Title

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Effects of asperity distribution on fluid flow and induced seismicity during deep geothermal exploitation

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Abstract

This work investigates the injection-induced seismic response of a heterogeneous fault plane, featuring low-permeability asperities embedded into a high-permeability damage zone. We simulate the pressure evolution with a hydrogeological simulator, accounting for the heterogeneous fault plane. Seismicity occurs then on the asperities, represented as unstable patches reactivating by means of the Mohr-Coulomb criterion. The hydrological and seismic modules are implicitly coupled to account for effects of asperity reactivation on the permeability. Results show that permeability changes may cause at a later time a change in seismicity propagation. We also investigated such effects by varying the density of asperities.

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Keywords: induced seismicity; permeability changes; asperities; deep geothermal system

1. Introduction

Many induced earthquake sequences could be seen as the rupture of brittle asperities along a fault zone, in response to fluid pressure changes generated by an injection at depth. Furthermore, the relocation of seismicity often shows that these brittle patches only cluster on particular regions of the fault zone, indicating that the remaining regions are either creeping or not activated during the injection. This clustering behavior may indicate heterogeneous permeability conditions within the fault zone. This work tries to explain some features often observed in deep geothermal activities, during which a fault zone is stimulated to enhance fluid circulation. One known example that accounts for seismicity during deep geothermal operations is the case of St. Gallen, Switzerland [1]. Although in St. Gallen the fault zone was not really stimulated for proper geothermal operation, and the seismicity rate only largely increased following some well operations [2], a characteristic pattern was observed in the propagation of seismicity. In an initial phase, during which an event of magnitude 3.5 was triggered, the seismicity propagated at a rate of 1000 m/day towards SW. In a second phase, seismicity was also observed to propagate towards NE along the fault zone [3]. In this work, we aim at investigating the response of a heterogeneous fault to injection activities. The heterogenous fault plane features

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brittle asperities with low permeability embedded in a higher permeability and ductile matrix. We first simulate the fluid flow and pressure evolution with the TOUGH2 numerical simulator [4], which accounts for the heterogeneous permeability caused by the presence of a given distribution of asperities. In order to get the seismicity associated with the simulated injection, we modeled in a second step the fault as a planar frictional interface, where brittle asperities are represented as unstable patches that can reactivate following a Mohr-Coulomb criterion. This coupled modeling approach allows to compute the seismicity generated by a localized fluid injection, and to investigate how a cloud of induced earthquakes propagates along a fault. Furthermore, we investigate the effects of permeability changes due to seismic reactivation. In this second case, the hydrogeological and first-order mechanical models are implicitly coupled to account for effects of shear displacement on the permeability changes. Such permeability changes, may cause at a later stage of post injection a change in seismicity propagation. Finally we analyze how the density of the asperities may alter such propagation of the seismic cloud.

Nomenclature

κ asperity (fault core) permeability [m^2]
κ_0 initial asperity (fault core) permeability [m^2]
C constant value for slip-permeability relationship [-]
n exponent factor for slip-permeability relationship [-]
$d*$ critical slip for change in permeability [m]
Δd event slip derived from scalar seismic moment [m]
M_0 scalar seismic moment, derived from seed event magnitude [N·m]
M_w seed event magnitude [-]
$\Delta\tau$ stress drop associated with seed event magnitude [Pa]
μ coefficient of friction [-]
σ_H maximum horizontal stress [Pa]
σ_h minimum horizontal stress [Pa]
σ_V vertical stress [Pa]

2. Model setup

A modified version of the code TOUGH2-SEED [5] was implemented to study the effects of seismicity in a heterogeneous fault plane. TOUGH2-SEED couples the capabilities of the geothermal simulator TOUGH2 [4] with a stochastic-geomechanical model [6]. On one side, TOUGH2 allows the simulation of multiphase, multicomponent fluid flow and heat through porous media. On the other side, the stochastic model, so-called "seed model", accounts for reactivation of potential hypocenters (seeds). The main difference here is that the single "seed" represents an asperity, which also corresponds to a low permeability patch on the fault plane.

We simulate a 2D fault plane stimulated by fluid injection, which lasts for 15 days and it is followed by a 15-day post-injection period. Injection occurs at 4000 m depth, with a rate of 6 kg/s, which results in an overpressure of about 40 MPa in the worst-case scenario, given the 2D approximation. In literature, a fault zone is generally considered as embedded in a host rock and composed of a highly fractured damage zone and a lower permeability central core [7]. Such fault core is generally modeled as a continuous, low-permeability region, but here we assume the fault core as heterogeneous with low and high permeability patches. The low permeability ones represent the so-called asperities: unstable patches that can reactivate. A schematic view of the model as well as the values of permeabilities for the different domains are shown in Figure 1.

Initial pore pressure follows a hydrostatic gradient, while stresses at seed are randomly assigned with average value following an extensional stress regime ($\sigma_H = \sigma_h = 0.8\sigma_V$). The seeds are assumed to be optimally oriented for reactivation. Reactivation on a given seed occurs if the Mohr-Coulomb criterion is satisfied, assuming a coefficient of friction $\mu = 0.6$. When reactivation occurs on a seed, magnitude is randomly assigned assuming a b-value depending on the stress condition at the given seed [6]. In order to account for multiple failures of the same seed, we consider a

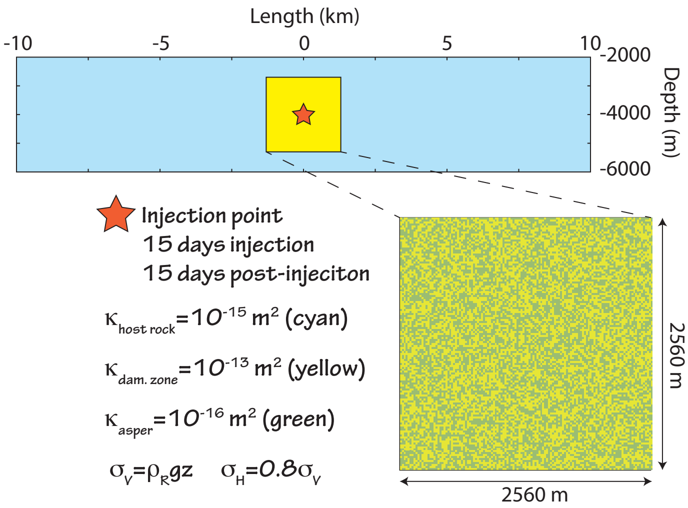

Fig. 1. Schematic view of the computational domain.

shear stress drop upon failure, with the amount of stress drop depending on the normal effective stress [5,6,8]. At this stage we do not consider earthquake interactions, although these latter may further increase the seismicity rate [8].

Upon reactivation the failing asperity may increase in permeability and create a new pathway for the fluid to propagate. Following previous numerical effort [9], we related the changes in asperity permeability to the magnitude of the occurring event. Given the earthquake magnitude it is possible to calculate the possible slip associated to an earthquake, and we then calculate the permeability enhancement as function of the associated slip:

$$\kappa = \kappa_0 \left[1 + C\left(1 - e^{-\frac{\Delta d}{d^*}}\right)\right]^n, \quad \Delta d = \frac{M_0 \left(\frac{16\Delta\tau}{7M_0}\right)^{\frac{2}{3}}}{G\pi} \tag{1}$$

where κ_0 is the pre-failure permeability, C and d^* and n are fitting parameters, based on previous numerical results [9], and $\log_{10} M_0 = 3/2M_w + 9.1$, with M_w the moment magnitude.

3. Results

3.1. Base case simulation

Figure 2 shows the pressure evolution and ruptured seeds for the base case scenario, where there is no permeability enhancement associated with the rupturing of the asperities. The figure shows the 15-day injection and the following relaxation time. The distribution of asperities, although random and uncorrelated, provides a preferential direction for the fluid flow. In the analyzed case, the injected fluid and pressure mostly distribute downwards, and the propagation of the seismic cloud reflects the pressure distribution, although is contained into the pore pressure change area, since stress transfer from the rupture has been neglected in this study. Worth of note is that at all time considered in Figure 2, the seismicity always propagates in the same direction, indicated by the arrow.

3.2. Effects of permeability changes

Accounting for permeability increase, as described to the relation in Eq. 1, results in a different distribution of pressure and seismicity, as shown in Figure 3. The pore pressure cloud has a similar shape to the base case, especially at early times (Fig. 3a). However, when the asperities start reactivating in a large number, the permeability of the medium is increased (up to 100 times) allowing other regions of the fault to be pressurized and affected by fluid flow.

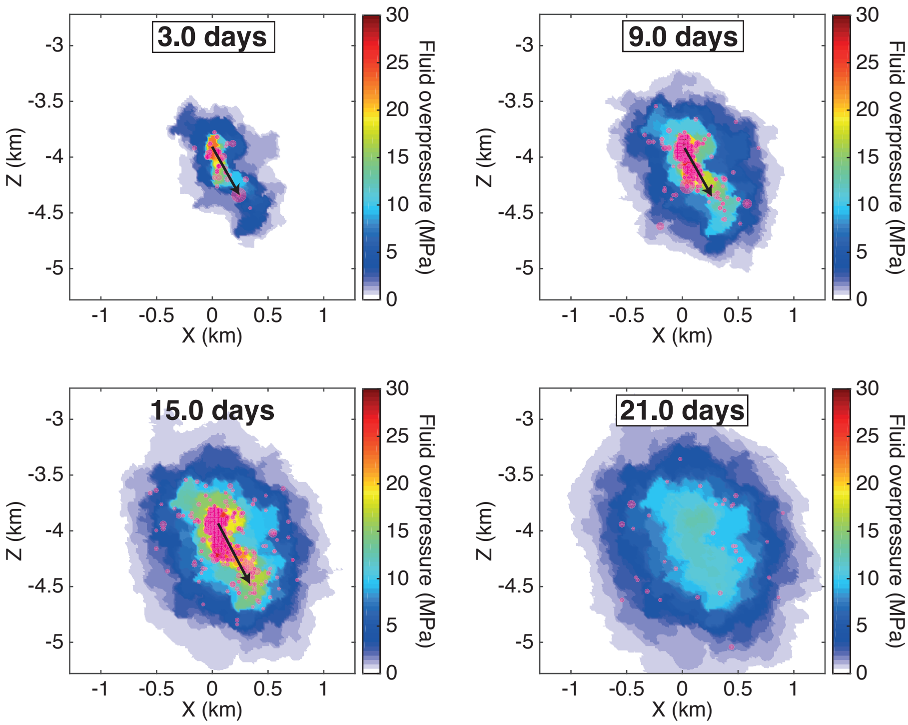

Fig. 2. Pore pressure (colored contour plot) and ruptured asperities (pink dots, the magnitude of the event is proportional to the size of the dot) evolution for a 15-day injection. No feedback between rupture and permeability, the arrows indicate the direction along which seismicity is increasing.

The resulting increase in permeability has two main effects: (i) it reduces the maximum changes in the pore pressure and (ii) alters the seismic cloud, both in term of of its propagation pattern and the rate of events. At the beginning, until day 3, the propagation of the seismic cloud is towards the bottom, as in the previous case (Fig. 3a), but then the event cloud starts to spread out almost equally above and below the injection point along the directions indicated by the arrows (Fig. 3b and 3c). The post-injection pressure distribution is very similar in size and shape in the two cases, with a small upward-shifting (Fig. 3d).

Figure 4 shows the temporal evolution of pore pressure at the injection point and the rate of seismic events for the cases with and without permeability changes, respectively. When the permeability changes as function of the asperities rupturing, the rate of seismic events decreases, since pore pressure does not reach the same peak values as in the base case.

3.3. Effect of density of asperities

The role of the asperity density in the fault is shown in Fig. 5. The fluid flow and therefore the pore pressure are influenced by the relative area occupied by the asperities. The cloud of seismic events is almost absent in case of higher average permeability (referred from now on as the “sparse” case, when asperities are occupying 30% of the area). When the asperities are covering 50% of the fault area (“mid-density case”), a behavior similar to the one described in Figures 3 and 4 occurs, showing one or more directions of preferred propagation according to the amount of permeability changes. Finally when the fault zone is mostly covered by asperities, with 70% or more of the area (referred to as the “dense” case), the seismic cloud distributes quite homogeneously, spreading around the injection point.

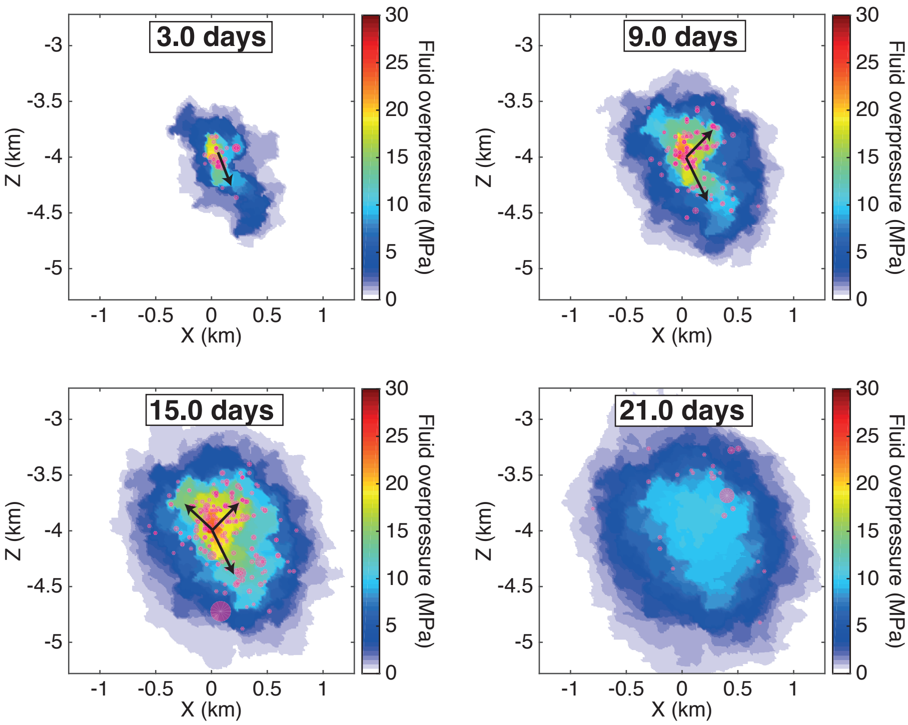

Fig. 3. Pore pressure (colored contour plot) and ruptured asperities (pink dots, the magnitude of the event is proportional to the size of the dot) evolution for a 15-day injection. Increase in permeability is associated with rupture of the asperities, the arrows indicate the direction along which seismicity is increasing.

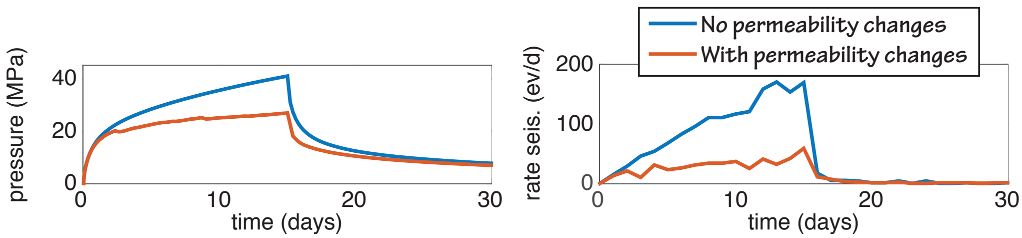

Fig. 4. Pore pressure change with time at the injection point and seismic rate evolution.

4. Discussion

The injection-induced seismic response of a heterogeneous fault composed of brittle, low-permeable asperities and a more permeable damage zone has been investigated, considering fluid pressure changes as the trigger. How much area of the fault is composed by asperities strongly determines the seismic response of the fault. If the asperities are sparse (30% of the area or less), the seismic events obviously are dispersed and do not present a specific pattern. When the asperities occupy an area roughly between 30% and 70% of the area, with the contrast in permeability we used here, fluid does not move as easily as in the previous case and the seismic cloud shows some distinct pattern, starting close to the injection point and then propagating towards the bottom. Events close to the injection point continue to

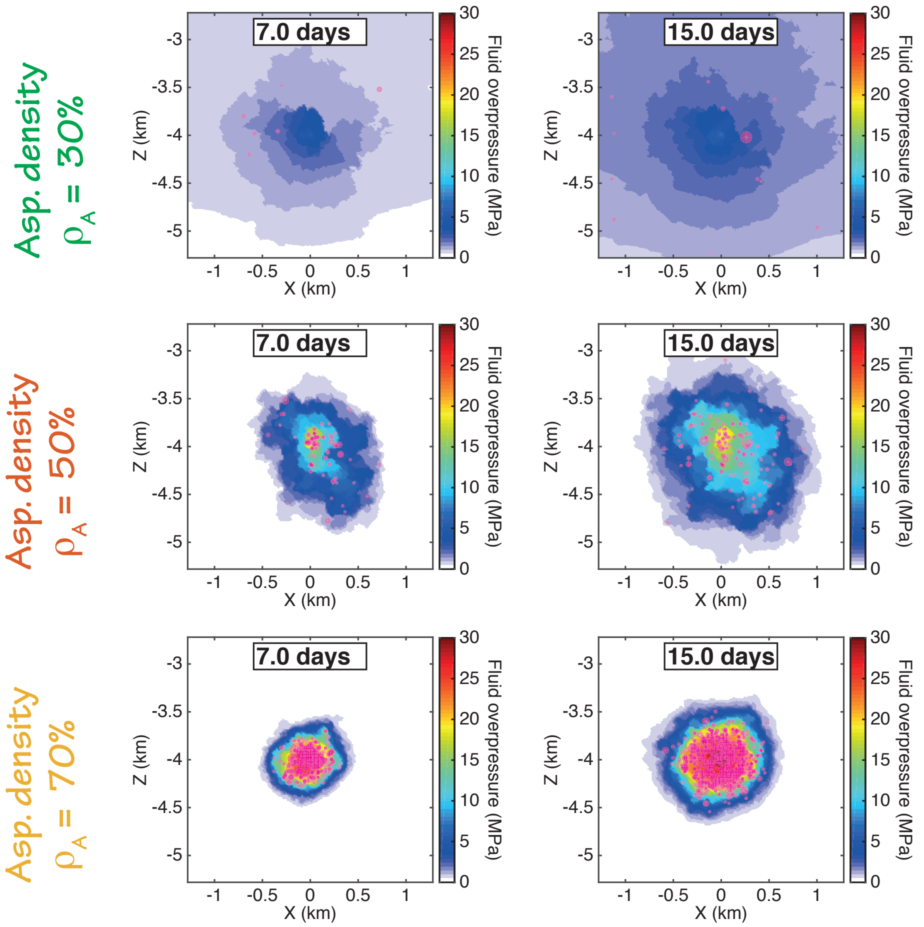

Fig. 5. Pressure (colored plot) and seismic events (pink dots) evolution for three different density of asperities, taking into account the permeability enhanced by rupture of the asperities.

take place, since pressure is monotonically increasing with the continuous fluid injection. Finally, when the asperity density is 70% or more, the distribution of seismic events is quite homogenenous and the pore pressure values are higher and less spread out, since the permeability of the fault is dominated by the permeability of the asperities.

The initial contrast in permeability present between the asperities and the damage zone is mitigated by taking into account the effects of shear displacement on the permeability changes, which here has been done implicitly assuming that permeability increases with rupture and scales with the magnitude of the rupture. An increase in permeability with shear displacement is the expected response of fractured granite mass and of fault zones cutting through it. The permeability increase does not significantly affect the pattern of seismicity in the cases where the asperities are sparse or dense, even though in this latter case the fluid flow is strongly constrained by the low-permeable asperities. For the mid-density distribution of asperities, permeability increase by shearing does not affect the distribution of seismic events at the beginning: ruptures take place in close proximity of the injection point and start propagating from there towards the bottom, given the asperities distribution accounted for in this work. However, after some more days of continuous injection, events start to propagate from the injection well to the upper part of the fault, in opposite direction with respect to the initial propagation. Such an effect could be related to the permeability changes, which open up new pathways for fluid and pressure to propagate, and hence induce seismicity.

Propagation of the seismic cloud, pressure at the injection point and seismicity rate for these three cases are shown in Fig.6. The seismicity rate correlates with the pressure at the injection well: in this study the only triggering

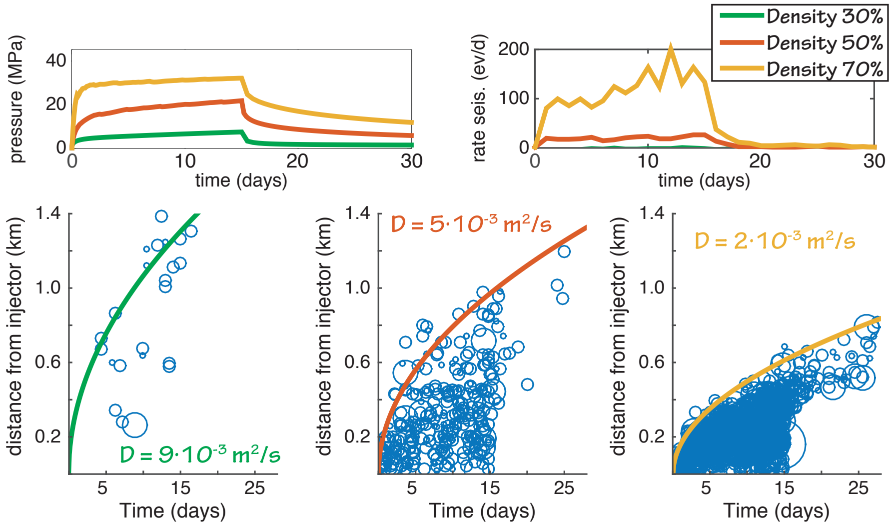

Fig. 6. Pore pressure at the injection point, seismic rate evolution, r-t plot for the different asperity density with rupture-enhanced permeability. Expected seismic front propagations for different diffusivities are superimposed in the r-t plots,

mechanism accounted for the seeds is the pore pressure change, higher injection pressures will lead then to more seeds failing.

The $r - t$ plots in Figure 6 show the propagation of the seismic events from the injection point with time and the expected line along which the first event at a certain distance r would take place if hydraulic diffusivity had the specified value. Hydraulic diffusivity depends linearly on permeability, on the rock' specific storage (the volume of fluid released from storage per unit control volume per unit pressure decline) and on the fluid density and viscosity: pure shearing rupture in the rock mass is not expected to affect the fluid properties nor to change the specific storage, but it is known to affect permeability. Therefore, we expect that the diffusivity value that can be inferred by the $r-t$ plot scales with the permeability. However, comparing the diffusivity for the different cases analyzed in this work (always in the same order of magnitude, around 10^{-3} m^2/s), and knowing the permeabilities of the different units (spanning over 3 orders of magnitude, between an average of 10^{-16} m^2 in the dense case and 10^{-13} m^2 in the sparse case), there is not a linear relation between the two. This may suggest that it is not appropriate to describe the pressure propagation with the diffusivity estimated from $r - t$ as this may not be related to the average permeability of the medium, and hence not to the fluid flow. Furthermore, for the mid-density case, the $r - t$ plot does not clearly show that there is one (or more) preferential propagation direction with increased diffusivity, nor the back front resemble the analytical ones available in literature [10]. The only possible hint at the presence of preferential propagation from the $r - t$ plot is the abrupt end of seismicity, with a clear intersection between the triggering and the back front. This behavior has not been investigated in detail, but we can exclude that the abrupt end of seismicity is related to the finiteness of the asperity zone in the fault: the minimum distance between the injection point and the asperity boundary is 1.28 km, while the two fronts meet at 1 km distance from the injection point. Further investigations are required to clarify this point.

5. Conclusion

Injection into a fault zone represented by brittle asperities with low-permeability embedded in a damage zone, featuring a higher permeability and ductile matrix, have been modelled. The density of asperities plays an important role in defining the shape and time distributions of the seismic events. Flow path perturbations induced by asperity rupture has been included, associating permeability increase with the seismic slip.

The combination of asperity density and permeability increase shows a unique pattern of seismic events propagation for an intermediate value of asperities density: events propagate downwards at the beginning of the 15-day injection, but after a couple of days downward propagation is interrupted in favour of upward-trending seismicity (in two directions). Pressure dissipation by means of increased permeability promotes the spreading of seismicity, but it also activates different propagation directions. This behavior produces unique features, visible in the synthetic $r - t$ plots of the seismic cloud, although the increase in permeability, and therefore in diffusivity, is not as evident as expected by the fluid flow perturbation due to asperity ruptures.

Acknowledgements

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