# Fluid-induced anthropogenic and natural earthquake swarms driven by aseismic slip

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Key Points:

- Scaling laws show that injection-induced and natural earthquake swarms are following the same driving mechanism
- We show that aseismic slip contribution is always present, even if it differs from one swarm to another.
- We propose a model based on fluid-induced aseismic slip propagation that explains swarms behaviour

Abstract

Anthropogenic fluid injections at depth induce seismicity which is generally organized as swarms, clustered in time and space, with moderate magnitudes. Earthquake swarms also occur naturally in different tectonic contexts. While some similarities between natural and injection-induced swarms have already been observed, whether they are driven by the same mechanism is still an open question. Indeed, they are commonly related to fluid pressure processes, while recent observations suggest the presence of aseismic slip driving seismicity. Based on such observations, we propose a simple model that combines fluid and aseismic processes, in which seismicity is triggered by fluid-induced aseismic slip. The model reconciles the seismicity migration observed in natural and anthropogenic swarms, and allows us to quantify the seismic-to-total moment ratio. By validating our approach using 22 earthquake swarms, both from natural and anthropogenic origins, our findings provide a generic explanation of the swarm driving process.

## Plain Language Summary

Swarms are a particular type of seismic sequence, during which many earthquakes occur but with no mainshock distinguishable from the other events. They can be induced by anthropic injections at depth, like during geothermal exploitation. Natural swarms are also observed in a large variety of geological contexts. Natural and injection-induced swarms share a lot of similarities, like the migration of seismicity. But little is still known about their physics. Here, we explain the observed similarities by the fact that both types of swarms correspond to earthquakes triggered by the propagation of an aseismic slip transient, induced by fluid circulation. This allows to reconcile observations made over different length- and timescales, and provides a generic explanation of the processes occurring at depth.

1 Introduction

Fluid pressure changes at depth can induce seismicity, as shown by the increase in seismicity near fluid injection sites during geothermal activities (e.g., in Basel, Switzerland; Diechmann and Giardini, 2009) wastewater storage in Oklahoma (Hincks et al., 2018), or during fault activation experiments in France (Guglielmi et al., 2015). On the other hand, earthquake swarms of natural origin (i.e., sequences of clustered earthquakes with moderate magnitudes, generally below $M_w = 5$, without a mainshock-aftershock pattern) occur in various geological and tectonic contexts, such as mountain ranges (Jenatton et al., 2007), rift zones (De Barros et al., 2020) or along transform faults (Roland and McGuire, 2009). Earthquakes during those swarms are located over one or several fault planes *(*Lohman et McGuire, 2007; Baisch et al., 2009: Hong et al., 2020; Fischer et Hainzl, 2021*).* Migration of seismicity is the most characteristic behavior of both injection-induced and natural earthquake swarms (Goebel et Brodsky, 2018*;* Passarelli et al., 2018). Proposed physical explanations for swarm migration include fluid pressure diffusion (Shapiro et al., 1997), aseismic slip (Roland et McGuire, 2009), or a combination of both (De Barros et al., 2021), as well as cascading events (Fischer et Hainzl, 2021). However, identifying common properties and driving processes among swarms from different contexts and origins is complicated because of a lack of constraints on fluid circulation and deformation at depth. Understanding such processes is crucial to risk mitigation, especially for anthropic injections which can lead to dangerous quakes (Woo et al., 2019). To gain deeper understanding into these processes and evaluate how generic they are, here we compare injection-induced swarms with natural ones. Given the similarities identified here between the two types of swarms, we aim at evaluating if a common process may drive swarms in different geological contexts and origins.

2 Materials and Methods

## 2.1 Data

We focus on a global dataset of 22 earthquake swarms, from either injection-induced or natural origin. For natural sequences, geological contexts are diverse: for instance, the 2003-2004 Ubaye swarm (Jenatton et al., 2007) occurs in a near-zero strain-rate area in the French Alps, while the 2015 Corinth swarm (De Barros et al., 2020) takes place in a very fast extensional (~15 mm/year) rift zone in Greece. We here focus on natural swarms in which fluid processes have been previously discussed, and we do not consider swarms taking place near volcanoes or in subduction zones. Most of the injection-induced swarms we consider originated from geothermal exploitation. However, they span a wide range of characteristics, including the injected fluid volume and the injection depth (see Supp.).

## 2.2 Migration velocity

Migration velocity of the 22 swarms is computed by fitting the seismicity front. Seismic front has been modelled by either diffusive law, linear fit or more complex relationships. The shape of the migration is here not investigated, as we only focus on an average migration velocity, in order to make comparisons among the different swarms. Migration period is defined as the time during which the swarm is expanding. The spatial origin is chosen as the median of the coordinates of the 10 first events, and the origin time is defined as the time of the first event. We define the seismicity front as the $90^{\text{th}}$ percentile of event distances in a sliding window containing 50 events. We fit linearly the seismicity front with time, allowing us to get an average velocity for each sequence.

## 2.2 Seismicity area and effective stress drop computation

Following (Fischer and Hainzl, 2017), seismicity area is computed by fitting a 2D plane over the 3D distribution of hypocenters, after removing the outsiders biasing the plane fitting. Hypocenters are then projected over the plane, and a ConvexHull algorithm delineates and returns the seismicity area S. We then compute a characteristic size, defined as $\mathrm{R} = \sqrt{\mathrm{S}/}$.

The effective stress drop value is an indicator of the relative importance of aseismic moment release (Fischer and Hainzl, 2007): a low effective stress drop suggests distant seismic asperities embedded in a fault slipping aseismically, while values close to earthquake static stress drops suggest that seismic asperities cover most of the slipping area. By analogy with the moment-size rela-

### 3.1 Similar behavior of natural and injection-induced earthquake swarms can be explained by the propagation of aseismic slip

The migration of injection-induced and natural earthquake swarms has been generally explained as resulting from fluid pressure diffusion (Shapiro et al., 1997; Parotidis et al., 2003; Chen et al., 2012), but more recent evidence associates fluid circulation and seismicity, natural or human-induced, with aseismic slip (Guglielmi et al., 2015; Wei et al., 2015; Eyre et al., 2019). Aseismic moment release is thought to occur for injection-induced sequences, as revealed by moment-volume scaling relations (McGarr et Barbour, 2018; De Barros et al., 2019). It has also been observed for some sequences either directly with geodesy, like in the vicinity of a fluid injection site in the Brawley Basin (Wei et al., 2015), or indirectly by studying repeating earthquakes during the Soultz-Sous-Forêt sequences (Bourouis and Bernard, 2007; Lengliné et al., 2014). The relatively weak values of seismic moment released compared to the seismicity area also indicate that aseismic slip occurs over the whole seismicity area (Fischer and Hainzl, 2017). Aseismic slip has also been observed in association with natural swarms, using geodesy and slip inversions (Lohman and McGuire, 2007; Gualandi et al., 2017), or like during the 2015 swarm in the Gulf of Corinth, where repeating earthquakes and dual velocity migrations indicate that aseismic slip drives the increasing phase of seismicity in a regional context prone to fluid circulation (De Barros et al., 2020). Nevertheless, geodetic observations of aseismic slip associated with swarms remain rare and difficult to achieve, given the depth, long duration and

Figure 1. Common model for natural and induced swarms. (A) Conceptual view. Over a fault plane, fluid overpressure (blue arrows), either from anthropogenic or natural origin, induces aseismic slip (light green area). As the aseismic slip zone expands, it triggers seismicity near its edges (red patches) or within it (grey patches), through shear stress perturbation (brown curve, right). (B) Shear stress and fluid overpressure versus radial distance to the injection. The overpressure induces an aseismic slip, with a shear stress drop within the slipping area and a stress stress concentration at its tip.

This is analogous to the observed co-location of seismic and aseismic slip areas during large slow slip events (SSEs) in subduction zones, as in Cascadia (Bartlow et al., 2011). The seismic events (tremors or earthquakes) are triggered by the stress transfer from the SSEs, even though such SSEs are not necessarily driven by pore fluid pressure perturbation.

### 3.2 Aseismic slip drives the swarm's dynamics

If much evidence shows that aseismic slip plays a key role in the dynamics of both injection-induced and natural swarms, it should explain some of their characteristic features, like the migration of seismicity. For the 22 swarms studied here, we compute the migration velocity of each sequence (see Figure 2A-B). We fit a linear model over the seismicity front during the migration period of each sequence (see Methods). This procedure yields migration durations and average migration velocities for each sequence (Figure

**Figure 2.** Scaling of propagation velocity with duration for swarms and slow slip events (SSEs). (A) Space-time distribution of seismicity in the Basel sequence (Herrmann et al., 2019*)*. Blue dots represent individual event hypocenters while red circles represent the computed seismicity front. Linear fitting (magenta line) over the seismicity migration period, delimited by the vertical blue line, yields a propagation velocity of 81 m/day. (B) Same but for the Corinth 2015 swarm (De Barros et al., 2020). The seismicity front migrates at a velocity of 105 m/day. (C) Scaling of velocity with duration. Red dots represent SSE data from (Gao et al., 2012). Filled triangles and pentagons represent injection-induced and natural swarms, respectively, for which we determined migration velocity and duration based on seismicity catalogs. Empty symbols represent migration velocities and durations directly taken from the literature (see Supp.). Black line represents the best-fitting line between our computed velocities and durations ($R^2 = 0.76$).

Two main observations can be made. First, injection-induced and natural swarms follow the same scaling $V \;\; T^{-}$ of velocity with duration, with $\; = 0.6$ and $\; = 0.7$ when considering each subset individually. In addition to the other similarities discussed before, this is direct evidence that both types of swarms obey the same physics. As anthropogenic seismicity is induced (though indirectly) by fluid injection (Bentz et al., 2020), this confirms that natural swarms are also a consequence of fluid pressure perturbations. The continuous scaling of velocity with duration for

Figure 3. Seismicity area ($m^2$) as a function of the cumulative seismic moment released during 20 of the swarms studied here. Triangles correspond to injection-induced sequences while pentagons refer to natural swarms. Black lines represent different values of the effective stress drop $\Delta_e$.

Based on migration velocity and effective stress drop analysis, both natural and injection-induced swarms seem to share the same driving processes, in which aseismic slip seems ubiquitous. However, this aseismic contribution might be different from one swarm to another.

### 3.3 Aseismic contribution differs among swarms

Studies have shown that aseismic slip plays a key role in the moment release of injection-induced sequences (McGarr and Barbour, 2018; De Barros et al., 2019). However, aseismic slip quantification is difficult for injection-induced sequences. Indeed, deformations associated with those episodes are small, over durations from days to years, leading to small strain rates that are challenging to observe. This issue stays the same for natural swarms.

Once the total moment $M_{0,total}$ for each swarm is computed, we compare it to the seismic moment released by introducing the seismic to total moment ratio *r*:



$r = \frac{M_{0,seismic}}{M_{0,total}}$ (Equation 7)

A value of *r* close to 1 indicates that moment release is mainly seismic, while a lower value shows that moment release is significantly aseismic. We

**Figure 4. (A) Seismic to total moment ratio, as a function of the seismic moment released during each swarm, for the 20 sequences studied here. (B) Duration as a function of the estimated total moment. Black line represents the 1:1 scaling. Red dots correspond to the SSE data from Gao et al., 2012. (C) Seismic to total moment ratio for the swarms studied here, as a function of the product of the migration velocity and the effective stress drop. The black lines correspond to different values of $\frac{V_{max}}{n}$, assuming G = 30GPa (see Equation 8).**

**Interestingly, one can also note that the scaling of duration with estimated total moment (Figure 4b) seems to be 1:1, similarly to the scaling between event duration and aseismic moment observed for SSEs (Ide et al., 2007; Peng and Gomberg, 2010), while seismic moment vs duration does not exhibit such a scaling (Passarelli et al., 2018). Indeed, with our total moment estimate, we are able to measure the "hidden" aseismic slip release. As hypothesized (Peng and Gomberg, 2010), the apparent branching off of the swarms in the moment duration can be corrected when considering the aseismic deformation.**

For aseismic slips, rupture velocity can be related to the strength drop (i.e., peak to residual shear stress difference; Ampuero and Rubin, 2008; Rubin, 2008). If we suppose that the static stress drop $\Delta_{total}$ (i.e., initial to residual stress change) is proportional to the strength drop with a factor n (Hawthorne and Rubin, 2013; Lambert et al., 2021), we then have Equation 5.

Given that swarms are assumed to be driven by an aseismic slip (Figures 1,2), we can apply the same relation to the swarm sequences, with the rupture velocity being the migration velocity. Such a relation allows us to express the seismic-to-total moment ratio r (see Methods) as

$r = \frac{\Delta_{e} * n * V_{migr}}{G * V_{max}}$ (Equation 8)

We can therefore relate the seismic to total moment ratio to two observables, effective stress drop and migration velocity (see Figure 4). We estimate $V_{max}/n$ being between $10^{-10}$ and $10^{-7}$ m/s, which is consistent with expected orders of magnitudes (Roland and McGuire, 2009; Glowacka et al., 2001) if we consider a value of n~10 (Hawthorne and Rubin, 2013; Lambert et al., 2021). Variability in $V_{max}$ explains why the observed scaling between r and $\Delta_{e} * V_{migr}$ is not as linear as expected. As the general trend shows a scaling different than the isovalues of $V_{max}/n$, it means that $V_{max}$ also depends, through fault and stress properties, on the seismic-to-total seismic ratio. The slip velocity, together with the migration velocity and the effective stress drop, are the crucial parameters to characterize the seismic and aseismic moment partitioning in swarms. Among other properties, these three parameters depend on the stress state and on the proximity of the fault to failure (Hainzl and Fischer, 2002; Fischer and Hainzl, 2017; Passelègue et al., 2020; Wynants-Morel et al., 2020). These relationships therefore deserve to be investigated in order to anticipate the swarm evolution, especially given that similarities are found between swarms and foreshock sequences of some major earthquakes (Chen and Shearer, 2013).

**In this work, we confirmed that injection-induced and natural swarms are governed by the same physics, as was previously shown for particular sequences (Fischer and Hainzl, 2017). By analyzing sequences covering a wide range of geological contexts, migration velocities, durations and injected fluid volumes, we showed a global unity in the swarm's dynamics.New swarm catalog studies might help refine our findings. After confirming that fluid induced aseismic slip explains observations made on swarms, like their migration or their spatial seismic moment release, we exploited the similarities between swarms and slow slip events to introduce a simple mechanical framework that relates the seismic and aseismic moment partitioning to physical and observable parameters (Equation 8). This opens interesting perspectives to better understand swarms and improve their monitoring in order to anticipate potential large earthquakes.**

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**Open Research**

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