Incorporating Seismic Concerns in Site Selection for Enhanced Geothermal Power Generation

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ABSTRACT

Enhanced geothermal electric generation systems (EGS) may provide significant reductions in greenhouse gas emissions, if they can be successfully sited. One potential threat to that siting is induced seismicity, which has led to EGS projects being stopped in Switzerland and Germany. We create and implement a framework for identifying regions with low risk of induced seismicity risk. Using a widely known and used model with high spatial resolution, we find that, to a first approximation, 60% of the best areas for EGS plants based on purely geological considerations meet this standard. Taking advantage of this potential requires two next steps in these regions. One is using the best available tools for local modeling of triggered seismicity, rather than the coarse national model used here. The second is creating a viable social process for securing the informed consent of local communities.

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1. INTRODUCTION

Enhanced (or engineered) geothermal systems (EGS), also known as hot dry rock (HDR) or hot fractured rock (HFR) systems, are geothermal reservoirs artificially created through hydraulic fracturing of hot (temperature, T well above 100°C), relatively impermeable (permeability, $\mu < 10^{-16}$ m^2) dry rock masses (granite is a representative material), generally at depth > 3 km. Water is circulated through fractures made in the HDR, thence to the surface, and used to create steam that is piped to a turbine to generate electric power.

Only a portion of the geothermal heat in place can be successfully recovered and converted into electricity. A number of factors determine recovery potential, including initial rock temperature, temperature of the underground heat source and its thermal capacity, stimulated rock volume, effective heat-exchange area, and flow rate of the water through the connected fractures(1). Hydrothermal systems typically recover about 40% of the available heat(1). Given the technical hurdles of EGS, Tester *et al.*(1) used both 2% and 20% recovery factors to calculate recoverable reserves. With a 2% recovery factor, EGS reserves are estimated at 2,800 times 2005 US total energy consumption. Tester *et al.*(1) estimate that installed EGS capacity in the US could reach 100GW by 2050 if the R&D investments needed to improve the recovery fraction are made soon. By comparison, total current US installed electric generating capacity is 1000 GW.

EGS-related greenhouse gas (GHG) emissions are estimated as 50-100 g/kWh(2), much less than the life-cycle GHG emissions from pulverized coal and combined-cycle natural gas, estimated at 850-875 g/kWh and 420-450 g/kWh, respectively(3), and similar to those from other renewable sources, as well as nuclear and hydroelectric power. Moreover, EGS has the potential to provide baseload (i.e., non-variable) power. As a result, EGS could become a significant source of low-pollution electric power.

Research in the 1980s and 1990s identified EGS potential in general terms, but without detailed geological analysis. Using published data from well logs and well-site geology maps, Tester *et al.*[1] computed the stored thermal energy on national and state levels, at depths from 3 to 10 km. They used *Geothermal Map of North America*[4] as a primary data set, refining it with thermal gradient exploration data collected from 4,000 wells by the geothermal industry during the 1970s and 1980s, along with 20,000 well bottom-hole temperature measurements conducted for hydrocarbon exploration[1]. The well-based datasets were merged using a minimum curvature algorithm to construct heat flow contours. Tester and colleagues computed the temperature at depth from heat flow, thermal conductivity, layer thickness, and the radioactive depth variable constant.

Although EGS seems attractive as a renewable, non-intermittent, abundant energy source, it has drawbacks. One is cost. The levelized cost of electricity for EGS is estimated at 8 - 19 cents per kilowatt-hour (kWh)[5], higher than US wholesale electricity prices of 5-6 cents/kWh, although the low end of the cost range is comparable to the cost of other low-carbon baseload power sources. A second potential drawback is that EGS water can entrain potentially hazardous contaminants that require treatment[1]. A third potential impediment to large-scale deployment of EGS, and the focus of our analysis, is its potential for induced seismicity [1][6][7][8][9][10]. EGS-triggered tremors caused enough public opposition in Basel, Switzerland (after a magnitude 3.4 tremor) and Landau, Germany (magnitude 2.7) for plants to be shut down. A 3.8 magnitude earthquake occurred in Cooper Basin, Australia, near the GeoDynamics EGS plant[11], but had little effect, presumably because of the site's remote location. Thus, the problem posed by induced seismicity depends both on the magnitude of the event and the attention it draws.

Induced and triggered seismicity is not unique to EGS. Mining (e.g., Kalgoorli-Boulder, Australia), water reservoir impoundment (Koyna, India), oil and gas production (Gazli, Uzbekistan), waste disposal activities (Rocky Mountain Arsenal, USA), and fluid injection (Ashtabula and Youngstown, USA) have all triggered small earthquakes[(8)(11)(12)].

The mechanisms that can induce an EGS earthquake include pore pressure increase, temperature decrease, volume changes due to fluid withdrawal and injection, and chemical alteration of fracture surfaces. Several models have been developed to predict induced earthquake risk[(10)(13)(14)(15)]. For the Basel earthquake, Deichmann and Giardini[(16)] analyzed structural mechanisms, while Deichmann and Ernst[(17)] considered stress dynamics based on seismological data recorded by a six-station borehole network near the operation site. Baisch *et al.*[(18)] estimated that an event as large as 4.5 magnitude was possible had the EGS site continued operating. Bommer *et al.* [(19)] examined the relationship between fluid injection and seismicity in the 2003 event in Soultz-sous-Forets, France and Berlin, El Salvador, as well as the mitigation potential of several hazard control measures.

Although unlikely to cause casualties, earthquakes in the observed range can produce economic loss from building damage and business interruption. Although induced seismicity has yet to engender any tort liability cases, such suits might arise based on a number of legal theories, including trespass, strict liability, negligence and nuisance[(20)]. Of course, political opposition can stop development, even without a formal basis in law, as in Germany and Switzerland. These prospects could increase the cost of capital for proposed EGS projects, by adding uncertainty regarding when they will be completed (if ever) and what developers' liability exposure will be.

Here, we investigate three questions central to managing these threats to the viability of EGS: (a) Can the risk of triggered seismicity be lessened by locating EGS projects away from population centers? (b) How much of the potential recoverable resource of EGS is lost with such remote siting? (c) How can the industry's external stakeholders (the public, politicians, local economic interests) be engaged so as to ensure a fair evaluation of EGS?

Section 2 develops a general modeling framework for estimating the risks and benefit of EGS developments. Section 3 applies that framework, first nationally and then to identify areas of high value and low risk. Section 4 proposes policies for ensuring fair public assessment of EGS, informed by these analyses. In this initial scoping analysis, we use a modeling tool, HAZUS, that provides roughly comparable estimates across the US – and is widely familiar to planners, some of whom are required to use it. Regions with high EGS potential and low seismic risk merit detailed analysis with more sophisticated models taking full advantage of scientific knowledge regarding local conditions. We demonstrate the next level of analysis for such regions.

2. MODEL DEVELOPMENT

We define areas as having high EGS potential if they have regions with mean temperature ≥ 300 °C at 7.5 km (as predicted by Tester *et al.*[(1)]), a depth that may become feasible with technology potentially available in the near future (Figure 1). After examining this potential in the US as a whole, we present a case study of one region with temperatures in the range 250-300 °C at 7.5 km. Generally speaking, the resource increases with depth due to the geothermal gradient and has roughly similar shapes at various depths. The relatively few locations with high temperature in shallower depths typically resemble deeper locations in other geological features relevant to EGS development (e.g. porosity, permeability, geochemistry).

In these regions, we estimated potential EGS-triggered earthquake damage with a widely used resource HAZUS-MH4(22), which simulate the effects of earthquakes, floods, and hurricanes on property and people, using data from the 2000 Census (for building structures, infrastructure, and population) and Dun & Bradstreet (for commercial businesses). We used two HAZUS metrics: (a) direct economic loss (DEL), equal to replacement plus repair costs, and (b) number of casualties/injuries.

We chose HAZUS because of its broad familiarity to government offices (e.g., emergency management, GIS/mining/geology, transportation, homeland security), private sector support firms, and academic researchers. Although HAZUS is widely known and used, it also has some significant limitations [(23)]. Some of those limits arise from its use of national databases for population demographics and the properties of building stocks and infrastructure. As a result, FEMA treats HAZUS results as acceptable for aggregate estimates of economic losses and number of casualties, using nationally comparable data, but not for smaller-scale analyses. Other limits include its insensitivity to how earthquake wave propagation properties vary with local geology. As a result, HAZUS produces imperfect results in small areas close to faults and overestimates the effects of smaller earthquakes (<M6.0) in areas with substantial infrastructure.

Recognizing these (and other) limits, FEMA views HAZUS as a work in progress, which needs updating with loss data from actual earthquakes. Given these limitations, our goal is to understand the regional variation in earthquake damage, using data that are better for large-area comparisons than local analyses. As a result, our individual simulations should not be interpreted literally, but as illustrations of how the location of epicenters produces geographic heterogeneity in expected damages. After taking advantage of HAZUS's national scope, we consider how our conclusions might change with more precise local models – and how those models might be deployed to refine our conclusions.

HAZUS computes seismic ground motion using the following user-specified parameters to characterize local conditions affecting ground shaking and seismic events: local soil conditions (see section 2.1 below), earthquake magnitude (2.2.1), attenuation function and fault type (2.2.2), and fault orientation and dip angle (2.2.3).

2.1 Local conditions determining ground shaking

Local soil conditions affect the ground shaking caused by seismic waves. In the absence of a user-supplied soil map, HAZUS uses the default soil type "stiff soil," which has been found to produce generally accurate results at a regional scale [(23)]. We adopt this default in our analyses.

2. 2. Earthquake Parameters

2.2.1. Earthquake Magnitude

The smallest earthquake that HAZUS can simulate is magnitude 5. EGS-triggered earthquakes have historically been less than magnitude 4. In order to assess the feasibility of extrapolating from the higher values in HAZUS to the lower ones relevant to EGS, we examined the pattern of damages predicted for simulated earthquakes of magnitudes 5.0, 5.3, 5.6, and 5.9. For each magnitude, we simulated nine earthquakes spaced with 1.5 km longitude separation at latitude 44.08 N near a planned EGS site south of Bend, Oregon. Direct economic loss (DEL) varies due to the heterogeneous distribution of towns, roads, and other infrastructure along the test latitude. Figure 2 shows log-linear trendlines bracketing these DEL estimates as well as reported DELs for historical earthquakes triggered by human activities[(24)]. These reported DEL show a log-linear relationship with the corresponding magnitudes similar to that in the HAZUS simulations. Figure 3 compares actual DELs from US triggered events with those estimated by HAZUS for the same events, revealing a modest tendency for HAZUS to overestimate DEL, consistent with one of its known limits.

Because DEL shows a log-linear trend from 5.0 to 5.9 magnitude, we cautiously assume that the same trend holds with smaller EGS-triggered seismic events. We do not suggest that the interpolation is valid below magnitudes less than 3, where there is little or no damage – although there is potential for annoying residents, as with the series of magnitude 2.7 events in NW Ohio that led to suspension of fluid injections in late 2011. All the analyses that follow assume earthquakes of 5.0 magnitude. As a result, they systematically overestimate damages for the smaller earthquakes expected from EGS, to a degree that can be estimated from Figure 2.

2.2.2. Attenuation Function and the Fault Type

Attenuation functions describe how an earthquake's intensity decreases with distance from its hypocenter, the point where the earthquake starts. (The epicenter is the surface point directly above the hypocenter.) We use HAZUS's attenuation functions for the Western United States (WUS), where the dominant fault is extensional and the hypocenter is in shallow crust (<50km).

HAZUS offers predictions for normal and strike-slip fault types. Figure 4 shows DEL estimates for the two fault types, using earthquakes simulated along a horizontal 100-km line (constant latitude of 44.055 N) near Bend, Oregon. These estimates are essentially identical. In the analyses that follow, we use the HAZUS default of a "strike-slip" fault, representing the predominant extensional stresses in the WUS.

2. 2. 3. Epicenter and Fault Parameters

A fault's orientation is the line representing the intersection between the fault plane and the horizontal. Its dip angle is that between the fault plane and the horizontal. Tables I and II shows the sensitivity of HAZUS estimates to variation in fault orientation and dip angle, using a range of plausible values for El Centro, California, an urban area with large EGS potential. The tables show that DEL and injury estimates are relatively insensitive to variations in these parameters. Thus, we chose the HAZUS default values of 0° and 90°, for fault orientation and dip angle, respectively.

2. 3. Defining an Array of Hypothetical Epicenters

In order to determine the required spatial resolution for our site-specific simulations, we varied the separation of simulated earthquakes along a 90-mile line transecting the 300 °C EGS region near El Centro, California. As seen in Figure 5, the 9-mile separation missed much of the local maximum near -115.5° longitude, as revealed in the 0.09 mi separation. Given that the 0.9 mi and 0.09 mi separations produce similar results, the former represents a reasonable compromise between precision and computational cost. With this separation, approximately 21,000 simulated earthquakes are needed to cover the four high EGS regions (300 °C).

3. MODEL APPLICATION

Figure 6 shows simulated economic damages from earthquakes in the four EGS regions with excellent geothermal resource (300 °C). There is great geographic variation in these estimates, reflecting differences in population and infrastructure and indicating opportunities to reduce damage by appropriate site selection.

AltaRock, a US EGS development company, is preparing to drill approximately 20 miles south of Bend, Oregon[25]. The project site (near the Newberry Crater National Monument) has the benefit of being close to transmission lines and the drawback of being in a moderately settled area (indicated by the population circles in Figure 7). DEL estimates vary widely by location, as one would expect from the variation in population (Figure 7). Earthquakes at the proposed

AltaRock site (indicated by the arrow) would produce some of the greatest damages relative to other locations in the region. Sites further south along the same transmission line have much less expected DEL.

In order to make an initial estimate of the fraction of EGS areas with good resource potential and low DEL, we simulated earthquakes in the four high US EGS areas discussed previously. We also simulated 26,000 earthquakes in the Central Oregon area with moderate EGS potential (250-300°C). Both used 0.9 mi epicenter separation. Figure 8 shows cumulative distribution functions (CDFs) for DEL in these two regions. Both CDF curves rise rapidly and have a flat tail, indicating that most EGS sites have very low DEL, while a small fraction of sites have DEL above $20M. Roughly 60% of the resource base lies in regions with DEL less than $1M.

These analyses assume that each simulated earthquake is equally likely. Figure 9 shows the result of asking whether the sites in the less populated areas further south of Bend would be as attractive if the probability of earthquakes there were higher. Specifically, it varies earthquake probability along a line following the Oregon transmission line, with the lowest values (20%) near Bend and the highest (80%) in the rural areas at the southern end of the EGS area. The horizontal axis shows the simulated epicenter numbers where 1 lies at the more heavily populated northwestern end of the transmission line and 110 at the more rural southeastern end.

Figure 10 examines sensitivity to earthquake probability using historical values, rather than worst-case assumptions (as in Figure 9). It uses the high EGS region in Southern California. Southern California is disadvantaged for EGS as a result of lacking of abundant water and being a seismically active region. Nonetheless, we explored the effects of small earthquakes because the region has good statistics for historical seismic activity. The annual Poisson probability for an earthquake at a location was estimated as:

$$P\ (x;\ \mu) = \frac{e^{-\mu}\mu^{x}}{x!}$$

Where P is the probability of x earthquakes (1 here) given μ earthquakes in the past.

Probabilities were derived from historical earthquake data between 1906 and 2000[26] and multiplied by the DEL for each location to compute expected property loss. There are many sites in this area where expected DEL is low, given historical seismic activity (Figure 10). As might be expected, these are areas with low population and infrastructure density. Thus, the risk of triggered seismicity can be reduced by appropriate selection of EGS sites. Of course, assuming uniform seismic potential, seismic risk must be lower in places with fewer people and less property. The analysis approximates the magnitude of these differences given the HAZUS estimates for these inputs.

4. DISCUSSION

In Europe, public reaction to triggered seismic activity has adversely affected EGS development. Similar reactions may occur elsewhere, unless two steps are taken. The first is to recognize that the risk of triggered seismicity can be reduced by strategic location of EGS sites. The present first-order analyses find that most of the US EGS resource lies in areas with low seismic risk, whether one uses worst-case estimates of earthquake probabilities (Figure 9) or assumes historic seismic activity (Figure 10). Moreover, that is true even with estimates for magnitude 5.0 earthquakes, larger than those expected with EGS. Figure 2 suggests how to extrapolate our estimates to those lower values. Central Oregon and Southern California both provide large areas with moderate to high EGS potential near existing transmission lines that provide access to the grid but have low potential for induced seismic events that might cause public concern. Of course, economic viability depends on other factors as well, such as whether the fractures in the hot rock are oriented roughly horizontally, allowing the water to be recovered and circulated; whether there are flowing aquifers that can carry heat away from the circulating pipes, hence require expensive insulation; and whether the fractures in the hot rock can be maintained when the volume of water circulating through them varies.

The second essential step for realizing the potential for low-risk EGS power is involving the public actively in the siting process. Long experience with other siting processes[(27)] has found that such involvement can increase the chance that the public will perceive risks accurately and respond to sensible policies (e.g., accept generously offered compensation to readily acknowledged damages). Such involvement requires a modest monetary investment in creating communication channels and clear, relevant messages[(28)]. Mostly, though, it requires leadership, recognizing that a technology's license to operate depends on public acceptance, which can be lost if either the technology or its operators lose public trust[(29)] .

The economic stakes riding on public acceptance include the risk of having an EGS plant shut down or never licensed, thereby losing the investment in it. Thus, the financial risk of a development includes not just having to provide compensation for direct economic losses (DEL) from triggered events, but also losing the capital invested in a project (less its salvage value) and expected future profit (Π) from it. In symbolic terms:

$$\text{Risk} = P(\text{Triggered Event})*\text{DEL}*(1- P(\text{Public Rejection}))+P(\text{Public Rejection})*(\text{Net CapEx}+ \Pi)$$

The first term corresponds to cases where the project goes forward, but a triggered seismic event occurs, causing direct economic losses. The second corresponds to cases where the project is stopped, causing a loss of the capital expense and expected future profit. Both probabilities should be lower if the site is remote from built-up areas. The second should be lower if the public has confidence in the technology and those managing it.

As noted, our analysis produced rough estimates of these values, using the HAZUS model to determine the broad outlines of such a siting policy. Within the regions identified as plausible areas for EGS development, actual siting decisions should be guided by economic and social models that incorporate local information and seismic models sensitive to local geological heterogeneity.

Majer and colleagues[(30)] have proposed a protocol for geothermal developers addressing induced seismicity, within the framework of International Energy Agency-Geothermal Implementing Agreement (2009):

1. Review laws and regulations
2. Assess natural seismic hazard potential
3. Assess triggered seismicity potential
4. Establish a dialogue with the regional authority
5. Educate stakeholders
6. Establish microseismic monitoring network
7. Interact with stakeholders
8. Implement procedure for evaluating damage.

This protocol, like ones proposed by Hunt and Morelli[(31)] and Morelli[(32)]), explicitly recognizes microseismicity, a factor ignored by the Geopower development in Basel[2]. However, it engages stakeholders very late in the process and treats them as the target of one-way communications "educating" them about the operator's view of the project. Such processes are likely to generate suspicion and opposition, rather than reduce them.

In June 2010, AltaRock Energy announced that it will address induced microseismicity[(33)], as part of a community outreach program, following the Majer *et al.* [(30)] protocol. It should be straightforward to make two-way engagement with the broader public (and not just officials) a part of that process and all other ones, once viable sites have been identified with reasonable confidence (so as not engage the public regarding projects that are unlikely to proceed). Such two-way communication processes have been crucial to public acceptance of other energy projects[(34)(35)]. They are, naturally, more likely to succeed with EGS sites whose seismic risk is low.

EGS could contribute to a low-carbon energy portfolio. However, demonstration sites in Europe have shown the economic risks of choosing sites that expose the public to triggered seismicity and failing to engage it effectively. Our initial investigation, based on an admittedly crude (but widely used) tool developed by the Federal Emergency Management Agency, has found that a large fraction of the EGS resource base in the US lies in areas where triggered seismicity risks are minimal. As more mature tools become available, they can be used with the analytical framework developed here. The principle of involving stakeholders early in the site selection process is likely to be insensitive to the details of the tool used, and has been successfully used in other energy siting decisions. Restricting site selection to those areas should greatly reduce the risk of public rejection, especially when coupled with the active outreach needed to secure trust of the technology and its operators. Taking these steps will increase the chances of EGS making its contribution to a clean energy future.

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TABLES

Table I. Relative DEL (in $ million) as a function of fault orientation and dip angle, with simulated earthquakes, at an epicenter near El Centro, CA (latitude 32.8N, longitude -115.57).

Orientation/ Dip angle (deg)	90	60	30	0	-30	-60	-90
0	57.8	60.1	61.4	65.7	59.1	58.4	57.8
23	57.5	60.6	63.6	71.4	58.3	58.0	57.5
45	57.2	60.5	64.2	74.4	58.8	58.3	57.2
68	57.1	59.9	63.1	71.9	60.6	59.0	57.1
90	57.2	59.6	62.1	68.3	61.2	59.4	57.2
113	57.5	59.9	62.4	68.8	59.6	59.0	57.5
135	57.9	60.1	61.8	66.5	59.1	58.8	57.9
158	58.0	59.9	60.7	63.9	59.4	58.7	58.0

Table II. Number of injuries as a function of fault orientation and dip angle, with simulated earthquakes, at an epicenter near El Centro, CA (latitude of 32.8, longitude of -115.57).

Orientation/ Dip angle (deg)	90	60	30	0	-30	-60	-90
0	11	12	12	13	12	12	11
23	11	12	13	15	12	12	11
45	11	12	13	15	12	12	11
68	11	12	13	14	12	12	11
90	11	12	12	13	12	12	11
113	11	12	12	13	12	12	11
135	11	12	12	13	12	12	11
158	11	12	12	13	12	12	11

FIGURES

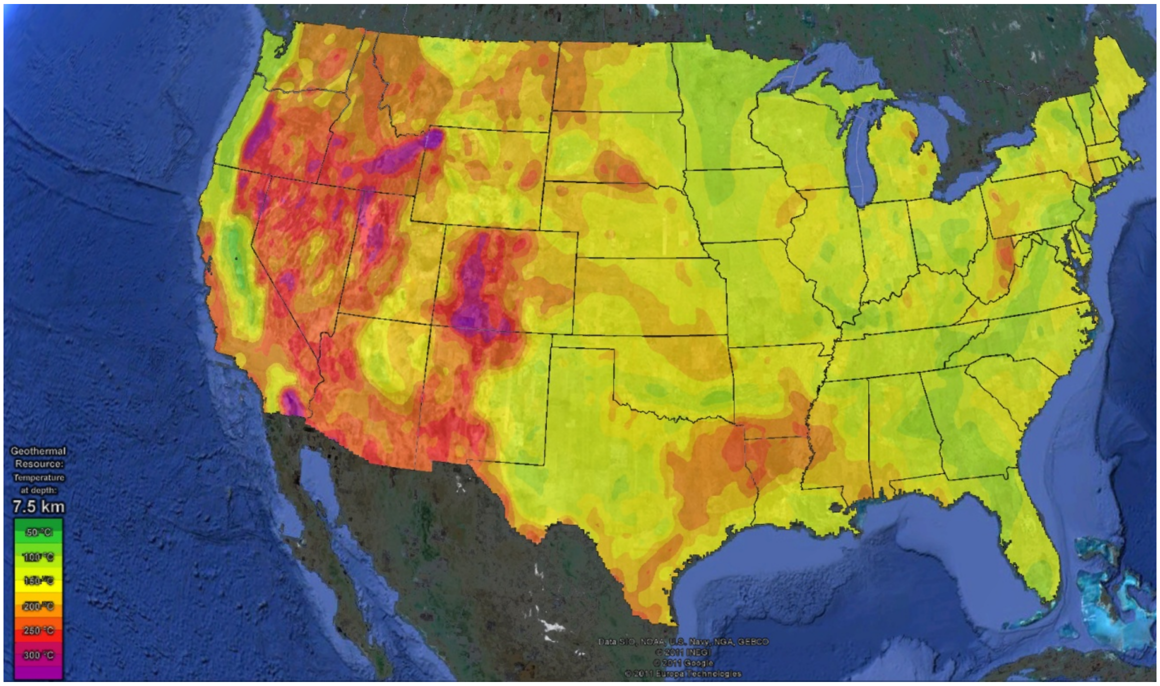

Figure 1. Average temperature at 7.5 km depth in the US, based on Tester *et al.* [1]. The geothermal resource data file is from Google.org EGS[21].

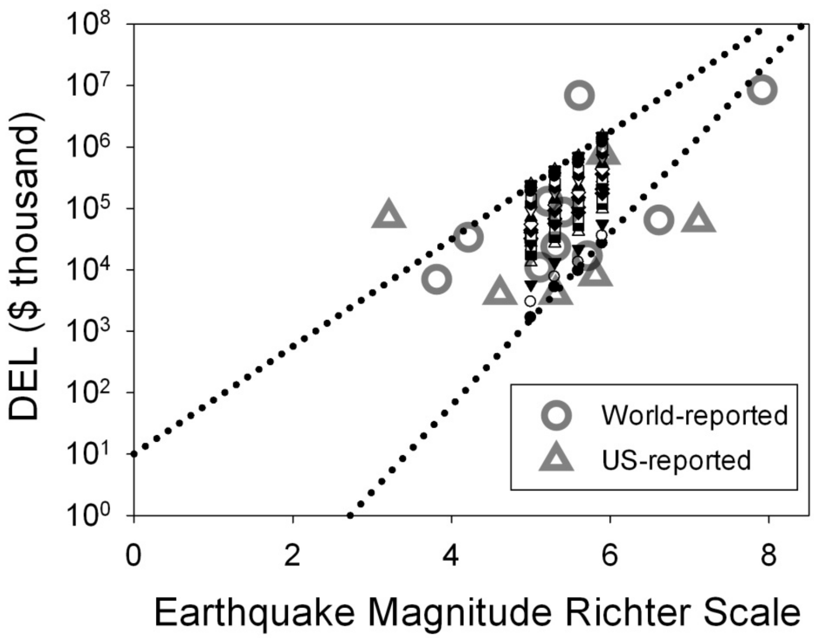

Figure 2. Relative Direct economic loss (DEL) estimates as a function of earthquake magnitude. Each symbol represents a simulated earthquake along latitude 44.083 N between longitudes -121.937 and -121.281. The dotted lines connect the extreme values as simulated by HAZUS. Triangles represent US-reported DEL's and circles represent events in other countries. Historical DEL values are from Klose[(24)].

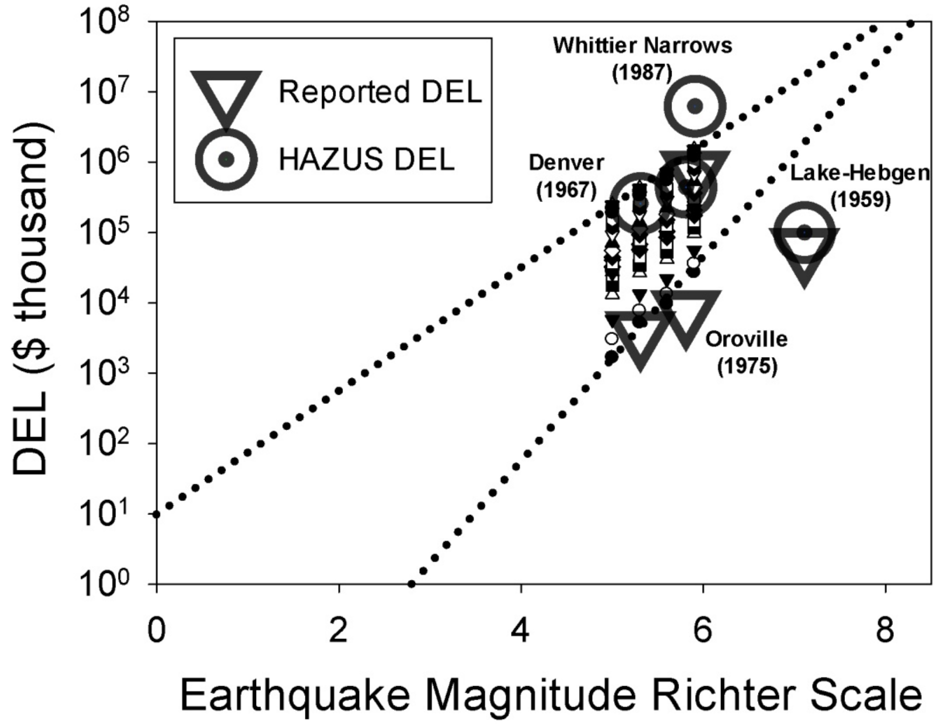

FIGURE 3. Relative Direct economic loss (DEL) estimates as a function of earthquake magnitude. Each symbol represents a simulated earthquake along latitude 44.083 N between longitudes -121.937 and -121.281. The dotted lines connect the extreme values as simulated by HAZUS. Reverse triangles represent reported DEL values for historical triggered events and dotted circles represent the corresponding HAZUS relative DEL values. Historical DEL values are from Klose[24].

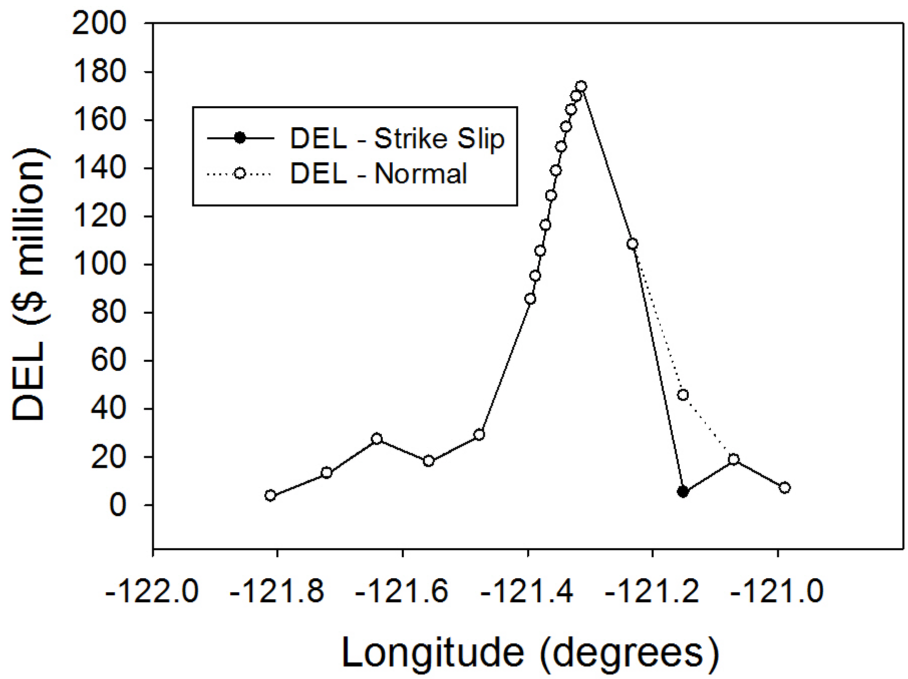

Figure 4. Relative DEL sensitivity for two fault types, with simulated earthquakes at latitude 44.055.

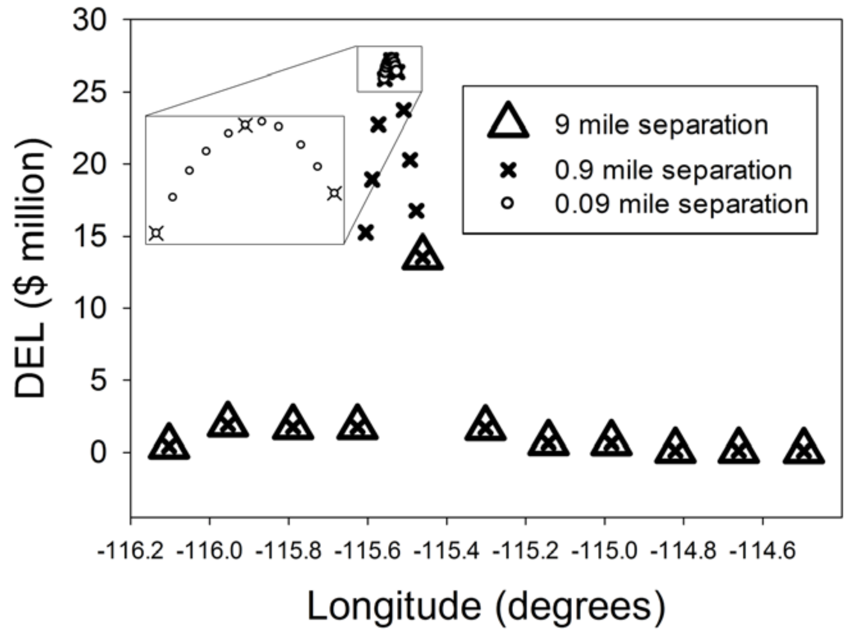

Figure 5. Relative DEL ($ million) for simulated earthquakes with different separations along latitude 32.98N.

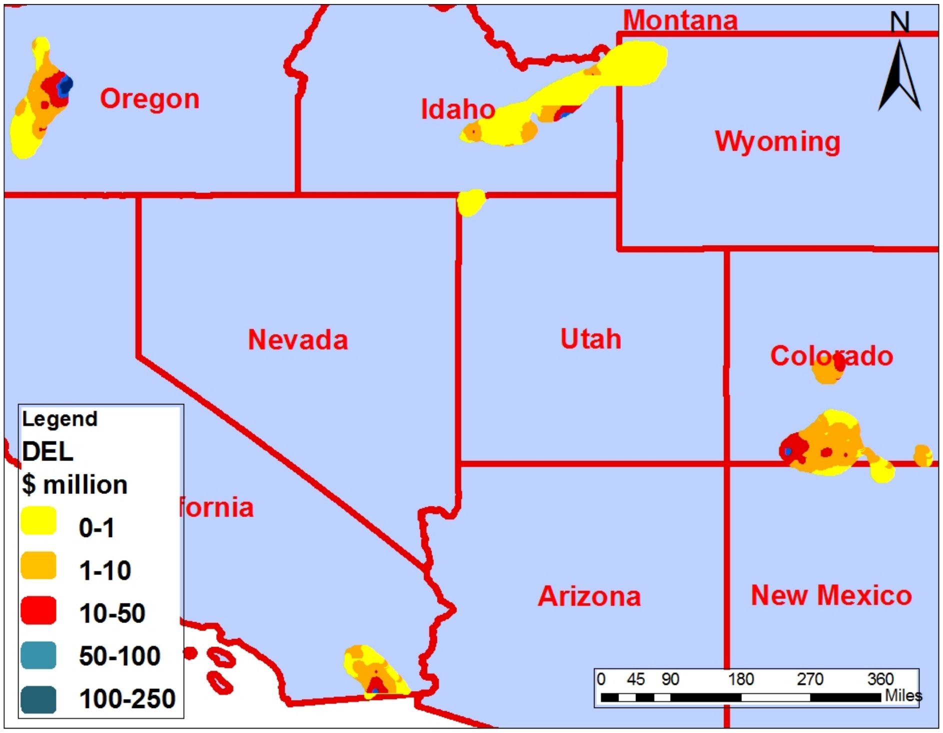

Figure 6. Relative DEL for the four US regions with high EGS potential (300°C).

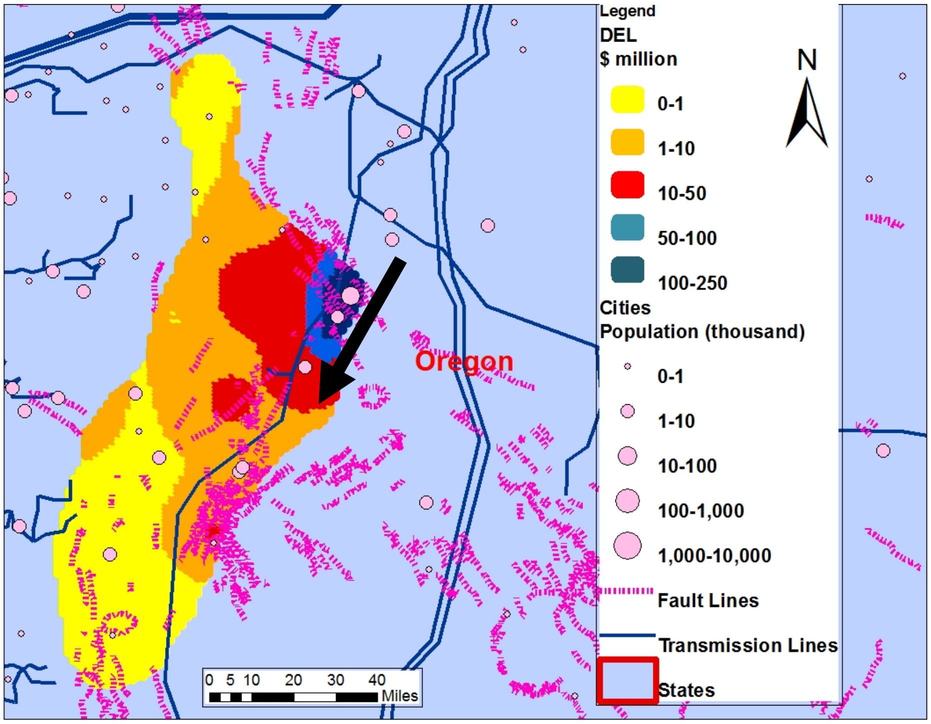

Figure 7. Estimated relative DEL Map for earthquakes associated with sites in the >300 ^{o}C EGS area of Central Oregon. The arrow indicates AltaRock's proposed EGS site. Blue lines indicate transmission lines. Pink hash marks show known geologic faults.

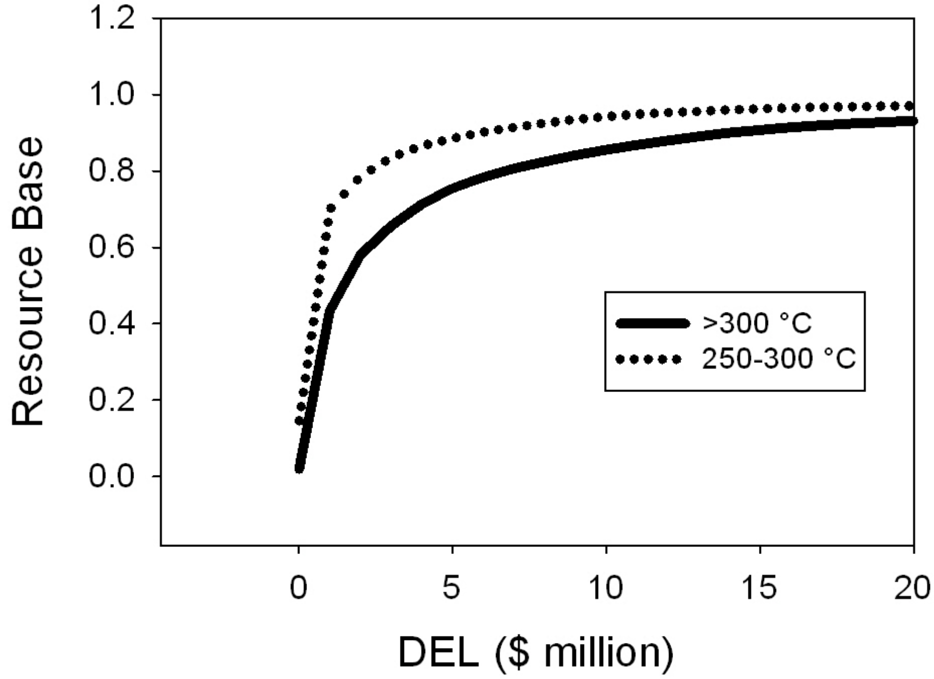

Figure 8. Cumulative distribution functions for relative DEL associated with simulated earthquakes in the moderate EGS potential (250-300°C) areas in Oregon (dotted line) and the high EGS potential (>300°C) areas in the US.

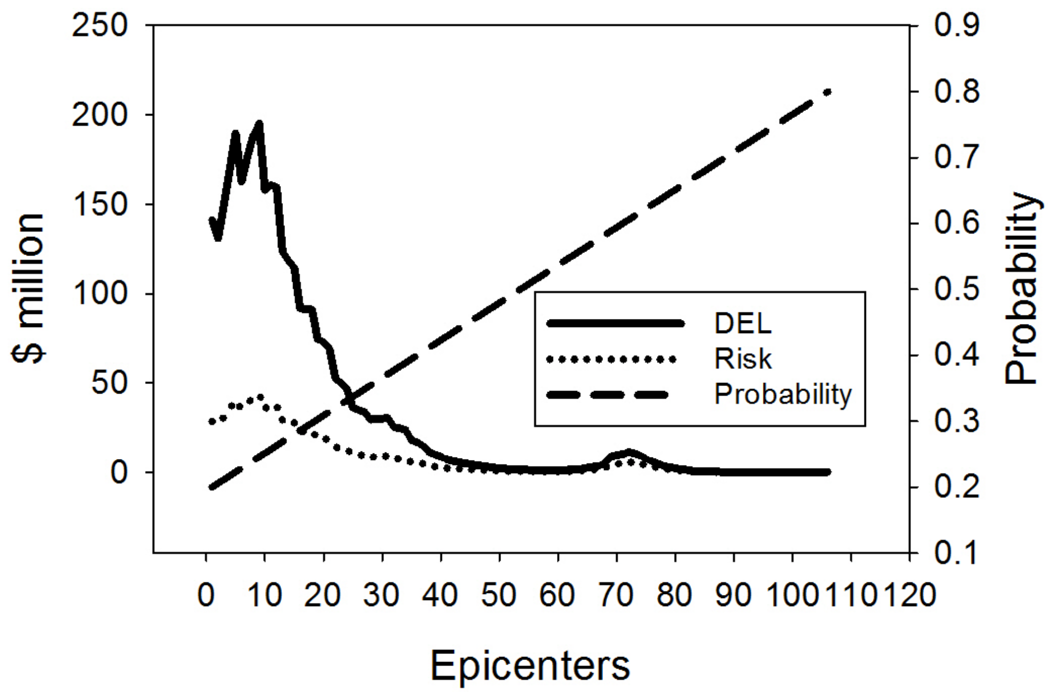

Figure 9. Illustration of geographic risk sensitivity to relative DEL (left scale) and probability (right scale). The relative DEL curve shows the HAZUS-simulated relative damages corresponding to the epicenters appearing on the horizontal axis. Probabilities were set to increase linearly from 0.20 to 0.80. The relative risk curve is the product of relative DEL and the probability for each epicenter.

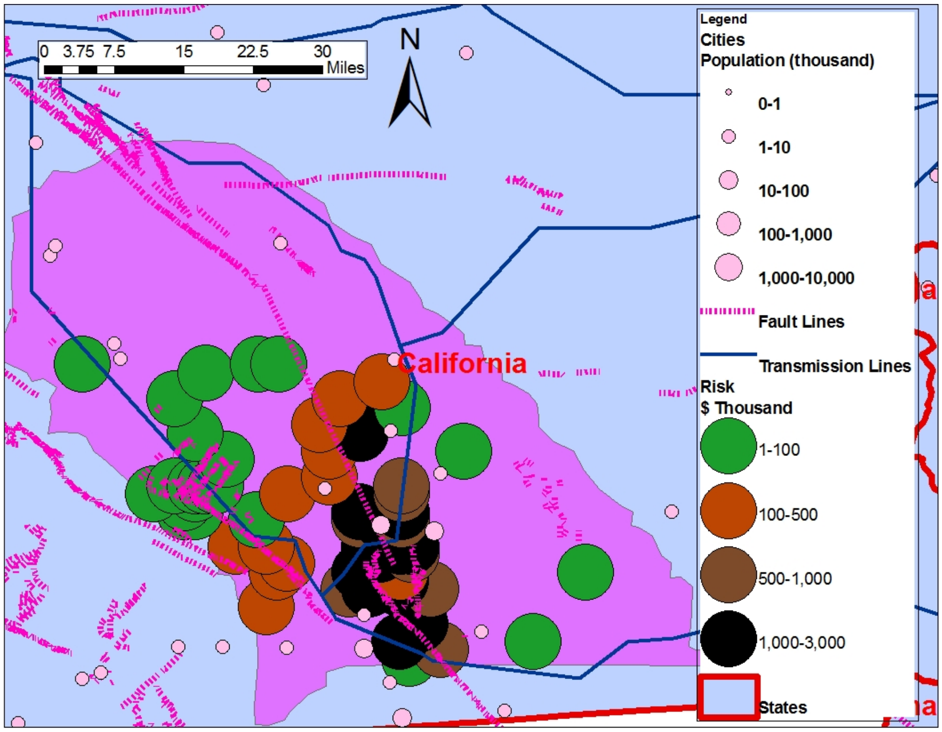

Figure 10. Relative risk Map for the area near El Centro, California, where the risk is computed by multiplying the calculated relative DEL by the historical probability of an earthquake.

FOOTNOTES

1. The heat flow data can be accessed at the Southern Methodist University (SMU) [(36)] Western Geothermal database (includes the USGS Great Basin database [(37)] :the SMU-compiled U.S. Regional Heat Flow database (Southern Methodist University); and the American Association of Petroleum Geologists (AAPG) bottom-hole temperature database [(38)].
2. An after-the-fact report by an independent entity, Serianex [(18)], found that the EGS site in the city of Basel, Switzerland sits on a fault system, where it could cause an earthquake as large as 4.5 magnitude and economic losses exceeding $600 million. Even though Geopower Basel paid only $9 million in insurance claims after the 3.4 earthquake in 2006, it had to abandon the project, presumably suffering much greater indirect losses.