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# How to discriminate induced, triggered and natural seismicity

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## Abstract

Human operations, such as mining, hydrocarbon production, fluid withdrawal or injection, drilling, hydro-fracturing and reservoir impoundments, can positively and negatively impact tectonic stresses, pore pressure, fluid migration and strain in the sub-surface. Earthquakes occurring in spatial and temporal proximity to such operations are immediately under suspicion to be triggered or induced. The **discrimination between natural, triggered, and induced earthquakes** is a difficult task, and clear rules and scientific methods are not well established or commonly accepted. The current practice to distinguish possible causes of earthquakes is not quantitative and individual cases are treated unequally, which often leads to questions on general liability. This situation has a negative drawback for private and public claimants and for companies performing the operations. Moreover, estimations of earthquake-related risk is still difficult.

## Introduction and status quo

Figure 1 shows a number of significant earthquakes (M>3) in Germany and adjacent areas that are associated with geo-engineering operations. The events are related to different types of human operations, ranging from salt mining, coal mining, gas extraction to fluid injection associated with deep geothermal power generations. Some of the plotted events caused cessation of the mining or hydrothermal operations (Saarbruecken, Basel). Other operations as waste fluid injection, $CO_2$ sequestration or gas storage facilities may also induce or trigger seismicity. However, in the same way geo-engineering activities can bring fault zones close to failure, they can also bring them away from failure (for instance refilling of a gas reservoir or the decline of a water table in a mine). This means that the seismic risk in the vicinity of the operation point is reduced (Klose, 2010). Figure 1 indicates that operations affecting a larger area in the subsurface, such as salt mining, gas withdrawal or coal mining induced/triggered the strongest events with magnitudes up to Ml=5.5. However, the problem of the possible magnitude of a triggered earthquake is complex and additionally depends on the regional stress and pre-existing faults. Additionally, triggered/induced earthquakes typically occur within the uppermost 6 km of the crust and are often superficial. Therefore, even weak events with M<3 can be felt by the population and may pose a seismic hazard at the epicenter and are thus important for

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the subject (e.g. Soultz-Sous-Foret, Ml 2.9, 10 June 2003; Landau, Ml  2.7, 15 August 1009; Unterhaching; Ml  2.5, 3 July 2010). They have been discarded in Fig. 1 for the purpose of a complete catalogue.

The FKPE working group proposed three major tasks to assess the triggered seismicity problem: (1) monitoring, (2) discrimination of natural and human-related seismicity, and (3) legal aspects. The discrimination between natural and human-related earthquakes is difficult to assess. Basic structural, geophysical/geological data and detailed information about man-made operations are often missing. Additionally, our scientific understanding of the earthquake triggering process is incomplete. The aim of the working group is to develop recommendations how to assess the discrimination problem, and how the probability of occurrence of a triggered or induced earthquake can be estimated.

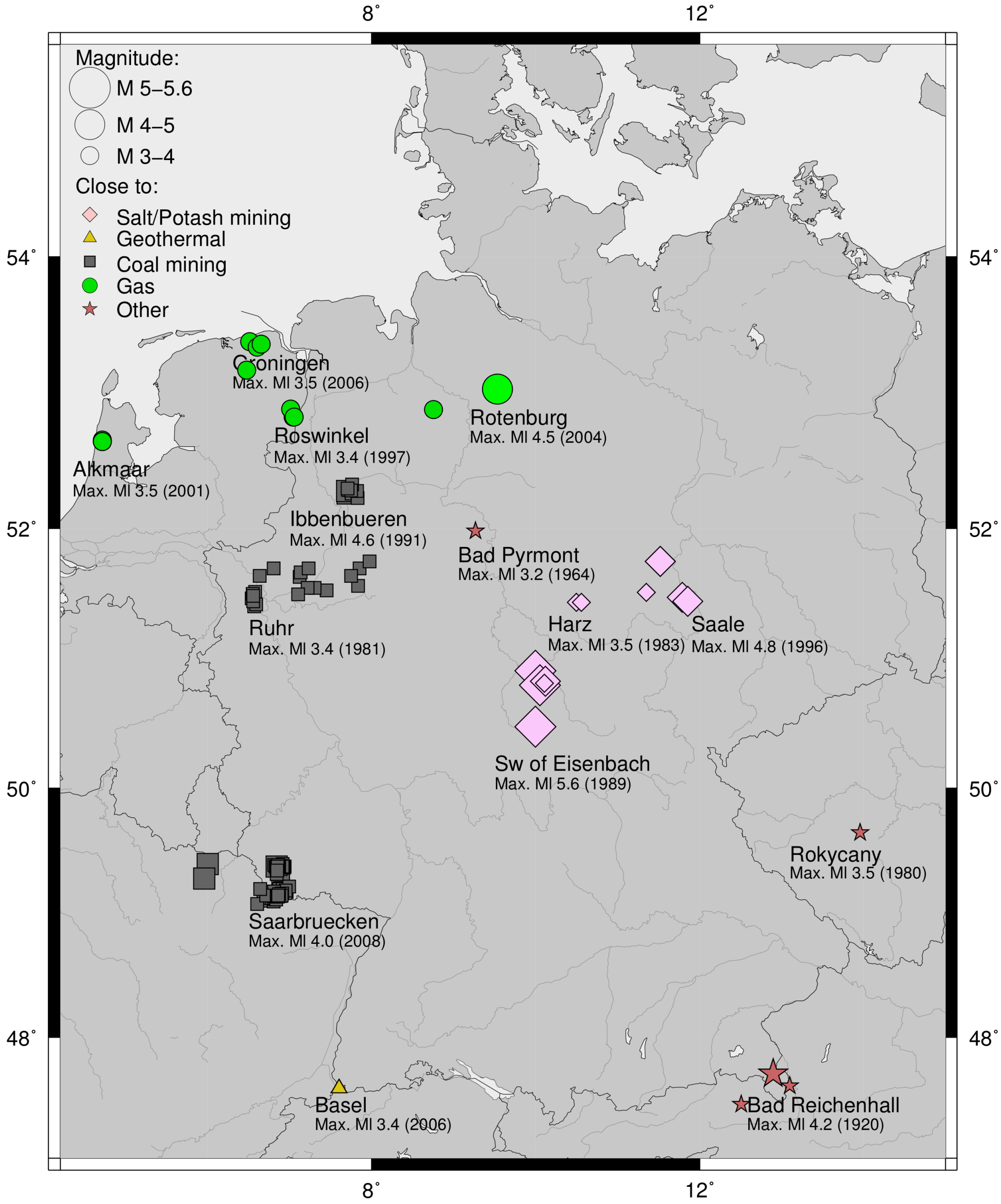


*Figure 1: Earthquakes with Ml>3 from 1899 until 2010 in Germany and adjacent areas with suspicion to be triggered or induced.*

A common approach to assess the probability if an earthquake has been triggered/induced is given by answering some plausible questions (modified from Davis et al. 1995). The more of these questions are answered by yes, the higher is the probability that the event was triggered or induced.

1. Is it the first known event of this character in the region?
2. Did the events begin only after the human operation had commenced?
3. Is there a clear correlation between operation and seismicity?
4. Are the epicenters within a specified distance from the affected area (e.g. from wells)?
5. Do some earthquakes occur at or near the depth of operation?
6. Do epicenters appear spatially related to the region affected by the operation?
7. Did the operation cause a significant change in stress and/or fluid pressure?
8. Did the seismicity begin only after the significant stress or pressure change?
9. Is the seismicity explainable in terms of current models relating the operations and the induced mechanical/hydrological processes to fault activity?

The approach is only qualitative and cannot be used for planning purposes before operations start. It does not motivate to improve the monitoring or pre-operation survey. As it stands, it cannot be used to delineate areas of potentially expected earthquakes (seismic hazards mapping).

## Basic assumptions and definitions

A standard assumption is that the stress in the Earths crust at depth of already a few km is controlled by the strength of the crust. Pre-existing zones of weakness and fault zones experience continuous tectonic loading and maintain a stress state close to failure. In this situation already a small positive Coulomb stress or overpressure increase may **trigger the nucleation** at the hypocenter. Under steady state tectonic loading, a steady state rate of background seismicity is observed which is incorporated in seismicity models as the background rate against which possible rate changes are measured (e.g. Dieterich, 1994; Ogata and Zhuang, 2006). The frequency-size distribution usually follows the Gutenberg Richter relation with a constant b-value, if there are steady state conditions and the regions considered is sufficiently large. However, there are also exceptions (e.g. Wiemer and Wyss, 2002). If induced weak earthquakes and aftershocks are considered, a typical assumption is that pre-existing planes of weakness in arbitrary orientation may be triggered. The planes of maximal Coulomb failure stress increase (ΔCFS) are considered to assess the triggering problem.
The **subsequent rupture** of stronger earthquakes may affect faults of several hundred meters or kilometers length. Rupture is driven by stress drops in the order of few MPa. Such large Coulomb stresses are assumed to be available on pre-existing faults at larger depths if they are favorably orientated, but it is typically not observed at very shallow depth and within soft sediments (see e.g. Zoback, 2007, for stress-depth profiles at shallow levels and in sedimentary basins). However, magnitude 3 and 4 tectonic earthquakes have also been observed at very shallow depth (1-3 km) within sediments close to the city of Fribourg, Switzerland (e.g. Kastrup et al., 2007).

**Human operations** comprise different actions affecting stress, pore pressure, strain, fluid saturation, fluid flow and rock strength in the subsurface. Induced stresses can range from a few tens of KPa, to several MPa. We assume that operations are monitored and pressure, stress, injection volume or other parameters of relevance are available or can at least be estimated in order to assess the discrimination question[1].

The e**arthquake case** may consist of a single or of a sequence of earthquakes in the neighborhood of the site. The epicenter, depth, occurrence time and strength must be provided. Uncertainties shall be provided as probability density function (PdF, see e.g. Lomax et al., 2000). In some cases, the source mechanism and the size and parameters of the rupture may additionally be known. The questioned earthquake(s) may be (see also McGarr and Simpson, 1997; McGarr, Simpson and Seeber, 2002):

- **natural/human-made:** Triggering and driving of the rupture is controlled by natural or by human-made stress or pressure perturbations. For steady state loading the background rate of natural earthquakes is often constant and the frequency-size distribution obeys a power law (parameterized in log-log formulation by a- and b-values). Human-made loading is typically not steady state and modifies the seismicity rate and b-values (e.g. Harsh, 1972; Gibowitz, 2001). However, also some natural processes like static and dynamic triggering from other natural earthquakes and natural pore pressure changes have the potential to modify the seismicity rate.
- **triggered/induced:** Triggering concerns the nucleation. The occurrence of a triggered event is advanced in comparison to the background rate, but the size of the event is controlled by the existing natural stress field and fault structure. The induced event is evaluated on terms of its size. For instance, the rupture is driven by the human-related (induced) stress or pressure perturbation, or by a strong stress perturbation induced by a natural transient process (dissolution, magma-diking, earthquake). The size of the rupture plane of the induced event is equal or smaller than the spatial extension of the induced stress or pressure perturbation. The earthquake would not occur without the human operation.

Distinguishing triggered and induced earthquakes may become important if the seismic hazard and earthquake size is questioned.

## Modules in probabilistic influence diagrams

In order to obtain a measure of the probability that an event is either natural or human-related, and whether it is triggered or induced, qualitative criteria like those of Davis et al. (1995) have to be transformed into a quantitative formulation that can be integrated into the decision process. Such a scheme may consist of different modules, each of which may define a probability of a triggered event or sequence. Similar to developments in volcanology and seismic hazard analysis, the probabilistic outputs of the different modules may be combined into **probabilistic influence diagrams** (Bayesian belief network, Fig. 2).

In the following we present some examples of possible modules that may be implemented in a future decision scheme. This list is neither complete nor can it be expected that all modules are applicable for every study which is especially true in the

[1] Completeness of monitoring and earthquake location accuracy is crucial for assessing the discrimination problem. Recommendations regarding the monitoring concept are developed within the monitoring group and not considered here. Furthermore, a close cooperation with the operating company is necessary to obtain information about underground activities and to get assess to a list of explosion times in case such operations are performed.

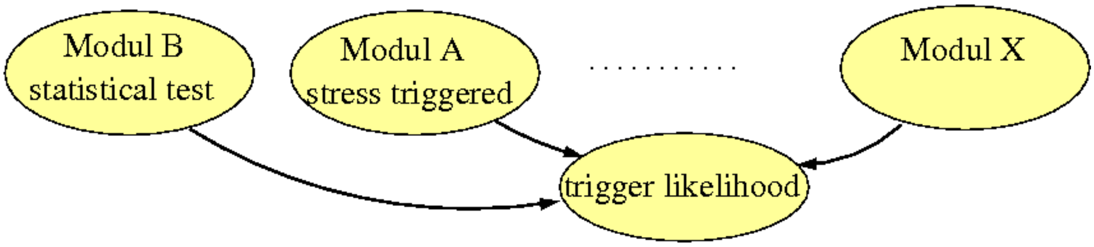


*Figure 2: Schematic sketch of a probabilistic influence diagram to assess the event character.*

case of only very few observed events in a historically aseismic region which makes a statistic evaluation almost impossible. However, the modularity of the approach allows to choose the appropriate modules and makes it easy to include new or modified components into the decision process. Thus, further input and the development of additional modules from the seismological and engineering community is welcome and highly encouraged. Each proposed modul shall be discussed with a field case with a summary of main characteristics and related papers, in order to develop catalogs of useful human-related and natural triggered events.

*Sample Modul A- stress based seismicity model (Pst)*:
The seismicity model of Dieterich (1994) (rate and state dependent friction) is used to estimate the probability of an event to be triggered as a function of space and time. Input values are background seismicity rate r(x,y,z) and ΔCFF(x,y,z;t). Parameters of the model are an aftershock decay constant and the sensitivity of the rock to stress loading. The loading history of the rock volume has to be estimated from the specific operation using for instance numerical models of stress transfer, pore pressure or pore fluid diffusion. The output of the rate and state dependent model is a theoretical seismicity rate R(x,y,z;t). The probability that the earthquake case of given size was natural is r/R, and the theoretical probability to be triggered is Psm (x,y,z;t) = 1 – r/R. The PdF of the earthquake is multiplied by the normalized probability of triggering to calculate the probability that the specific event was triggered (Fig 3).

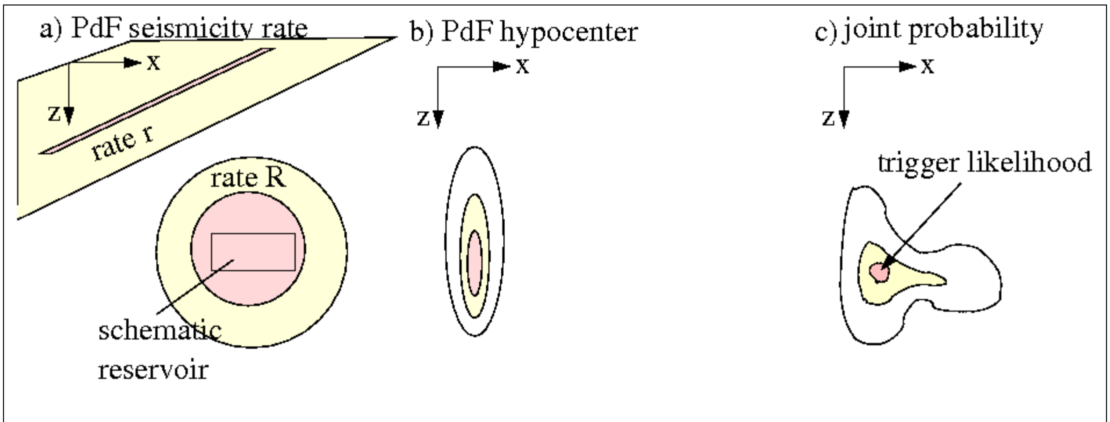


*Figure 3: Schematic sketch in 2D showing the PdF of the natural and induced seismicity rate (a), the PdF of the event hypocenter (b) and the joint PdF of the likelihood of a triggered case (c).*

*Sample Module B – Probabilistic seismicity model (Ppr):*
The short term characteristics of natural seismicity can be usually well described by a combination of constant background activity and triggered aftershock sequences. In particular, the epidemic type aftershock sequence (ETAS) model (Ogata, 1988; Ogata and Zhuang, 2006) has been shown to reproduce the spatiotemporal characteristics of earthquake clustering very well (Woessner et al., 2010). The application of this model to a specific region can directly yield the probability that the earthquake under consideration is a natural event, i.e. that it can be related to background activity or ongoing aftershock sequences.

*Sample Module C – Past induced earthquake model (Ppi)*
If induced earthquakes are common in some region and tectonic events are unlikely in the same region, then new earthquakes are classified as "induced" without further detailed analysis. Such simple discrimination is common practice during routine analysis in earthquake centers to classify the large amount of small induced earthquakes in certain areas. The Ppi-module takes up this common practice in a systematic way: If the human activity is more or less stationary or changes occur only on a long time scale, the rate of induced earthquakes can be approximated to be more or less stationary in many cases. E.g. Shapiro et al. (2007) give several examples for a stationary induced earthquake rate caused by a stationary fluid injection rate. If the assumptions apply, the probability of a new event to be induced is "number of past induced events" divided by "number of all past events".

*Sample Module D – Consistency of the earthquake slip to background stress (Psl)*
This refers to question 1 of the Davis scheme. Slip of a natural event is typically in the direction of the maximal shear stress resolved on the fault. Slip of a purely induced event is controlled by the induced stress perturbation. For instance, an earthquake induced in the central section of the over- and under-burden of a mining gallery or an oil field formation favors reverse sense of slip. The PdF of the expected and observed slip direction may be obtained by bootstrap analysis. Multiplying both PdF's gives Psl.

*Sample Module E – Non-double couple source mechanisms (Pnd)*
In mining seismicity the percentage of non-double-couple components is often quite high. High percentage of non-double couple component indicates high probability of induced events in mines.

*Sample Module F – Fluid-Induced Events (Pfi)*
Different sites of borehole fluid injections are characterized by different levels of seismotectonic activity. The "Seismogenic Index" (SI) is introduced as natural constant quantifying the seismotectonic activity of the injection site. The SI along with the injection rate controls the magnitude distribution of induced events (Shapiro et al., 2010). Shapiro et al. (2010) suggest that if the seismogenic index and the b-value can be estimated from the observed induced seismicity, the occurrence probability of induced events in the future can be calculated. For an event or a series of events of interest one can try to estimate if their occurrence does fall outside of the probability expected (thus, a higher likelihood of tectonic triggering in such a case).

Other criteria and models may be proposed and developed, which is a major aim of the group. For instance, waveform similarity may be used, the temporal evolution of earthquake strength in relation to injection pressure (injection case), or the multimodality of the Gutenberg Richter relation (mining). Additionally, the role of tectonics/geology and engineering plans need to be considered in the different modules.

It is expected that the different operations may use different criteria, and that often only a subset of criteria can be estimated. Therefore, probabilistic influence diagrams shall be developed in future in order to help decision makers, claimants and companies to assess the question. Essential for this development is the availability of calibration data. Better data and open data policy will play a crucial role to calibrate modules.

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