Inferring In Situ Hydraulic Pressure From Induced Seismicity Observations: An Application to the Cooper Basin (Australia) Geothermal Reservoir

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Abstract
An approach is proposed for estimating in situ reservoir pressure changes based on induced earthquakes with overlapping slip patches. The approach is independent of absolute (tectonic) stresses and can also be applied in a scenario where the (unknown) tectonic stresses are strongly heterogeneous. Based on Coulomb friction, the approach makes use of the fact that stress-strength conditions are in equilibrium at the time of seismic activation. Coseismic stress changes inferred from seismogram recordings provide the stress-state relative to the failure stress immediately after seismic activation. If the same fracture patch is seismically activated again, relative changes of fluid pressure, that is, the fluid pressure change at which stress-strength conditions reach equilibrium again, can be inferred from the stress-deficit when accounting for stress re-load from neighboring patches. The performance of the technique is demonstrated using a data set of 20,736 earthquakes induced during a hydraulic injection experiment in a geothermal reservoir in the Cooper Basin, Australia. The spatial hypocenter distribution indicates that the seismicity mainly occurred on a single-layer structure with slip direction controlled by the regional stress field as evidenced by fault mechanisms. Due to the high earthquake density, interearthquake stress interaction is pronounced. The spatial stress impact associated with each earthquake is simulated using a slider-block type propagation pattern based on Okada’s analytical solutions. Using the scalar seismic moment determined from S-wave spectra, the spatio-temporal evolution of hydraulic pressure changes is inferred on a reservoir scale. Results indicate that hydraulic flow is most pronounced into NW-SE direction.

1. Introduction
For managing geothermal and hydrocarbon reservoirs, knowledge of in situ hydraulic pressure is of primary importance. Reservoir models typically rely on a limited number of pressure measurements at wellbore locations, whereas hydraulic pressure away from wells is a modeled parameter and inherently ambiguous (e.g., Horne, 1995).

Already in the 1950s it was recognized that hydraulic overpressure caused by fluid injection into subsurface reservoirs can induce seismicity (Healy et al., 1968; Hubbert & Rubey, 1959). Different approaches were proposed to obtain hydraulic reservoir properties from this apparent relationship between overpressure and induced earthquake occurrence. For example, Talwani and Acree (1985) and later Shapiro et al. (1997) relate the spatio-temporal evolution of induced seismicity to hydraulic diffusivity and reservoir permeability (Shapiro et al., 1999). Terakawa et al. (2012) and Terakawa (2014) infer hydraulic pressure from focal mechanisms of induced earthquakes. A similar approach is applied by Mukuhira et al. (2017). These approaches, however, require an a priori assumption regarding in situ stress-strength conditions, for example, an assumption about the level of hydraulic overpressure required to cause seismicity. This information, however, is subject to large uncertainty as neither fault strength nor in situ (tectonic) stresses are usually known. For example, Shen et al. (2019) sample stress-strength conditions within a Monte Carlo framework for inferring the critical fluid pressure level at which slip is induced in the Duvernay (Canada) formation. Their results indicate that cohesion plays an important role for fault stability.

By calculating stress changes induced by precursory events, Hainzl et al. (2012) estimate the pore pressure increase required to trigger swarm earthquakes occurring in the Vogtland area, Czech Republic. The approach presented in the current paper follows a similar concept of modeling the stress deficit associated
with previous seismicity for inferring the pressure level at which subsequent seismicity occurs. Different to
the study of Hainzl et al. (2012), the current approach is based on fracture (patches) slipping repeatedly dur-
ing fluid injection, thereby eliminating the dependency on absolute (tectonic) stresses.

Densely spaced clusters of induced earthquakes are commonly observed during fluid injection experi-
ments (e.g., Baisch et al., 2006; Deichmann et al., 2014; Moriya et al., 2002). Frequently, the interevent
spacing is much smaller than the source dimensions, indicating repeated slip of the same fracture patch.
Based on waveform similarity, Baisch et al. (2008) identified a sequence of repeated slip induced by high
pressure fluid injection at the German deep drilling site (Kontinentale Tiefbohrung [KTBI]).
Conceptually, this can be explained by the model of Baisch and Harjes (2003), where repeated activation
of the same fracture patch is a consequence of coseismic stress drop being small compared to the total
shear stress acting on the fracture. Once activated, the fracture remains close to stress criticality due to
a small stress drop.

Sequences of repeated slip bear the information of stress-strength conditions being in exact equilibrium at
the time of seismic activation. Immediately after seismic activation, the amount of additional stresses
required to reactivate the fracture (the stress deficit) can in principle be deduced from seismogram observa-
tions, for example, using the stress drop parameter in the Brune (1970) model.

As shown in this article, a simple relation between coseismic stress changes and interevent fluid pressure
increase exists when assuming that the changes of effective stresses required for re-activation are solely
caused by pore pressure increase. The focus of this study, however, is on the more general case where stress
conditions on a fracture patch are altered by the combination of pore pressure increase and stress transfer
from neighboring seismicity.

Based on the slider-block concept (Burridge & Knopoff, 1967), I provide a framework for inferring the
spatio-temporal evolution of pore pressure changes for the specific scenario of induced seismicity occurring
on a single, larger scale fault. Previous studies demonstrate that this scenario applies to the seismicity
induced during hydraulic stimulations of a geothermal reservoir in the Cooper Basin, Australia (Baisch
et al., 2006, 2009, 2015). I use data from the most recent, best-controlled injection experiment to determine
the spatio-temporal pore pressure evolution following the proposed framework.

2. Methodology

Consider an arbitrary patch on a fault with coordinates \( r_0(x_0, y_0, z_0) \), which is repeatedly activated in the
course of continuous pore pressure increase. The earthquakes activating this fault patch do not have to be
repeating earthquakes in the sense that the earthquakes share the same slip area. It is solely required that
the slip areas of the earthquakes are overlapping at location \( r_0 \). Let \( t_i \) \((i = 1, 2, 3, ..., n)\) denote the time of
seismic activation, then the critical stress-state immediately prior to slip initiation can be described by
Coulomb friction as

\[
\tau(r_0, t_i)/(\sigma(r_0, t_i) - P(r_0, t_i)) = \mu
\]  

(1)

with \( \tau(r_0, t_i) \), \( \sigma(r_0, t_i) \) denoting shear- and normal-stress resolved on the fault patch at time \( t_i \) and location \( r_0 \)
and \( P(r_0, t_i) \) denotes the fluid pressure. The static coefficient of friction \( \mu \) is assumed to remain constant
throughout the experiment, and cohesion is neglected, as the proposed approach is independent of the
fracture cohesion acting at the first slip of a fracture patch. It is assumed that barriers and asperities of
a fracture are broken during the first slip and that the same fracture behaves cohesionless thereafter over
the timescale of the injection experiment.

It should be noted that resolving \( P(r_0, t_i) \) directly from Equation 1 is not practicable since it primarily reflects
a priori assumptions of stress conditions at \( r_0 \).

Using Equation 1, the relative change of fluid pressure at \( r_0 \) between the critical stress-state at times \( t_i \) and \( t_j \)
can be expressed by the relative change of shear and normal stresses
\[
\Delta P(r_0, t_i, t_j) = P(r_0, t_j) - P(r_0, t_i) = \left[ \sigma(r_0, t_j) - \sigma(r_0, t_i) \right] - \frac{1}{\mu} \left[ \tau(r_0, t_j) - \tau(r_0, t_i) \right] \\
= \Delta \sigma(r_0, t_i, t_j) - \frac{1}{\mu} \Delta \tau(r_0, t_i, t_j) 
\]

(2)

Note that relative fluid pressure changes \( \Delta P(r_0, t_i, t_j) \) are independent of absolute stresses \( \tau, \sigma \) and solely depend on the relative stress changes \( \Delta \tau(r_0, t_i, t_j) \) and \( \Delta \sigma(r_0, t_i, t_j) \) occurring in between successive slips of the same fracture patch. Equation 2 provides the basis for the proposed methodology.

Let \( \Sigma \) denote the slip area of event \( i \). The relative stress changes in Equation 2 can be expressed by a contribution resulting from slip on \( \Sigma \) initialized at \( t_i \) and a contribution resulting from slip occurring outside \( \Sigma \) between time \( t_i \) and \( t_j \) as well as from aseismic, poroelastic, and thermoelastic contributions:

\[
\Delta \tau(r, t_i, t_j) = \Delta \tau(r \in \Sigma, t_i, t_j) + \Delta \tau(r \notin \Sigma, t_i, t_j) + \Delta \tau_{\text{aseis}} + \Delta \tau_{\text{poro}} + \Delta \tau_{\text{thermo}} \\
\Delta \sigma(r, t_i, t_j) = \Delta \sigma(r \in \Sigma, t_i, t_j) + \Delta \sigma(r \notin \Sigma, t_i, t_j) + \Delta \sigma_{\text{aseis}} + \Delta \sigma_{\text{poro}} + \Delta \sigma_{\text{thermo}} 
\]

(3)

For the data example in the next section, I will argue that aseismic, poroelastic, and thermoelastic contributions are of secondary order and in the following I assume

\[ \Delta \tau_{\text{aseis}} = \Delta \tau_{\text{poro}} = \Delta \tau_{\text{thermo}} = \Delta \sigma_{\text{aseis}} = \Delta \sigma_{\text{poro}} = \Delta \sigma_{\text{thermo}} = 0. \]

The coseismic stress changes on \( \Sigma \) can in principle be estimated from seismogram recordings, for example, through moment tensor inversion (e.g., Jost & Herrmann, 1989) or by inferring the stress drop parameter from seismic source spectra (Brune, 1970; Madariaga, 1979).

Similarly, seismic slip induced on fault patches outside \( \Sigma \) can be determined from observations and subsequently be related to stress changes on \( \Sigma \) using numerical modeling. In the data example presented in the next section, induced earthquakes are interpreted to occur on patches of the same, large-scale fault and to share a common rake direction. In this scenario, stress interaction between different patches of the fault, that is, the stress contribution at location \( \Sigma \) resulting from an earthquake located outside \( \Sigma \), can be modeled analytically using the slider block concept. Here the 2D face of the large-scale fault consists of many smaller fault patches, which may slip independently but are mechanically coupled to their neighbors (Bak & Tang, 1989; Burridge & Knopoff, 1967). The stability of a fault patch is controlled by Equation 1. Slip occurs whenever the ratio of resolved shear stress to effective normal stress on a patch exceeds the coefficient of friction. Thereby the shear stress resolved on the patch is reduced by the amount of stress drop, and shear stress on the neighboring patches is increased due to mechanical coupling. Assuming a homogeneous, elastic half space, the stress transfer pattern is determined using Okada’s (1992) semi-analytical solutions. The resulting pattern for shear stress (Figure 1) agrees within a few percent with the one determined by Wassing et al. (2014) using a finite element numerical model. Note that the propagator pattern is independent from the orientation of the slider-block model relative to the stress field.

The total amount of stress contributions \( \Delta \tau(r \notin \Sigma, t_i, t_j) \) and \( \Delta \sigma(r \notin \Sigma, t_i, t_j) \) results from summing over the stress contributions of all earthquakes occurring in the time interval \( t_i, t_j \) outside \( \Sigma \). Note that \( \Delta \tau(r \notin \Sigma, t_i, t_j) \) and \( \Delta \sigma(r \notin \Sigma, t_i, t_j) \) correspond to a stress re-load and generally have opposite sign to \( \Delta \tau(r \in \Sigma, t_i, t_j) \) and \( \Delta \sigma(r \in \Sigma, t_i, t_j) \). The amount of normal stresses redistributed is considered to be of secondary order for the data example presented in the next section. Therefore, the associated propagation pattern for normal stresses is not shown.

3. Seismicity Induced by Hydraulic Stimulation in the Cooper Basin

Geothermal exploration in the Cooper Basin (Australia) was performed between 2002 and 2013. Six deep wells were drilled into the granite to a depth level of 3,629–4,852 m, and several large volume hydraulic stimulations were conducted to enhance the hydraulic conductivity in the subsurface, thereby inducing ~75,000 earthquakes in the magnitude range \( M_L 2.3 \) to \( M_L 3.7 \). Seismicity was monitored with a 24-station network consisting of ten 1-Hz three-component surface seismometers and 14 three-component geophones deployed in boreholes at depth levels of 78–370 m. A detailed description of the stimulation experiments is
presented by Baisch et al. (2006, 2009, 2015). These studies provide evidence that most of the induced seismicity is consistent with a relatively simple model where seismic deformation occurs on a single plane and is driven by the regional stress field. As outlined by the spatial distribution of induced seismicity, the plane is oriented subhorizontal, dipping 6° towards the southwest.

Although image logs indicate the existence of a fracture network, logging data confirm that the granite is hydraulically impermeable with hydraulic flow restricted to the single fault as outlined by the seismicity distribution (Holl & Barton, 2015). The fault was penetrated by all four deep wells drilled at the Habanero location, sometimes causing severe drilling issues due to its high hydraulic conductivity. Based on an acoustic image log conducted in the Habanero#3 well, the fault has been characterized by a 5- to 6-m-thick damage zone and a 1-m-thick cavern of broken out granite representing the active fault plane (Holl & Barton, 2015).

Fault plane solutions indicate shallow thrust faulting consistent with the approximate E-W orientation of $S_H$ in the Cooper Basin as determined from borehole breakouts and drilling induced tensile fractures (Reynolds et al., 2005). The current study focuses on the most recent hydraulic stimulation of the well Habanero#4, providing the best-controlled induced seismicity data set.

Figure 2 shows the associated spatial hypocenter distribution. Consistent with observations from previous hydraulic stimulations, hypocenters align along the same subhorizontal flat structure (strike 204°, dip 6°) with an apparent vertical extension in the order of 150 m (Figure 2d). Average location errors on a 2$\sigma$ confidence level are 57, 52, and 94 m into the eastern, northern, and vertical directions, respectively. Considering the vertical location accuracy, the apparent thickness of the structure is primarily caused by

Figure 1. Sketch of shear stress redistribution for slip on the central patch. The black arrow denotes slip vector on the central patch. The amount of shear-stress redistribution is indicated in percent of the stress drop on the central patch. For example, if the stress drop on the central patch is 1 MPa, then the stress transfer to the adjacent patch in slip direction is 0.178 MPa. Circle indicates scaling to source radius r as referred to in the text.
data scattering, thus supporting the single-plane interpretation (Figure 2d). About 86% of the seismic events exhibit a $P$-wave polarity pattern that is consistent with the compound fault plane solution determined from previous seismicity (Figure 2b).

Based on the circular crack model of Brune (1970), seismic moment and stress drop were determined by fitting $S$-wave spectra with an $\omega^{-2}$ model. A constant time window of 0.3 s was used, and the displacement spectra were corrected by the average $Q$-value ($Q = 112$) determined for a different set of induced events in the Cooper Basin reservoir (Baisch et al., 2009). A minimum signal-to-noise criterion was implemented into the fitting procedure, discarding data where the spectral signal amplitude does not exceed the noise amplitude at least by a factor of 10. Noise spectra were determined on a 0.2 s time window immediately prior to the $P$-onset. From a total number of 20,736 located events, source parameters could be determined for 12,161 events. The resulting corner frequencies are strongly clustered around 10 Hz, independent of the seismic moment (Figure 3). This may indicate that spectral fits are dominated by unmodeled contributions of the signal attenuation and that corner frequencies are not correctly resolved, which was not recognized in a previous study (Baisch et al., 2009). Sensitivity tests based on different $Q$-models yield a dependency of corner frequencies from the assumed attenuation model, whereas the seismic moment is affected only to a small extent. For example, average corner frequencies increase by a factor of 2.6 when assuming $Q = 50$, while seismic moment, on average, changes by approximately 5%.

It is thus assumed that the seismic moment of the 12,161 events for which source parameter could be determined is reasonably well constrained by seismogram data. For these events, the moment magnitude $M_w$ was

Figure 2. (a) Map view of absolute hypocenter locations of earthquakes induced during Habanero#4 stimulation in 2012. The region of previous seismic activity is indicated by contour lines. The solid contour line indicates the 2003 seismic activity (Baisch et al., 2006), and the dashed contour lines indicate the 2005 seismic activity (Baisch et al., 2009). Coordinates are given with respect to the top of Habanero#1 ($27^° 48'59''S/140^° 45'35''E$). Fracture intersection of the Habanero#4 injection well is indicated by a star. (b) Stereographic projection (lower hemisphere) of $P$-wave polarity data for 525 of the strongest earthquakes (Baisch et al., 2015). Beachball indicates compound fault plane solution determined from previous seismicity (Baisch et al., 2009). (c) Absolute hypocenter locations in perspective view with best fitting plane determined by linear regression. (d) Histogram of vertical distances of the absolute hypocenter locations to the best fitting plane. The dotted line denotes the normal distribution with 0 mean and 47 m standard deviation corresponding to the average location error into vertical direction.
determined using the relationship of Hanks and Kanamori (1979). Linear regression indicates that moment magnitude scales with local magnitude $M_L$ by (see also Figure S1 in the supporting information)

$$M_w = 0.65 \times M_L + 1.12 \quad (4)$$

which is approximately consistent with the two-third scaling factor expected from theory (Deichmann, 2017; Munafò et al., 2016). For those 8,575 events, for which seismic moment could not be determined from source spectra, $M_0$ was determined from local magnitude using Equation 4 and the moment magnitude definition (Hanks & Kanamori, 1979).

For the current data set, where the seismicity occurs on a single plane and predominantly exhibits the same slip direction, the cumulative shear slip associated with multiple events can be estimated by simply adding the individual slip contribution of events with overlapping source area. Since corner frequencies (and hence stress drop) could not be resolved from the source spectra, a constant stress drop of 0.1 MPa was assumed for calculating cumulative slip. It is acknowledged, however, that this is an arbitrary value. Implications resulting from the constant stress drop assumption will be discussed at a later stage.

Based on seismic moment $M_0$ and an assumed stress drop of $\Delta \tau = 0.1$ MPa, the slip area

$$A = \pi \cdot (7 \cdot M_0) / (16 \cdot \Delta \tau)^\frac{3}{2} \quad (5)$$

and the average slip

$$d = M_0 / (A \cdot G) \quad (6)$$

were determined for each event assuming a shear modulus of $G = 12$ GPa. The cumulative slip induced during the Habanero#4 stimulation (Figure 4) exceeds several centimeters over a large region of the reservoir and reaches a peak value of 27 cm close to the injection well. Given that the Brune (1970) model yields submillimeter to about 7 mm slip for an earthquake in the magnitude range under consideration, deduced cumulative slip values provide indication for the occurrence of pronounced repeated slip due to overlapping source areas of different earthquakes.

4. Spatio-temporal Evolution of Pore Pressure

For applying the methodology introduced above, hypocenters of all 20,736 seismic events were projected onto the best-fitting plane determined by linear regression. Subsequently, projected hypocenters were rotated into the horizontal plane and the coordinate system was aligned with the $S_H$ direction. A discrete grid of dimensions $2,910 \times 1,910$ m and 10 m spacing was introduced, representing the slider block model. Grid dimensions were chosen such that the entire region of seismic activity is covered and that the slip area of the smallest magnitude event ($M_w = -0.25, A = 170$ m$^2$) is slightly larger than the size of a single grid cell ($A = 100$ m$^2$) to avoid undersampling.
Assuming a circular fracture model centered on the hypocenter, the grid cells $\Sigma_i$ associated with the slip area of each individual event $i$ were determined by Equation 5 assuming a stress drop of 0.1 MPa. Minor adjustments to the assumed stress drop were applied to account for the inherent error resulting from approximating a circular slip area with rectangular grid cells. By requiring conservation of moment, the event specific stress drop values were adjusted such that the seismic moment of the circular and rectangular slip geometries were the same. Resulting variations of the stress drop are generally smaller than 0.0002 MPa.

Until here, each of the 20,736 earthquakes has been associated with a set of $n \geq 1$ slip patches on the discrete grid representing the slip area $\Sigma_i$ of the $i$th event. Subsequently, stress changes were determined in an iterative procedure:

1. A memory variable of the shear stress on each grid cell was initialized with arbitrary values. For simplicity, initial shear stress was globally set to 0. It should be kept in mind, however, that the proposed approach is independent of any assumption on the initial stress conditions (see Equation 3).
2. Seismic events were sorted in chronological order. Starting with the first event $i = 1$, the constant stress drop $\Delta \tau$ was subtracted from the stress memory variable for all grid cells $\Sigma_i$ associated with event $i = 1$.
3. Subsequently, the stress propagator shown in Figure 1 was applied to simulate the shear stress transfer to adjacent grid cells. For this, the propagator pattern was scaled to the source radius of event $i = 1$ as indicated in Figure 1. The transferred stress values resulting from the propagator pattern were added to the memory variable, which is now representing the spatial shear stress distribution at time $t_i = 1$.
4. For the current data set, changes in normal stress were assumed to be of secondary order and were thus neglected (compare the discussion section). The proposed methodology, however, is not limited to this assumption, and changes in normal stress could be considered in the same way as shear stress changes.
5. Steps 2 and 3 were repeated for events $j = 2, \ldots, n$. Whenever the slip area $\Sigma_j$ of event $j$ includes a grid cell $\kappa$ that has previously experienced slip during event $i$, Equation 2 was used to solve for fluid pressure changes $\Delta P(r, t_i, t_j)$ with $r$ denoting the location of cell $\kappa$. A constant coefficient of friction of $\mu = 1.0$ was assumed.

Figure 5 shows the resulting distribution of cumulative fluid pressure changes determined from overlapping slips at the six locations in the reservoir indicated by corresponding colors in the small figure inset. Five locations were selected along a profile line connecting the grid cell with the largest cumulative pressure change (red) with the northern rim of the zone of seismic activity. The sixth location (yellowish green) was selected at the eastern rim of the seismically active zone. (bottom) Temporal evolution of the pressure changes $\Delta P_{\text{whd}}$ measured at the wellhead of Habanero#4 during the stimulation. Pressure changes were determined by subtracting the initial overpressure of 33 MPa from pressure readings. The gray lines indicate flow rate $Q$ and cumulative injected volume $V_{\text{cum}}$, respectively. See text for details.
blocked and the Habanero#3 well was cemented following a blowout. Daily averaged wellhead pressure was in principle recorded continuously at the Habanero#1 wellhead with a memory tool. Associated data, however, are missing in the data base of the operator for unknown reasons. Therefore, pressure changes inferred in the current study can only be compared to pressure data measured at the wellhead of the Habanero#4 injection well.

When comparing inferred $\Delta P(r, t_i, t_j)$ with wellhead pressure it needs to be accounted for that cooling the well during injection causes additional overpressure at reservoir level, which is not measured at the wellhead. Although not explicitly modeled, this effect is estimated to gradually increase from 0 to 2.4 MPa during the injection.

The largest pressure changes are observed approximately 140 m southeast of the injection well (red). Here, earthquakes with overlapping slip area occurred already at an early stage of the prestimulation on 14 November 2012. Inferred pressure changes at this location are predominantly positive leading to a systematic increase of cumulative pressure changes. On average, the temporal evolution of pressure changes at this location appears to be consistent with the evolution of the wellhead pressure. On a smaller scale, however, negative pressure changes of smaller magnitude occur. These are interpreted to result from the idealized source geometry and the constant stress drop assumption inevitably leading to errors in mapping the slip distribution of an individual event. As more neighboring earthquakes with overlapping source area occur, however, the impact of the individual source geometry tends to average out.

It should be noted that this averaging effect only works if negative pressure changes are not discarded in the processing scheme.

After 28 December 2012, inferred cumulative pressure changes at this location systematically exceed the pressure changes measured at the wellhead by up to 5 MPa. Accounting for the temperature-density effect resulting from well cooling (as discussed above), inferred pressure changes are still 2–3 MPa larger than those measured at the wellhead. Basic physical principles require that pressure changes at any location inside the geothermal reservoir cannot exceed the maximum overpressure applied at the injection well. Although a short pressure pulse of ~35 MPa is measured at the wellhead on 27 December 2012, pressure changes at the wellhead are systematically smaller than inferred pressure changes thereafter. This may indicate that inferred pressure changes are slightly overestimated due to one of the factors discussed in the next section.

The evolution of pressure changes at the more distant locations to the North of the injection well exhibits similar characteristics. As could be expected from a hydraulic diffusion process, the amplitude of the pressure changes decreases and the delay increases with distance from the injection well. A remarkably different signature is observed near the Eastern rim of the zone of seismic activity (yellowish green). Here, inferred pressure changes are predominantly negative implying systematic shear stress accumulation, which is not
compensated by seismic slip. The associated fracture patches exhibit overcritical stress conditions even when the hydraulic pressure is lower than the initial pressure. The eastern rim of seismic activity was previously interpreted to reflect a structural limit where the fault zone is vertically offset (Baisch et al., 2015). In this case, Equation 1 becomes invalid as slip beyond the Eastern rim requires fresh fracture propagation.

Figure 6 shows the spatial distribution of cumulative pressure changes at four different times. At each grid cell, cumulative pressure changes were linearly interpolated in time for displaying the cumulative pressure changes at different grid cells on a common time basis. No information exists at those grid cells where either no repeated slip has occurred at a given time, or where the repeated slip sequence has already terminated. Associated grid cells are displayed in white. It should be noted that the cumulative pressure changes are stated relative to the pressure level at which the first slip occurs, which can vary over the grid. At an early stage of the injection, relative pressure increase is concentrated within a few hundred meters of the injection well (Figure 6a) and propagates outwards with increasing injection time. It is not finally clear why maximum pressure changes are not exactly centered at the injection point. As a possible explanation, the observed ~140 m offset between injection well and the region of largest pressure changes might be caused by a systematic bias of hypocenter locations resulting from the assumed seismic wave velocity model (see Baisch et al., 2015, for details regarding the hypocenter location procedure).

Positive pressure changes are frequently accompanied by small-scale negative changes on adjacent patches, which is attributed to inaccuracies of the stress mapping discussed above.

5. Discussion

I have proposed an approach for inferring fluid pressure changes from fracture patches slipping repeatedly during fluid injection experiments. Spatio-temporal changes of stress conditions are inferred from observed seismic moment of induced earthquakes in combination with a slider-block model describing coseismic stress redistribution. The stress deficit required to reach stress criticality at the time of observed failure is used to determine fluid pressure changes in between the time of successive activation of the same slip patch.

An important characteristic of the proposed methodology is that it is independent of absolute stresses, and no assumption is required regarding tectonic stresses. In particular, the methodology can be applied even if the initial (tectonic) stress conditions are strongly heterogeneous. In this respect, the proposed methodology differs from previous approaches suggested by, for example, Terakawa et al. (2012) and Mukuhira et al. (2017), which infer absolute fluid pressure by directly solving Equation 1 under the assumption of homogeneous (tectonic) stress conditions. Although, at a certain project location, this assumption might be justifiable prior to fluid injection, it may become invalid during fluid injection as induced seismicity can lead to a strongly heterogeneous stress field on a reservoir scale. This follows immediately from Figure 1. Compared to previous approaches by, for example, Mukuhira et al. (2017), Shapiro et al. (1997), Talwani and Acree (1985), or Terakawa et al. (2012), the current approach also differs in the way induced earthquakes are represented. While the previous approaches are based on a point source approximation, the current approach takes the physical dimensions of the induced earthquakes into account, providing the basis for considering earthquake-earthquake stress interaction.

5.1. Dominating Processes

The proposed approach is based on several simplifying assumptions focusing on processes that are considered to be of first order. Induced earthquakes are assumed to be driven by hydraulic overpressure and shear-stress redistribution following seismic slip, while poroelastic and thermoelastic processes are ignored. In principle, contributions from these processes could be quantified by numerical modeling, which has not been done here. It is noted, however, that direct pressure effects are often assumed to dominate over poroelastic stresses in regions with good hydraulic coupling to the injection well (e.g., Buijze et al., 2019), as is the case for the fault that was stimulated during the Habanero#4 injection. Furthermore, numerical simulations by Jeanne et al. (2017) indicate that thermoelastic stresses associated with cold water injection into a fault are mostly restricted to the cooled rock area (Figure 10i in Jeanne et al., 2017). For the Habanero#4 stimulation, the cooled area is estimated to be in the order of a few tens of meters around the injection well. Therefore, thermoelastic contributions to shear stress are considered a second-order effect in the current context.
Another assumption is that all induced deformation is seismic. Several deca-scale fluid injection experiments in sedimentary rocks demonstrate that aseismic deformation can dominate over seismic deformation, for example, De Barros et al. (2018) or Duboeuf et al. (2017). For a hydraulic stimulation in granitic rock at Soultz-sous-Forêts, Cornet et al. (1997) arrives at a similar conclusion. Noting that observed shear-slip at the borehole wall is much larger than suggested by the maximum earthquake magnitude occurring during injection, they conclude that most deformation during the hydraulic stimulation must have been aseismic. This line of argumentation, however, does not consider the possibility that slip contributions of multiple events may accumulate if the associated events occur on the same fault plane. Subsequent investigation of the seismicity induced at Soultz-sous-Forêts has revealed strong limitations of the downhole seismic monitoring network, causing pronounced scattering of the hypocenter distribution, which was previously interpreted in terms of fracture complexity. If location uncertainty is accounted for, most of the seismicity in the deep Soultz-sous-Forêts reservoir could actually have occurred on the same fault (Baisch et al., 2010). In this case, observations of large shear deformation at the wellbores could be explained without having to assume contributions from aseismic slip. For the current data set the relevance of aseismic deformation is unknown and it remains a hypothesis that first-order characteristics of the failure process can be described by the simple model proposed here.

### 5.2. Interpretation of Inferred Pressure Changes

A limiting factor in resolving relative pressure changes, as done with the current approach, is the unknown reference pressure, which can complicate the interpretation of inferred pressure changes. In a straightforward approach, inferred pressure changes can be compared to pressure changes predicted by a numerical model, in which case the accuracy of the numerical model can be evaluated. For illustrating this approach, the pressure evolution during the Habanero#4 injection has been numerically simulated with a simple finite element model. The underlying finite element model consists of a horizontal fracture with homogeneous hydraulic properties embedded into an impermeable rock matrix. Simulations were performed with Comsol Multiphysics assuming Darcy flow and model parameters according to Table 1. Spatial model dimensions are 3 km × 5 km with a no-flow boundary implemented 400 m to the east of the injection point. All other boundaries are implemented as constant pressure boundaries mimicking coupling to the far-field. Figure 7 shows simulated pressure as a function of time at five different locations. The locations are the same as in Figure 5, but the injection well has been moved by approximately 140 m for matching the location of the largest inferred pressure changes (compare the discussion in the previous section).

For comparison, pressure changes inferred from induced seismicity at the two locations close to the injection well are overlain by assuming a location-specific reference pressure. In principle, the reference pressure at a certain location is defined by the numerically simulated pressure value at the time of the first seismic activation at this location. The ~140-m location uncertainty of the positions at which pressure values were inferred, however, also implies an uncertainty of the reference pressure. This uncertainty is largest near the injection well, where spatial pressure gradients are most pronounced. Therefore, the reference pressure was adjusted by eye in order to optimize agreement between simulated and inferred pressure curves.

Near the injection well (red curve in Figure 7), the amplitude of the two pressure peaks during prestimulation on 14 and 15 November 2012 is overpredicted by the numerical model, which could, for example, indicate that the permeability in the near-wellbore region is higher than assumed in the model or that the compressibility is

### Table 1

| Parameter                  | Value       |
|----------------------------|-------------|
| Fracture transmissibility  | 3e⁻¹³ m²/s  |
| Porosity-thickness product | 0.27 m      |
| Fluid compressibility      | 4e⁻¹⁰ Pa⁻¹  |
| Rock compressibility       | 7.3e⁻¹² Pa⁻¹|
| Fluid viscosity            | 2.1e⁻⁴ Pa.s |

Figure 7. Numerically simulated pressure during Habanero#4 stimulation as a function of time at different locations as indicated in the inset (top right). At two locations, modeled pressure (red and blue lines) is compared to pressure changes inferred from repeated slip (red and blue crosses). Inset shows the underlying finite element model in top view. The colored squares denote the locations of observation points for which pressure changes are shown in the main plot.
underestimated. Comparison of the pressure increase during the main stimulation starting 19 November 2012 exhibits a temporal offset (red curves), which could indicate that the assumed storativity is too small. Starting at 22 November 2012, the two curves start to systematically deviate. This could result from the small dimension of the numerical model in combination with the assumed constant pressure boundaries to the north, west, and south, limiting pressure amplitude and causing rapid pressure fall-off after the injection. By using a larger-scale model with no-flow boundaries in all directions, the simulated pressure curve (red) can be bent upward to better match the inferred pressure changes. At the same time, no-flow boundaries can enhance post-injection pressure increase at the most distant location (brown curve in Figure 7) to better match inferred pressure changes (compare Figure 5), which are not well represented by the current model.

A good match of the pressure amplitude during prestimulation is obtained at the second location (blue curve in Figure 7), while the pressure during the main stimulation is slightly overpredicted by the numerical model. This could be another indicator for a larger storativity than assumed in the numerical model.

As part of ongoing research we are currently developing an iterative procedure, where deviations between inferred pressure changes and numerically simulated pressure are minimized through adjusting model parameters. In our approach, fracture permeability can be spatially heterogeneous and time-dependent to account for stimulation effects.

### 5.3. Constant Stress Drop

For the current data set, corner frequencies, and hence source radii, could not be determined reliably due to signal attenuation of the high frequencies. Instead, a constant stress drop value of 0.1 MPa was chosen for all events, making the simplifying assumption that the coseismic stress changes associated with each event are homogeneous over the source area. Hereby dynamic slip evolution is ignored, which can lead to heterogeneous stress changes over the source area. These simplifying assumptions inevitably lead to a mismapping of the spatial seismic slip distribution of an individual earthquake. As discussed by Baisch et al. (2009), the impact of the assumed stress drop on the cumulative slip distribution tends to average out if the slip area of neighboring earthquakes is overlapping. The inferred pore pressure evolution benefits from the same averaging effect. This is demonstrated in Figure 8 showing the spatial distribution of the maximum fluid pressure changes inferred from repeated slip in map view. The time at which the maximum cumulative fluid pressure change is reached varies over the reservoir. Pressure changes are stated in megapascals according to the color map, which is saturated at 20 MPa. The star denotes the fault intersection of the well Habanero#4. The contour line denotes the main region of seismic activity as outlined by the hypocenter distribution. The arrow indicates the north direction. A constant stress drop of (a) 0.1 MPa, (b) 0.5 MPa, and (c) 1.0 MPa was assumed for determining fluid pressure.

![Figure 8](image.png)
pressure change at each grid cell for three different constant stress drop models of 0.1, 0.5, and 1.0 MPa, respectively. As noted above, any interpretation of the spatial pattern is conditional upon the reference pressure being the same over the entire grid.

Although the location of maximum pressure changes deviates on a smaller scale in the three models, similar patterns are observed within 500 m of the injection well. The higher stress drop models (i.e., 0.5 and 1.0 MPa) exhibit larger spatial fluctuations of the inferred pressure changes. In an extreme case, the inferred pressure changes vary between positive and negative values on adjacent grid cells. This is interpreted to result from the decreasing number of repeated slips associated with the higher stress drop models. In the 0.1-MPa stress drop model, the maximum number of slip repetitions on a grid cell is 471. This value decreases to 185 and 129 repetitions in the 0.5- and 1.0-MPa stress drop models, respectively. Consequently, the averaging effect decreases with increasing stress drop.

If the event-specific stress drop cannot be determined from observation data, as in the current data example, the choice of a specific constant stress drop value reflects a compromise between resolution and scattering, both increasing with the assumed stress drop. For the sake of data smoothing, I have chosen a low stress drop value of 0.1 MPa. With this choice, resulting pressure changes are mostly smaller than those measured at the wellhead, consistent with basic physical principles. This consistency is not obtained for the two higher stress drop models tested here. It is worth noting, however, that the pattern of pressure increase within 500 m of the injection well and the prevailing negative fluid pressure changes at the Eastern reservoir boundary are observed even when varying the assumed stress drop by 1 order of magnitude. These observations can be crucial for the development strategy of a geothermal reservoir in order to reach economic scale.

5.4. Stress Propagation
For deriving fluid pressure changes in the Cooper Basin reservoir, changes of normal stresses were neglected. This simplifying assumption is motivated by the maximum injection pressure at reservoir level being 15–20 MPa smaller than the least principle stress (Holl & Barton, 2015). Under these conditions, hydraulic fracture opening is restricted to shear dilation where the fracture opening component is small compared to the shearing component as observed, for example, in laboratory experiments (Chen et al., 2000).

It is also worth noting that stress propagation has a significant impact on the inferred fluid pressure changes. If stress re-load was neglected (i.e. assuming $\Delta \tau_r(\mathbf{r} \notin \Sigma, t_i, t_j) = 0$ in Equation 3), inferred fluid pressure changes during the Habanero#4 stimulation would be by up to a factor of approximately 5 larger, which clearly contradicts observations.

5.5. Catalogue Completeness
The inferred pressure changes are depending on the completeness of the earthquake catalogue. For an earthquake missing in the catalogue, pressure changes at the associated slip patches will be underestimated, whereas pressure changes at the neighboring patches are overestimated since stress re-load from the missing event is not considered. Underestimating pressure is the dominating effect.

The maximum curvature method (Wiemer & Wyss, 2000) indicates catalogue completeness down to the magnitude level $M_L \approx -1$ (Figure S2). Contributions from smaller magnitude events to the total seismic moment are estimated to be minor. For example, the cumulative moment of events in the magnitude range $M_L = -5$ to $M_L = -1$ is in the order of 10% of the observed cumulative moment assuming a $b$-value of 1. Since the proposed approach is based on mapping seismic moment, effects on pressure changes associated with earthquakes below the detection threshold are considered to be small.

Although most earthquakes induced in the Cooper Basin reservoir share the same fault mechanism, deviating fault plane solutions were obtained for a small number of events. Their contribution to the cumulative slip was estimated to be 14% (Baisch et al., 2015). It is possible that the associated earthquakes occurred on smaller fractures intersecting the main fault plane, in which case the inferred pressure distribution is biased by falsely including these earthquakes in the analysis. Compared to earthquake misses, the impact is reversed and fluid pressure changes are predominantly overestimated. Based on the linear relationship between changes of fluid pressure and shear stress (Equation 2), associated errors are estimated to be in the order of 14%.
5.6. Other Sources of Uncertainty

Inferred pressure changes depend on the coefficient of friction according to Equation 2. In the current study a constant coefficient of friction of $\mu = 1.0$ is assumed, which is at the upper end of values determined from laboratory experiments (Beblo et al., 1982; Zang & Stephansson, 2010). Assuming a smaller coefficient of friction primarily affects the amplitude of inferred pressure changes but not the spatial pattern. For example, assuming $\mu = 0.8$ increases peak pressure changes in Figure 5 and Figure 6 by approximately 5 MPa.

Errors in determining the seismic moment also affect inferred pressure changes. While random error contributions of event specific seismic moments tend to average out, systematic bias, for example, resulting from the assumed $S$-wave velocity or the rock density, has a systematic impact on the inferred fluid pressure changes. For example, overestimating seismic moment by a factor of 1.5 leads to overestimating pressure changes by approximately 16% in Figures 5 and 6.

In the current approach, fracture cohesion is neglected (see Equation 1), which, in principle, could bias inferred pressure changes. The impact of this assumption, however, is considered low since pressure changes are inferred from repeated slip and are independent of the fracture cohesion acting at the first activation. It is assumed that barriers and asperities of a fracture are broken in the course of the first fracture activation and that the same fracture behaves cohesionless thereafter over the timescale of the injection experiment.

5.7. Further Applications

In the current study hydraulic pressure changes were inferred from seismicity repeatedly activating the same patches of a large-scale, planar fault. Within this geometrical simple model, stress interference of adjacent earthquakes can be treated with a straightforward approach based on the slider-block concept. Observations from fluid injection experiments into crystalline basement indicate that other geothermal reservoirs could also be dominated by larger-scale faults, in which case the proposed methodology might also be applicable. For example, seismicity induced by fluid injection into a geothermal reservoir underneath the city of Basel aligns along a subvertical planar structure (Figure 7 in Häring et al., 2008). Most of the relative hypocenter locations determined for earthquake clusters with similar waveforms did not reveal any substantial thickness of the structure on which the seismicity occurred (Deichmann et al., 2014). Fault plane solutions, however, show larger variations than observed in the Cooper Basin data set, making Deichmann et al. (2014) conclude that the internal structure of the fault is more complex. These authors nevertheless find evidence for the local occurrence of repeated slip of the same fault patches.

Another example for a potentially fault-dominated reservoir is the deep geothermal system at Soultz-sous-Forêts. Although previously characterized by a complex fracture network (e.g., Michelet & Toksöz, 2007), recent analysis of the Soultz-sous-Forêts reservoir indicates that the fracture complexity deduced from the cloud of hypocenter locations might primarily be an artifact of ill-constrained data and that the reservoir might be dominated by a single fault (Baisch et al., 2010). Fault-like structures outlined by fluid injection induced earthquakes were also identified in the context of waste-water disposal (e.g., Schoenball et al., 2018) and hydraulic fracturing (e.g., Wessels et al., 2011). To what extent the proposed methodology can be applied to these data examples is subject of future research.

Due to the lack of cross-well pressure measurements in the current data set, the applicability and accuracy of the proposed method have not yet been confirmed by independent measurements. Including such measurements in future applications could add further confidence to the pressure changes inferred with the proposed approach.

6. Conclusions

A new approach for inferring relative fluid pressure changes from induced seismicity observations is presented. The method is based on fracture patches slipping repeatedly during fluid injection, in which case relative changes of stress conditions can be related to relative changes of the in situ fluid pressure at the time of fracture reactivation. The approach does not require assumptions on absolute (tectonic) stresses and can be applied in a scenario where the (unknown) tectonic stresses are strongly heterogeneous.

The performance of the proposed methodology is demonstrated using a data set of seismicity induced during hydraulic stimulation of a geothermal reservoir in the Cooper Basin, Australia. In this data example,
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Seismograms used in this study were collected using local seismic networks operated by Q-con GmbH on behalf of Geodynamics Limited (now Renu Energy Limited). Waveform data and seismic event catalogues are available to the scientific community through the Department of State Development (SDS) of South Australia. Data can be requested by email (dpc.petroleum@sa.gov.au) and will be transferred on external hard drives due to the large size of the data set. The earthquake catalogue and hydraulic data used in this study are available at IS EPOS (Leptokaropoulos et al., 2019), doi.org/10.25171/InstGeoph_PAS_ISEPOS-2020-001. I would like to thank Geodynamics Limited (now Renu Energy Limited) for allowing me to publish this study. I thank Christopher Koch assisting me in preparing the manuscript and Robert Vörös for conducting the FE simulation. I gratefully acknowledge valuable comments by Douglas Schmitt and four anonymous reviewers, which helped to significantly improve the initial manuscript. This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement 764810.

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Seimicity occurs on a single, large-scale plane with fault mechanisms driven by the regional stress field. Based on the seismic moment determined from source spectra, the slider-block concept is used for modeling the coseismic stress changes associated with each earthquake. Relative changes of stress conditions on a particular fracture patch are determined by superimposing the stress contributions from neighboring earthquakes. Due to the large number of fracture patches slipping repeatedly, the temporal evolution of relative stress changes (and hence relative changes of the in situ fluid pressure) could be inferred over a large area of the geothermal reservoir. Inferred pressure changes indicate that fluid flow during Habanero®4 stimulation is not radial symmetric but most pronounced into NW-SE direction. This is an important constraint for the conceptual understanding of the reservoir and for assessing reservoir performance.

The proposed methodology can potentially be applied at other locations where pronounced seismicity has occurred. Besides enhanced geothermal reservoirs, hydraulic fracturing and waste-water disposal sites are potential candidates. In principle, the methodology is not limited to the specific setup where induced seismicity aligns along a single, larger scale plane as in the data example presented here.
