Development of a 3D hydrogeological and geomechanical model of an Enhanced Geothermal System using microseismic and ground deformation data from a 1-year injection program

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ABSTRACT

In this study, integrated coupled process modeling and field observations are used to build a three-dimensional hydrogeological and geomechanical model of an enhanced geothermal system (EGS) at the northwestern part of The Geysers geothermal field, California. We constructed a model and characterized hydraulic and mechanical properties of relevant geological layers and a system of multiple intersecting shear zones. The characterization was conducted through detailed coupled modeling of a 1 year stimulation injection with simultaneous field monitoring of reservoir pressure, microseismic activity, and ground surface deformations. The structural reservoir properties were characterized through a dynamic analysis of the microseismic activity recorded during the injection. The analysis of ground surface deformations were found to be particularly challenging as the subtle ground surface deformations caused by the injection at >3 km depth are intermingled with deformations caused by both tectonic deformations and seasonal ground surface effects associated with rainfall. However, through a detailed analysis of the field data we isolated local surface deformations associated with injection. Using the coupled fluid flow and geomechanical analysis of reservoir pressure responses in a number of monitoring wells and microseismic activity around the injection well, we back -calculated the hydraulic and mechanical properties of relevant rock mass layers and shear zones. Finally, we discuss the causes of induced microseismicity and the influence of pre-existing tectonic structures on the EGS development.

1. INTRODUCTION

An Enhanced Geothermal System (EGS) is a technology for extracting geothermal energy under circumstances and locations where conventional production is not economic (Tester et al., 2006). Generally, EGS would be applied for extracting geothermal energy at sites where the reservoir rock is hot (has sufficient heat content) but has insufficient permeability for economic production. If an EGS could be created and successfully managed, then large untapped geothermal resources could be utilized. The current strategy is to increase permeability by reactivating shearing fractures through water injection at a relatively low rate and a bottom-hole pressure less than the estimated minimum principal compressive stress at injection depth. The aim is to avoid the propagation of a single hydraulic fracture set and to create a more pervasive stimulation zone by diluting a network of pre-existing fractures though shear reactivation (Tester et al., 2006). This process is frequently accompanied with a strong increase in microseismic activity, and characterizing mechanisms of inducing microseismicity can increase knowledge about their role in enhancing permeability.

The scientific challenges of EGS are to investigate injection strategies, their effects upon EGS development and to predict the extent of the stimulation zone. To address such challenges it is desirable to develop reliable hydrogeological and geomechanical models to assist in designing and optimizing the exploitation of the EGS. Such models require reliable input data in the form of large scale hydrogeological and geomechanical properties and relevant field monitoring data for validation and confirmation. In this context, large scale hydrogeological and geomechanical field data can be acquired from monitoring of reservoir pressure, microseismicity and surface deformations.

In this paper, we present results obtained during the Northwest Geysers EGS Demonstration project (Garcia et al., 2012; Rutqvist et al., 2013), where microseismicity (Boyle and Zoback, 2013) and surface deformations acquired by TerraSAR-X satellites (Vasco et al., 2013) were monitored before and during the injection. In this area, deformations can be related to (1) tectonic forces associated with the motion between the North American and Pacific plates (McLaughlin, 1981; Oppenheimer, 1986; Stark, 2003), (2) to cyclical trends related to seasonal effects, and (3) to a long term trend linked to reservoir exploitation since 1960.

The main goal of this work is to understand the development of the EGS. We used a coupled analysis of the microseismicity and the surface deformations to clearly identify (1) the injection-induced deformation and stress changes, (2) the significance of vertical permeable structures, and (3) to build a reliable 3D hydrogeological and geomechanical model of the EGS to help its design and development.

2. GEOLOGICAL SETTING

The Geysers geothermal field is the largest geothermal electricity generating operation in the world. It is a vapor-dominated geothermal reservoir. Two significant, inactive right lateral strike-slip faults, the Mercuryville and Collayomi fault zones, (Fig.1a) that parallel the San Andreas fault system (located ~40 km to the West), form the southwest and northeast boundaries of the hydrothermal system (McLaughlin, 1981; Hulen and Norton, 2000). This hydrothermal system was formed following the intrusion of a composite granitic pluton about 1.1 Ma.
The Northwest Geysers EGS Demonstration Project is located in the Northwest Geysers area where a high temperature zone (HTZ) up to 400°C has been identified extending downward from 2.6 km below the surface. The HTZ underlies a normal temperature reservoir (NTR) between 1.6 and 2.6 km below the surface, where temperatures are ~240°C (Garcia et al., 2012). The rocks are composed of graywacke in the NTR and of contact metamorphosed biotite hornfelsic metagraywacke ("hornfels") in the HTZ. These two geothermal reservoirs are bounded above by very low permeability formations ("graywacke caprock") and below by granitic intrusions ("felsite") encountered at a depth of approximately 4.0 km. Lockner et al. (1982) suggested that fracturing has weakened the rock to such an extent that only a frictional sliding load can be supported by the rock, and shear stress in the region is probably near the rock-mass frictional strengths. Therefore very small perturbations of the stress field could induce microseismicity. Here, we use the term, “shear zone” as a generalized term to include short, discontinuous faults, transtensional faults and shear zones, and Reidel shears.

Two previously abandoned exploratory wells Prati 32 (P32) and Prati State (PS31) were re-opened and deepened as an injection/production pair for the EGS Demonstration Project (Garcia et al., 2012). One of the re-opened wells (P32) was deepened to penetrate a thick portion of the HTZ, and was dedicated as an injection well. Three other wells: P31, P38 and P25 were used to monitor fluid pressure variations inside the reservoir during the initial injection in P32 (Fig.1b), which began on 10/06/11. Injection began with a high initial rate of 1200 gpm (gallons per minute) during the first 24 hours to collapse the steam bubble in the well bore and surrounding rock. Thereafter, the injection rate was maintained at 400, 1000, 700 and 400 gpm steps during 55, 100, 105 and 35 days respectively (Fig.2a), with negative wellhead pressure (about -13 psig) during each of these steps.

![Figure 1: Geological setting with: (a) the location of the studied area (white star) in the San Andreas fault zone system, (b) the structural map of the Enhanced Geothermal System area with the well locations P25, PS31, P32 and P38.](image)

3. MICROSEISMICITY ANALYSIS

The microseismicity is recorded by a dedicated seismic array deployed at The Geysers. The seismic array consists of 31 three-component short-period stations with a sampling frequency of 500 Hz (Majer and Peterson, 2007). In addition, 15 temporary stations have been located around the EGS demonstration area. Microseismicity events are located using methods derived from conventional earthquake seismology. The events were located with SimulPS using a minimum of 22 picks, P or S. Events had a maximum RMS travel-time residual of 0.1s, and had horizontal and vertical errors between 200 m and 600 m (Boyle and Zoback, 2013). Microseismicity data presented in this paper were recorded from September 1, 2011 to August 10, 2012, i.e., almost 1 year of monitoring. After 270 days of injection, the microseismicity data show a period of three weeks when deepening of the hypocenters below 5 km (blue area in Fig. 2b) took place. This phenomenon occurs over the entire Northwest Geysers area (~ 90 km²). We have mainly focused our study on an area of about 2 km² around the injection wells. In this area, before injection began in P32, no microseismicity activity was detected (from September 1, 2011 to October 6, 2011), whereas after the start of the injection, 2919 microseismic events were recorded. The detected event magnitudes for the study area range between 0.4 and 3, but only 41 microseismic events have a magnitude higher than 2 (Fig.2).

![Figure 2: (a) Evolution of the injection rate in P32, (b) microseismicity evolution: depth versus time (Days after start date of injection-stimulation at P32). The blue strip represents the period of three weeks when deepening of the hypocenters below 5 km occurred.](image)
3.1 Microseismicity evolution

The study area has been horizontally divided into 900 cells of $2.3 \times 10^3$ km$^2$. In each cell we have counted the number of microseismic events occurring during the 10 month injection period considered (Fig.3a), and we have summed their seismic moment (‘Mo’, Fig.3b). It appears that approximately 70% of the microseismic activity and the energy releases are located in a zone of 0.38 km$^2$. This zone is not centered on the injection zone but slightly shifted towards the north. To understand this microseismicity distribution and try to highlight the main fluid paths, we have accurately studied the spatial appearance of the microseismic events daily. Although there are large horizontal errors associated with the located microseismic events, we have tried to identify visually if the microseismic events appeared along zones with a preferential orientation. Six relevant periods are described below and presented in Figure 4, where the distribution of the microseismic events are presented (1) with our interpretation and the main fault mapped on the field and (2) without any interpreted faults to allow the reader to judge for themselves the chosen interpretation.

![Figure 3: Microseismic density as number of microseismicity events per bin during the first 270 days of injection.](image)

Figures 4a and 4b show the microseismicity distribution from the 6th (beginning of injection) to 20th of October, 2011. During the first two days, only 5 microseismic events occurred. Then, from the 8th to the 10th, forty-five microseismic events occurred, with 1/3 of the events aligned along a line trending N130 (called ‘F5’, bigger black points). F5 seems to be in the continuity of a part of the Squaw Creek Fault (Fig. 4b). From the 11th to 17th of October 2011, thirty-five microseismic events were detected; a third of these events are aligned along ‘F5’ (small red triangle), and another third are aligned along a new N130 shear zone (called ‘F4’, red triangle). From the 18th to 20th the microseismic events kept spreading toward the NE (green stars). These two shear zones (‘F4’ and ‘F5’), appears to be near vertical (Fig. 5a).

Figure 4c, 4d and 5b show the microseismicity distribution in November 2011 for two periods of 6 days and one period of 3 days. Each period corresponds to the appearance of microseismicity in areas previously lacking (or with few) microseismic events. In each case, the microseismic events are aligned along a N130 direction highlighting the presence of three N130 shear zones (green stars; ‘F3’ which seem to correspond to the Squaw Creek Fault, yellow triangles: ‘F2’, blue squares: ‘F1’). Elsewhere, the microseismic events seem to occur randomly in the reservoir (grey points), or along the aforementioned N130 shear zone: F4 and F5 (red and black points). The shear zones F1, F2 and F3 seem to be also near vertical.

Figure 4e and 4f shows the microseismicity distribution during the 6 first days following the increase of the injection rate in December 2011 (from 400 to 1000 gpm). Two new fluid flow paths appear on the basis of the microseismicity. The increase of the injection rate have led to a N050 shear zone (Fa) reactivation allowing fluid migration to the southeast of the study area, where a N130 shear zone is reached (F7). For the sake of simplicity, Figure 5c represent only the microseismicity occurring along the shear zone ‘Fa’ during this period, and the vertical alignment of these events indicates that this shear zone is near vertical.

Finally, we defined four additional shear zones, two N050 (Fb and Fc) and two N130 shear zones (F6 and F8), based on the alignment of the microseismic events recorded during the two last weeks of December 2011 and during the first hundred days of 2012 (Figure 4g and 4h). Fb and Fc correspond to the two N050 fault mapped in the field, and during the injection, 8 events with magnitudes ranging between 2.2 and 2.9 occur along ‘Fc’ (Fig.6). F6 seems to be a NW continuation of the Squaw Creek Fault, and its presence can explain the steam entries observed in P31 and P32. We also added F8 to explain the presence of steam entries along P32.
Figure 4: Dynamic appearance of microseismic hypocenters presented in detail for four relevant periods. For the same period two maps are presented, one with all the microseismic events detected during this period, and another map with our interpretation and the main faults mapped on the field. The black squares represent the steam entries.
Figure 5: View in 3D of the dynamic appearance of microseismic hypocenters along the shear zones (a) F4 and F5, (b) ‘F2’ to ‘F3’ and (b) along ‘Fa’. The black squares represent the steam entries F4 to F8.

This approach presents uncertainties caused by the horizontal location errors. But strong evidence suggest that the proposed structural setting (Fig.6) has to be considered and integrated in a geomechanical modeling to try to reproduce the reservoir response to the injection on the long-term. Indeed, we found a good match between (1) the shear zones and the faults mapped on the field, (2) the locations of steam entries along the wells and the N130 oriented shear zones, (3) as observed by Sammis et al. (1992) most of the steam entries seem correspond to near vertical northwest striking fractures, and (4) these shear zones are spaced from 150 to 200 m apart, which is also consistent with Sammis et al. (1992).

Figure 6: Structural map built from the microseismicity analyses, with the location of the largest microseismicity events (magnitude>2.0). The black squares represent the steam entries.
4. SURFACE MEASUREMENTS BY SATELLITE (INSAR DATA)

Lawrence Berkeley National Laboratory and Tele-Rilevamento Europa (TRE) commissioned the TerraSAR-X (TSX) satellite to monitor the possible vertical deformation associated with the EGS project. The monitoring period ranges from May 2011 (6 months before injection began) to September 2012.

Surface deformation, around the EGS area, was evaluated using 6750 measurement points (MPs) (Fig. 7a). For each measurement point, displacement time-series were produced using TSX range change data (changes in distance between the satellite and surface in the line-of-sight). To take into consideration all these points we have divided the domain into a grid and calculated average values for points within each 0.01 km$^2$ (100 by 100 m) grid cell (Fig 7b). Figure 7c shows three typical curves of surface displacement for points within each 0.01 km (100 by 100 m) grid cell (Fig 7b) obtained after 17 months of monitoring.

Three phases of surface deformation have been identified in the study area during this time interval where the general trends are characterized by: (1) subsidence, (2) uplift and (3) after 270 days of injection either by subsidence or uplift (Fig. 7c). Phases 1 and 2 show a northwest-southeast oriented central zone with a relatively high deformation velocity, indicating a deformable zone embedded in a more rigid environment. The orientation of this zone matches with the N130 shear zones previously identified. The comparison between the seasonal rainfall variations (Fig. 8) measured at The Geysers (Fig. 1a) with the time-series displacements...
Jeanne, Rutqvist, Vasco, Garcia, Dobson, Walters, Hartline, Borgia

(Fig. 7c) are well correlated with: subsidence during the dry periods (Phase 1), and uplift during the rainfall period (Phase 2). Phase 3 shows substantial uplift in the northeast part of the study area and subsidence in the southwest part. The boundary between these two zones corresponds to a shear zone oriented N130. Phase 3 occurs at the same time as the deepening of the hypocenters, suggesting that these surface deformations may be related to the regional tectonic activity.

Figure 8: the timing of rainfall measured at The Geysers

5. GEOMECHANICAL MODELLING

5.1 Numerical Analysis Method

We use the TOUGH-FLAC numerical simulator (Rutqvist, 2011), which has the required capabilities for modeling of non-isothermal, multiphase flow processes coupled with stress changes in a steam-dominated geothermal reservoir. The reservoir model consists of four layers: a caprock, a normal temperature (240°C) reservoir, a high temperature (400°C) zone, and granite intrusive body. The initial thermal and hydrological conditions (vertical distributions of temperature, pressure, and liquid saturation) are established through steady-state, multiphase flow simulations (Rutqvist et al. 2013). The initial reservoir temperature in the NTR is approximately 240 °C down to a depth of about 2.5 km, and then gradually increases up to 370 °C toward the bottom boundary at a depth of 6.5 km (this lower value was used because it is the upper temperature limit of the TOUGH2 module used). Null displacement was imposed on the bottom and side boundaries, so only the top boundary is free to move. Open flow boundaries were imposed (i.e., constant pressure and temperature). We simulate the rock mass as an equivalent continuum with implicit representation of fractures, whereas shear zones are explicitly represented as 15 m wide zones with different hydraulic and mechanical properties (Fig. 9).

Figure 9: Three dimensional numerical grid with (a) material layers and (b) shear zone network.

To estimate hydraulic properties of the hornfels layer and the shear zones, we performed a sensitivity analysis by using the EOS3 module of TOUGH2 (Pruess et al., 2011). The permeability and porosity of each rock unit and the shear zones were estimated by matching the monitored well pressure variations in PS31, P38 and P25 (Fig. 10). We also performed a series of simulations to test the relation between the N130 shear zone family and the N050 trending low permeability area marked Fc in Figure 6. These simulations were intended to investigate the distribution of permeability in areas where the N130 shear zones intersect the low permeability regions. The permeability values used for the caprock, the normal temperature reservoir and the felsite layer were taken from previous work (Rutqvist and Oldenburg, 2008), where the authors estimated the hydraulic properties of the reservoir by matching over forty years of injection and production data.

TOUGH-FLAC was used to perform a sensitivity analysis to estimate the Young’s moduli of the N050 and N130 shear zones as well as the rock mass. The best fit was found by fitting the predicted surface deformations with displacement time series measured at 8 points (Fig. 7b). To be sure that the surface deformations measured are related to the EG5 project, the eight selected points are located in the area of high microseismic density and with initial low velocity subsidence (close to 0 cm/year). Only one point (MP6)
was taken in the high deformation zone (Fig. 7b). Moreover, we didn’t consider the surface deformation occurring after 270 days of injection, when the surface deformations seem to be influenced by regional tectonic activity.

The calculation of the microseismicity potential is based on the concept of a critically stressed rock mass (Rutqvist et al., 2013). The authors evaluated the likelihood of shear reactivation along a fracture. They used a frictional coefficient of $\mu = 0.6$. The Coulomb criterion for the onset of shear failure can be written in the following form:

$$\sigma'_{1c} = 3\sigma'_{3}$$  \hspace{1cm} (1)

where $\sigma'_{1c}$ is the critical maximum principal stress for the onset of shear failure. Thus, shear reactivation of a fracture would be induced whenever the maximum principal effective stress is three times higher than the minimum principal stress. By studying how the stress state deviates from this near-critical stress state we may investigate whether the changes in the stress state tend to move the system into failure or away from the state of failure. The likelihood of shear reactivation would increase if the change in maximum principal compressive effective stress is more than three times the change in minimum principal effective stress (i.e., if $\Delta\sigma'_{1} \geq 3 \times \Delta\sigma'_{3}$). We may quantify how much the $\Delta\sigma'_{1}$ has to exceed $3 \times \Delta\sigma'_{3}$ to induce additional shear reactivation. We therefore define a stress-to-strength change margin as $\Delta\sigma'_{1m} = \Delta\sigma'_{1} - 3 \times \Delta\sigma'_{3}$. $\Delta\sigma'_{1m}$ represents the potential to induce shear reactivation and induced seismicity, in which a higher value would imply a higher potential for inducing seismicity. We therefore denote $\Delta\sigma'_{1m}$ as the microseismicity potential.

5.2 Model Calibration

The best solution to match (1) the pressure evolution in the surrounding wells (Fig. 10), (2) the surface deformations (Fig. 11) and (3) the maps of the cumulative microseismicity potential (calculated by summing the microseismicity potential estimated every 10 days during 270 days) (Fig. 3d to 3f) is obtained for highly contrasting hydraulic and mechanical properties between the host rock and the two shear zones oriented N050 and N130 (Figures 1b and 6).

The estimated host rock permeability ($K_{hr}$) in the HTR is $2 \times 10^{-15}$ m$^2$. The N130 shear zones have estimated permeability values up to two orders of magnitude higher than $K_{hr}$, ranging between $1 \times 10^{-13}$ m$^2$ and $5 \times 10^{-15}$ m$^2$. Estimated permeabilities of the N130 shear zones labeled in Figure 1b as “F1” to “F8” generally increase from the southwest to the northeast; the lowest permeability is obtained for F5 to F8 (k range between $10 \times 10^{-14}$ to $5.0 \times 10^{-15}$ m$^2$) and the highest permeability is obtained for F1 to F4 ($k = 5.0$ to $1.0 \times 10^{-13}$ m$^2$). The permeability estimated for the N050 shear zones labeled in Figure 6 as “Fa” and “Fb” is $5 \times 10^{-15}$ m$^2$ and is slightly lower than $K_{hr}$. For the shear zone Fc, the permeability across this zone is as much as five orders of magnitude smaller than that of the host rock ($K_{Fc} = 10^{-20}$ m$^2$). The estimated porosities are low (3%) in the host rock and in the N050 shear zones and higher (10%) in the N130 shear zones. To match the slight pressure response in Prati 38 (P38) to injection in P32 (Figure 10), a very low permeability in Fc is necessary and some of the N130 trending shear zones need to cut Fc without being affected by the permeability decrease in this area. A sensitivity analysis was performed by considering that Fc is cut by, either (1) the eight N130 trending shear zones (F1 to F8), (2) three of them (F2 to F4), (3) one of them (F4), or (4) none of them (Fig. 12). The best fit is found when considering that the shear zones F2, F3 and F4 are not affected by the permeability reduction in the low permeability area of Fc.

Figure 10: Comparison between the pressure evolutions measured in situ in wells PS31, P25 and P38 with the calculated pressure evolution. Note that the pressure monitoring for P25 was limited to the time before the well was placed into production.
The estimated Young’s moduli are 12 GPa for the host rock, 11 GPa for the N050 shear zones and 6 GPa for the N130 shear zones. The comparison between the average displacement time-series and the calculated vertical displacement are in good agreement.

Figure 11: Comparison between the evolution of the calculated vertical displacement with the surface displacement time-series measured by satellite in eight points (see Fig. 7b).

Figure 12: Sensitivity analysis performed on the relationship between the low permeability area ($F_c$) and the shear zones trending N130. Three cases are tested in which: (a) $F_c$ is cut by the eight shear zones N130 (F1 to F8), (b) three of them (F2 to F4), (c) one of them (F4), and (d) none of them. (e) Impact on the pressure evolution in P38.
The comparison between maps of simulated cumulative microseismicity potential and maps of observed microseismic density (Fig. 3) show a good similarity for some points. We reproduced an acceptable calculated extent of the stimulation zone in the vertical direction (up to 4.5 km depth into the granite intrusion) and in the N130 and N050 directions. On the other hand, cross sections are more heterogeneous in the field. This can be related to the presence of hydromechanical heterogeneity along the same shear zones. In our simulations, each shear zones is modeled with constant hydromechanical properties and constant geometrical properties for the sake of simplicity. Moreover, in the field there is quite a bit of observed microseismicity to the NNW of the injection well (Fig. 3a) that is not predicted in our model (Fig. 3d). During injection the microseismicity has slightly migrated toward the NW. This phenomenon is related to the reactivation of preexisting shear zones, causing an increase in permeability that allows fluids to move out further away from the injection well. This dynamic behavior is not captured by the model.

6. DISCUSSION

The injection has led to a pressurization of the reservoir at a kilometer scale. The tectonic structures visible on the surface have a strong impact on the fluid flow at several kilometers depth. Indeed, the shape of the pressurized area is strongly influenced by the pre-existing tectonic structures inferred from the regional tectonic activity: (i) the low permeable N050 shear zones, which act like an impermeable boundary, and by (ii) the more permeable N130 shear zones, which favor pressure diffusion. During the EGS project the shear zone F3, which corresponds to the high deformation area revealed by the satellite measurements, was reactivated by the regional tectonic stress. The regular reactivation of this shear zone explains its high permeability ($10^{-13}$ m$^2$) and keeps the fractures open inside the low permeability area.

The comparison between the map of the pressure (Fig. 13) variation and the map of the microseismic event density show a good agreement. Cooling is only observed around the injection point ($\Delta T = -180°C$) due to cold injected water. This suggests that injection-induced changes in the steam pressure are the dominant cause for triggering shear reactivation far from the injection well. The areas where the largest microseismic events could occur are at the intersection of permeable and low permeable shear zones, where high overpressure can quickly develop. During the injection the shear zone F3, (corresponding to the high deformation area revealed by the satellite measurements), was reactivated by the regional tectonic stress, and despite the large volumes of fluid injected, no large (> M 2.9) microseismic events were generated.

Figure 13: Calculated pressure distribution in the (a) N050 and (b) N130 orientation, temperature distribution in the (c) N050 and (d) N130 orientation, and liquid saturation in the (e) N050 and (f) N130 orientation after 270 days.
Finally, satellite measurements can be a powerful tool to monitor the surface deformations linked to the reservoir exploitation, but the data interpretation needs to be conducted very carefully. Several factors can strongly influence the interpretation of surface deformation: the regional and local geological setting, landslides, cyclical effects related to seasonal variations in rainfall, and the long-term trends related to reservoir exploitation. To consider all these factors it appears to be essential to correlate the surface deformation measurements with other data. The coupled analyses with the microseismicity enables (1) delineation of the face of the TOUGH thermal field. Proceedings of the 38th U.S. Rock Mechanics Symposium, San Francisco, California, USA, June 25-27, 2012.

7. CONCLUSIONS

During this study, we have shown that:

- Coupled analysis of microseismicity and ground surface deformations is a powerful tool for characterizing the site.
- Microseismicity distribution is strongly influenced by the regional geological setting.
- Permeable shear zones oriented N130 facilitates downward migration of fluids to create an EGS deep into the granite intrusion.
- The mechanism responsible for the EGS development into the granite intrusion is shear reactivation of pre-existing fractures caused by the combined effects of injection-induced pressure and temperature changes.

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