yr are removed. Strain rates are computed based on the methodology of Shen (2015).	No. The fault slip rates for geodetic studies for the 2023 NSHM have not been finalized yet.

Appendix B
2023 USGS faults in study region. Rates in mm/yr.

Code	Fault Name	Style	Dip Direction	Length (km)	Low Rate	Preferred Rate	High Rate
ACR	Arrow Canyon Range	Normal	W	25	0	0.099	0.26
ANN	Annabella Graben	Normal	NW	13	0	0.099	0.26
ANT	Antelope Range	Normal	NW	27	0	0.099	0.26
ANU	Antelope Range (unnamed)	Normal	W	27	0	0.099	0.26
ARC	Arrowhead - Citadel Ruins	Normal	E	11	0	0.099	0.26
BAB	Babbitt Lake	Normal	NE	8	0	0.099	0.26
BBA	Beaver Basin (east)	Normal	W	26	0	0.099	0.26
BBC	Beaver Basin (intrabasin, central)	Normal	W	19	0	0.099	0.26
BBE	Beaver Basin (intrabasin, east)	Normal	E	14	0	0.099	0.26
BBW	Beaver Basin (intrabasin, west)	Normal	E	8	0	0.099	0.26
BIP	Big Pass	Normal	NE	11	0	0.099	0.26
BLM	Black Mountains	Normal	NW	8	0	0.099	0.26
BPC	Black Point - Doney Mountain (center)	Normal	W	9	0	0.099	0.26
BPN	Black Point - Doney Mountain (north)	Normal	W	8	0	0.099	0.26
BPS	Black Point - Doney Mountain (south)	Normal	SE	8	0	0.099	0.26
BRC	Broadmouth Canyon - James Peak	Normal	NW	10	0	0.162	0.26
BSS	Big Sand Springs (north)	Normal	E	7	0	0.099	0.26
BSV	Big Sand Springs Valley	Normal	NW	14	0	0.099	0.26
CAG	Cameron Graben	Normal	NW	14	0	0.099	0.26
CAR	Carrington	Normal	NW	29	0	0.162	0.26
CAT	Cataract Creek	Normal	SW	51	0	0.099	0.26
CER	Cedar Ranch	Normal	E	10	0	0.099	0.26
CEW	Cedar Wash	Normal	W	12	0	0.099	0.26

Code	Fault Name	Style	Dip Direction	Length (km)	Low Rate	Preferred Rate	High Rate
CHC	Cherry Creek	Normal	NW	15	0	0.099	0.26
CLR	Campbell Francis - Large Whiskers - Rimmy Jim	Normal	W	19	0	0.099	0.26
CMC	Coal Mine Canyon	Normal	E	11	0	0.099	0.26
CMW	Cricket Mountains (west)	Normal	NW	52	0	0.099	0.26
CRB	Crater Bench	Normal	W	16	0	0.099	0.26
CRM	Crawford Mountains - Saleratus Creek	Normal	NW	37	0	0.099	0.26
DEV	Detrital Valley	Normal	E	11	0	0.099	0.26
DME	Drum Mountains (east)	Normal	W	15	0	0.099	0.26
DMN	Drum Mountains (northwest)	Normal	E	12	0	0.099	0.26
DMS	Drum Mountains (south)	Normal	W	8	0	0.099	0.26
DOV	Dover	Normal	E	23	0	0.162	0.26
ECC	Echo Canyon	Normal	E	8	0	0.099	0.26
EKA	East Kamas	Normal	W	15	0	0.099	0.26
ELS	Eastern Little Smoky Valley	Normal	W	32	0	0.099	0.26
ENG	Enoch Graben	Normal	W	13	0	0.099	0.26
ETN	East Tintic Mountains (northwest)	Normal	SW	19	0	0.162	0.26
ETS	East Tintic Mountains (southeast)	Normal	W	10	0	0.162	0.26
ETW	East Tintic Mountains (southwest)	Normal	W	11	0	0.162	0.26
FIS	Fish Springs	Normal	E	14	0	0.099	0.26
GAV	Garden Valley (unnamed)	Normal	E	36	0	0.099	0.26
GAW	Grand Wash	Normal	W	40	0	0.099	0.26
GOO	Gooseberry Graben	Normal	W	23	0	0.099	0.26
GOS	Goshen	Normal	NW	12	0	0.162	0.26
GUL	Gunlock	Normal	W	27	0	0.099	0.26
GUN	Gunnison	Normal	E	37	0	0.162	0.26
HOG	Hogsback	Normal	W	47	0	0.099	0.26
HOR	House Range	Normal	W	56	0	0.099	0.26

Code	Fault Name	Style	Dip Direction	Length (km)	Low Rate	Preferred Rate	High Rate
LIM	Littlefield Mesa	Normal	W	23	0	0.099	0.26
LVE	Little Valley (east)	Normal	W	14	0	0.162	0.26
LVW	Little Valley (west)	Normal	SE	16	0	0.162	0.26
MAC	Main Canyon	Normal	W	26	0	0.099	0.26
MAP	Maple Grove	Normal	W	14	0	0.162	0.26
MAS	Main Street	Normal	W	87	0	0.099	0.26
MEA	Mead Slope	Normal	SE	11	0	0.099	0.26
MES	Mesquite	Normal	NW	41	0	0.099	0.26
MMU	Mineral Mountains	Normal	W	37	0	0.099	0.26
MSN	Maverick Springs Range (north)	Normal	W	26	0	0.099	0.26
MSS	Maverick Springs Range (south)	Normal	NW	22	0	0.099	0.26
MUM	Murphy Meadows	Normal	NW	8	0	0.099	0.26
NEV	Newark Valley	Normal	NW	21	0	0.099	0.26
NGE	North Genola	Normal	W	8	0	0.162	0.26
NSM	Northern Snake Mountains	Normal	W	20	0	0.099	0.26
OVN	Ogden Valley North Fork	Normal	NE	27	0	0.162	0.26
PAU	Paunsaugunt	Normal	W	46	0	0.099	0.26
PAV	Pahranagat Valley (unnamed)	Normal	E	15	0	0.099	0.26
PCV	Pilot Creek Valley	Normal	E	8	0	0.099	0.26
PEH	Pearl Harbor	Normal	SW	15	0	0.099	0.26
PEP	Peko Peak	Normal	W	10	0	0.099	0.26
PIR	Pilot Range	Normal	W	11	0	0.099	0.26
POM	Porcupine Mountains	Normal	NW	32	0	0.099	0.26
PRE	Preston	Normal	E	17	0	0.099	0.26
REH	Red Hills	Normal	SE	27	0	0.099	0.26
ROV	Rock Valley	Strike-Slip	Vertical	64	0	0.076	0.2

Code	Fault Name	Style	Dip Direction	Length (km)	Low Rate	Preferred Rate	High Rate
SFM	San Francisco Mountains (west)	Normal	W	37	0	0.099	0.26
SHE	Sheep Range - East Desert Range	Normal	W	22	0	0.099	0.26
SHP	Sheeprock	Normal	E	16	0	0.099	0.26
SHR	Sheep Range	Normal	E	28	0	0.099	0.26
SHV	Southern Huntington Valley	Normal	E	23	0	0.099	0.26
SKP	Silver King Pass	Normal	W	9	0	0.099	0.26
SMF	Six-mile Flat	Normal	SE	18	0	0.099	0.26
SMP	Scipio - Maple Grove - Pavant Range - Red Canyon	Normal	E	42	0	0.162	0.26
SPC	SP Crater	Normal	W	10	0	0.099	0.26
SPR	Spotted Range	Normal	W	30	0	0.099	0.26
SRC	Steptoe (center)	Normal	W	27	0	0.099	0.26
SSR	Southern Snake Range	Normal	E	18	0	0.099	0.26
SSV	Southern Spring Valley	Normal	E	42	0	0.099	0.26
SUN	Sunshine	Normal	E	35	0	0.099	0.26
SVE	Steptoe Valley (east)	Normal	W	20	0	0.099	0.26
SVN	Snake Valley (north)	Normal	E	9	0	0.099	0.26
SVS	Snake Valley (south)	Normal	E	30	0	0.099	0.26
SVW	Steptoe Valley (west)	Normal	E	160	0.03	0.033	0.4
TCO	The Cove	Normal	E	25	0	0.099	0.26
THL	Thousand Lake	Normal	W	50	0	0.099	0.26
TIK	Tikaboo	Normal	E	9	0	0.099	0.26
TOH	Topliff Hill	Normal	W	22	0	0.162	0.26
TSV	Thousand Springs Valley	Normal	E	19	0	0.099	0.26
UTL	Utah Lakes	Normal	E	9	0	0.162	0.26
UVF	Uinkaret volcanic field	Normal	NE	19	0	0.099	0.26
WAH	Wah Mountains (south)	Normal	E	37	0	0.099	0.26
WCM	Wasatch (Clarkston Mountain)	Normal	SW	25	0.01	0.13	0.13

Code	Fault Name	Style	Dip Direction	Length (km)	Low Rate	Preferred Rate	High Rate
WCO	Wasatch (Collinston)	Normal	W	34	0.01	0.052	0.13
WDL	West Dry Lake	Normal	E	16	0	0.099	0.26
WFA	Wasatch (Fayette)	Normal	W	27	0.01	0.039	0.13
WFC	Wasatch (Malad City)	Normal	W	46	0.01	0.104	0.13
WFO	Wasatch (Foothills)	Normal	W	13	0.65	0.914	1.17
WFP	Washington (Fort Pearce)	Normal	NW	67	0.13	0.222	0.38
WHP	Wheeler Peak	Normal	W	17	0	0.099	0.26
WIW	Wildcat Wash	Normal	W	22	0	0.099	0.26
WRU	White River Valley (unnamed)	Normal	SE	31	0	0.099	0.26
WTV	Western Tecoma Valley	Normal	E	21	0	0.099	0.26
WVS	Wasatch (Virginia Street)	Normal	SW	5	0.65	0.914	1.17