Modelling earthquake location errors at a reservoir scale: a case study in the Upper Rhine Graben

Earthquake hypocentres constitute a unique source of information for understanding the physical processes at the origin of earthquakes, describing the subsurface and quantifying earthquake seismic hazard. For example, it is the primary attribute of an earthquake without which other characteristics such as occurrence time, seismic moment, magnitude or focal mechanism cannot be determined. Tectonic interpretation or fault identification using the spatial distribution of earthquakes is also the purpose of many studies. However, earthquake location errors exist and need to be properly quantified for reliable result interpretation. Therefore, in this work, the impact of several factors on the absolute location of earthquakes in a reservoir was investigated. The methodology, which used state-of-the-art techniques, consisted in relocating synthetic hypocentres under hypotheses different from the data modelling step, and comparing the initial and relocated hypocentres. Hence, the effects of the P- and S-wave onset time uncertainties and inaccuracies were examined as well as the effects of the velocity model uncertainties and inaccuracies. In particular, we looked at the location errors driven by using a 1D velocity model instead of several 1D or 3D velocity models. The analysis was applied to the Rittershoffen geothermal field, where seismicity was induced between 1000 m and 5000 m, under the seismic monitoring conditions existing during the chemical and mechanical stimulations of the well GRT1. The 3D analysis of the location uncertainties and inaccuracies covers a zone of a couple of kilometres around the open-hole section of the well. An overview of the different areas and networks used during our study are shown on Figure 1.

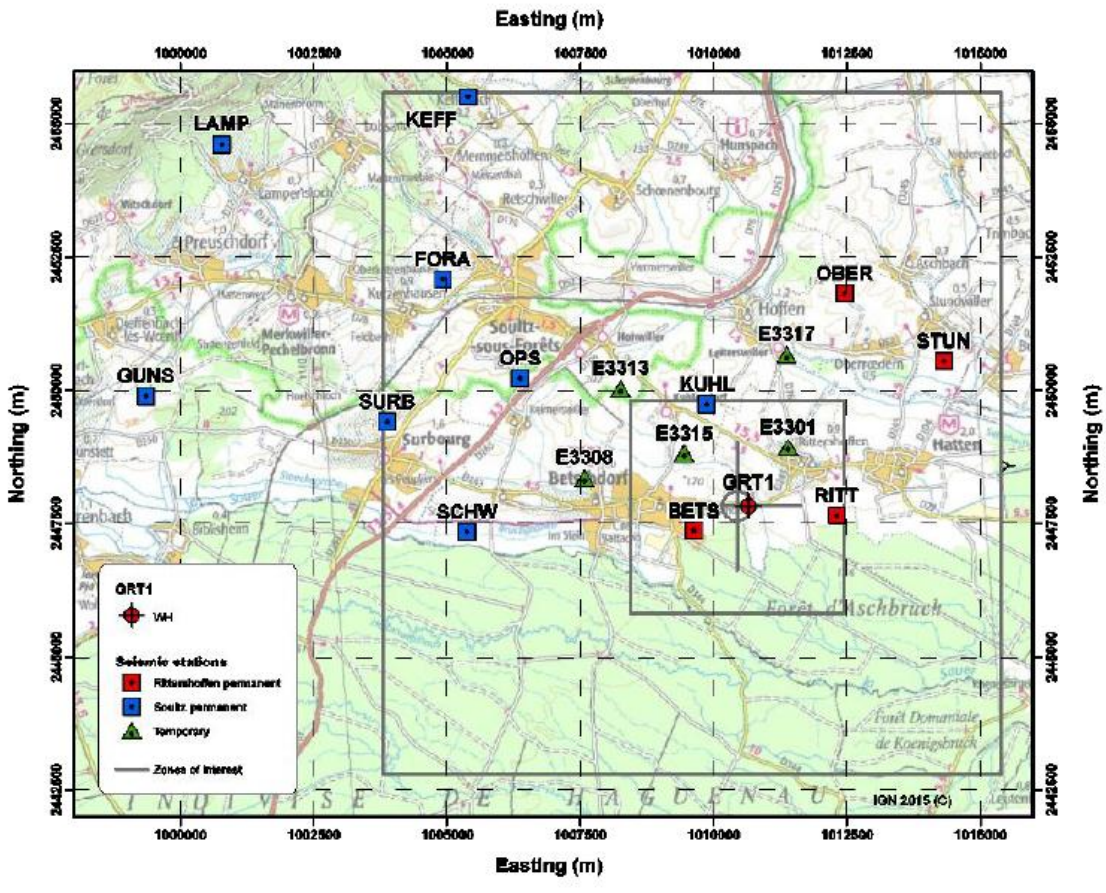

Figure 1: Map of the seismic network deployed at Rittershoffen. The Soultz-sous-Forêts permanent stations (blue squares), the Rittershoffen permanent stations (red squares) and the temporary stations (green triangles) are shown as well as GRT1

wellhead (red crossed circle). The largest rectangle delimits the velocity model zone used in this study. The smallest rectangle delimits the area in which the seismic sources are simulated; the two segments are the projections of the vertical sections of simulated sources. The projection of the zone with perturbed velocity is shown as a grey circle. All coordinates are in Lambert II extended system.

Results

At Rittershoffen, in an ideal case where, firstly, a 1D velocity model is well representative of the propagation medium, and secondly, the P- and S-wave pickings and their uncertainties are representative of the recorded induced seismicity, the earthquakes location uncertainties will range between 50 m at 400 m depth and 150 m from 2400 m depth (in the granitic formation). The coverage of the seismic network, which is deployed in the north of the GRT1 well, controls the spatial distribution of the uncertainties in amplitude and direction. This layout leads to uncertainties roughly pointing towards the KUHL station, which is located about 4 km NNW from GRT1 well-head. The spatial distribution of uncertainties at around 2400 m depth is given by Figure 2 for example. Although a picking precision of 10 ms leads to inaccuracies smaller than the uncertainties, their similar spatial distribution have a cumulative effect and the location inaccuracy cannot be totally considered has contained in the uncertainty. Such an effect would be typical of the use of a location algorithm requiring 10 ms picking precision as input. The location errors driven by the hypotheses associated with the velocity model may be very large. As shown, only 5% uncertainty in the reference 1D velocity profile of Rittershoffen can multiply by a factor of 2.5 the uncertainties of the ideal case, thus leading to uncertainties up to 650 m in the granite at 3200 m. On the contrary, decreasing by 10% the P- and S-velocities in the neighbourhood of the GRT1 open-hole section has negligible effect and makes such a feature undetectable with an absolute location method. Not considering the Rittershoffen fault and the associated block shift in the velocity model induces very strong location biases, larger than the uncertainties. Although the reference 1D velocity model is based on well data and centred on the zone of interest, it is not a good representative of the 3D model with the fault and does not minimize the location errors. While the location uncertainties range between 50 and 250 m, the expected sources are shifted by 200 to 400 m, mainly eastward (Figure 3). The location inaccuracies, however, vary continuously in space, thus making difficult any reliable interpretation of directions or surfaces delineated by the located seismicity.

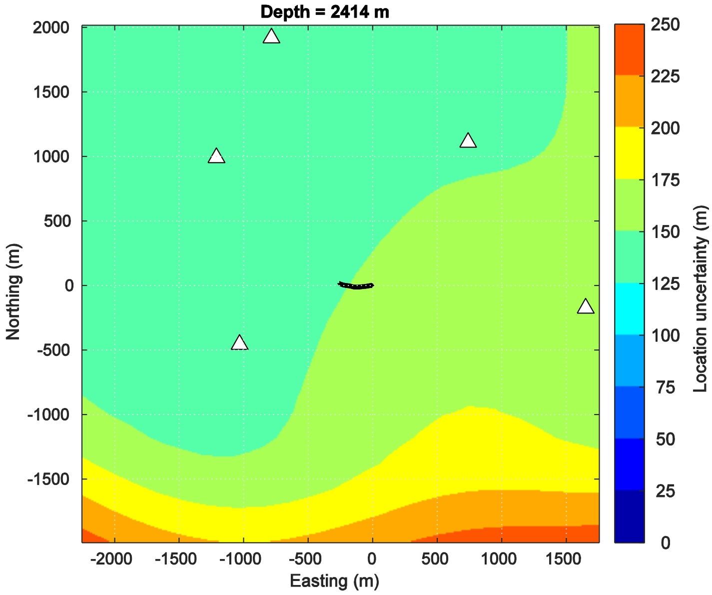

Figure 2: Horizontal section at 2414 m of the location uncertainty. The stations above the location zone are displayed (white triangles) as well as the GRT1 well trajectory (black curve).

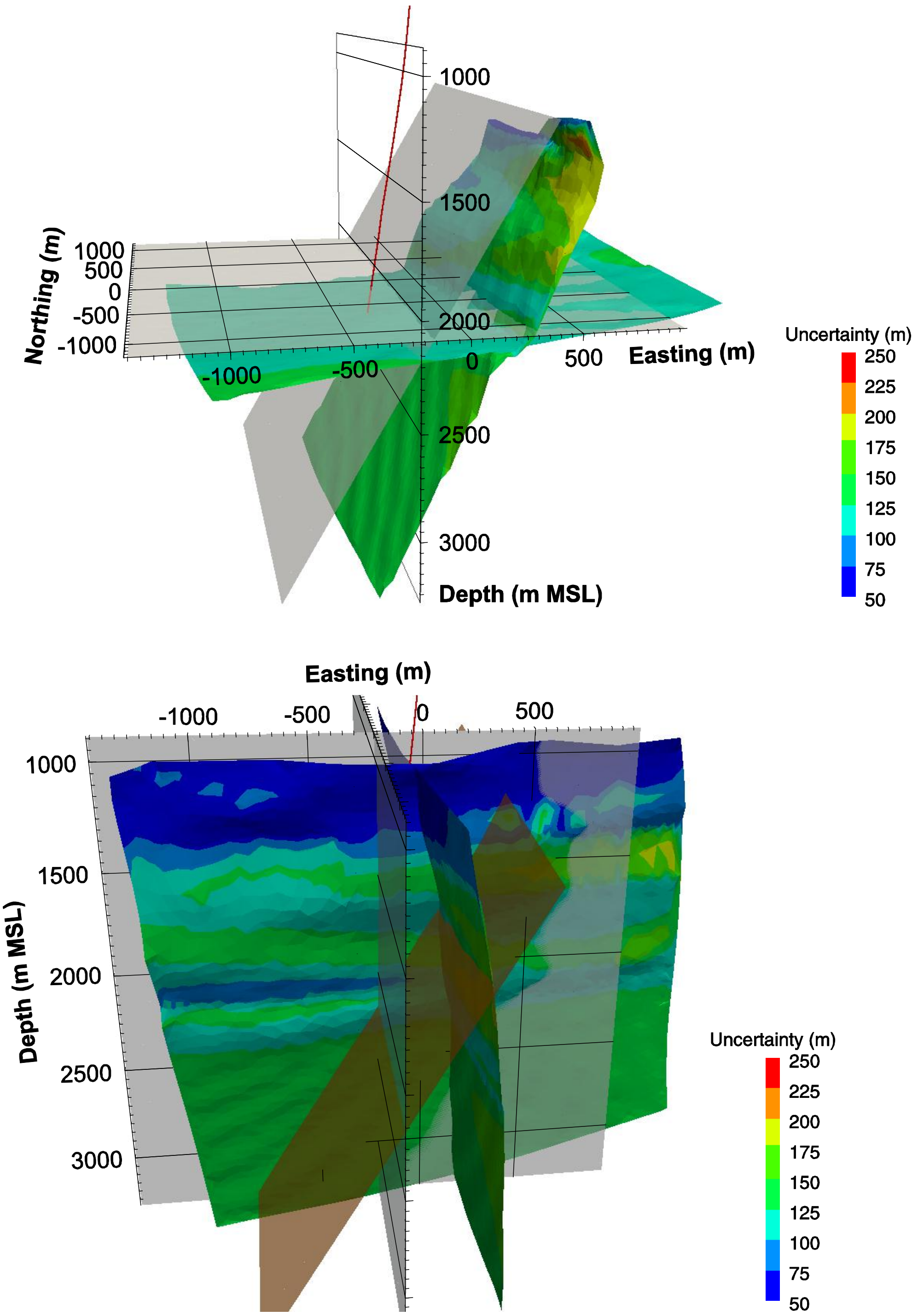

Figure 3: 3D view of the relocation of the synthetic events initially located on the horizontal plane and along the fault (top) and on the N-S and E-W vertical plane (bottom). The initial locations were on the grey planes whereas the relocations are on the coloured planes. The colour scale is associated to the largest uncertainty value which vary between 50 m and 250 m. The location of the fault is shown by the brown plane (bottom).

<u>Outlook and notes</u>

As emphasized, the location errors driven by the velocity model may be dominating at the considered reservoir scale. This confirms the common sense which recommends using any *a priori* information to better constrain the initial velocity model or to define its uncertainties, which can be later integrated into the location uncertainty. The 3D analysis of the results highlighted that the location errors are neither aleatoric nor isotropic but clearly driven by the seismic network coverage and the velocity model. This suggests that although location inaccuracies may be smaller than location uncertainties, both quantities may have a cumulative effect.

In this study, we did not perform an exhaustive analysis of all parameters which could influence the earthquake location at Rittershoffen. We focused on those which are usually not taken into account during standard location processing because they require synthetic modelling; in particular the discrepancies between the velocity model and the real seismic propagation medium. Moreover, we selected scenarios which looked the most relevant with regards to the *a priori* information available for Rittershoffen. To allow clear identification of each effect, the associated hypotheses for relocating the earthquakes were changed one by one. However, among numerous other options, it could be reasonable, for example, to jointly consider uncertainties of the 1D velocity profile and the inclusion of the fault. When studying the location errors driven by erroneous assumptions on the velocity models, we did not seek for a better velocity model which would minimize the location errors. This work, which would imply travel-time tomography, could constitute a future analysis.

For Rittershoffen, the quantitative results of this study can constitute an *a priori* knowledge useful for interpretation or processing of seismological data. Nearby geothermal fields such as Landau, Insheim, Bruchsal (all in Germany) or Soultz-sous-Forêts (France) have geological settings very similar to Rittershoffen geothermal reservoir. To some extent the present results can be used in these contexts, in particular at the Landau and the Insheim fields where seismicity was induced and for which the Triassic sandstone and the Paleozoic granite also constitute the reservoir. At Soultz-sous-Forêts, the geothermal reservoirs were developed deeper into the granite (below 3500 m); however, major faults also delimit lifted blocks which lead to velocity contrasts in the 1400 m-thickness sedimentary cover. Several geothermal fields in the URG are currently under development or explored and can benefit from the present study. Since the described methodology is independent from the induced seismicity recorded at the site, it can also help in quantifying the location capabilities of a given network at a given site, even prior to the network deployment.

The earthquake hypocentre constitutes the primary attribute of a seismic event. Error of this attribute on the determination of secondary ones should be investigated in future works. The impact on the focal mechanisms, which are used to better describe the reservoir structure, is of special interest. Finally, the present work focused on quantifying errors of earthquake absolute locations. The extensive use of relative location methods to obtain earthquake hypocentres indicates that adapting and applying the developed methodology to this processing frame is necessary.

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