Supporting Information for "Inferring field-scale properties of a fractured aquifer from ground surface deformation during a well test"

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Contents of this file

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Introduction

This supporting information presents the specifics of the elastic deformation model used in our study.

Text S1: Okada-based modeling strategy

Several studies address the problem of displacement fields generated by the dislocation of a dipping fracture buried in a homogeneous elastic half-space [*Davis*, 1983; *Okada*, 1985, 1992]. *Okada* [1985] provides a complete derivation for the analysis of vertical displacement and tilts observed at the surface from the tensile dislocation of a buried rectangular plane. The parameters of his analytical solutions are the fracture's upper edge depth F, length along strike direction LX, length in dip direction LR, dip α and Poisson's ratio of the elastic medium ν.

We used the original analytical solution of *Okada* [1985] in a specific manner in order to model ground surface deformation associated to a pressurized fracture plane embedded in a confined aquifer. In the routine, transient surface tilt is modeled from the progressive opening and lateral growth of two buried dislocation planes. The first one (P1, in red, fig. S1) mimics the elastic deformation produced by a volumetric increase of the entire sub-vertical fault zone and lateral pressure propagation during the forced hydraulic loading. The second one (P2, in blue, fig. S1) mirrors the effect of pressure loading that we would expect to be applied upwards from the fracture top and against the confining unit of Ploemeur's aquifer (hence, this plane is horizontal). We mean by "confining unit", the weathered layer of a few tenths of meters that overlies the fractured granite and mica schist units and play the role of an upper hydraulic barrier for pressure propagation (fig. S1 c).

The superimposition of two buried planes is needed to actually produce a ground uplift above the fracture's roof, which is not the case if we only take into account a single plane representing the dipping fault, unless it is sub-horizontal. Optical leveling data confirm that there is an uplift during the experiment and we attributed this effect to the pressure applied onto the confining body just above the fault's roof.

Under short-term transient conditions we discard the flow and associated deformation of the sub-horizontal contact zone which is therefore not taken into account in the model. Hence, two Okada solutions are superimposed and this allows for a more realistic but still simple representation of pressure conditions in this fractured groundwater system, despite the fact we transgress the homogeneous half-space assumption. In fact, to our knowledge there is no study in the literature dealing with the relevance of Okada sources summations. It is far beyond the scope of this study to treat this problem, however *Pascal et al.* [2014] reported that a point source superposed to a dislocation plane gave results in terms of surface displacement fairly consistent with similar finite-element numerical models (less than 5 % discrepancy) regardless distance between sources. Even if this test does not exactly match our case, we do superimpose two sources in a elastic half-space and expect our model to produce results with, at least, a realistic order of magnitude.

The lateral growth and opening of the buried fracture follows a temporal evolution which is typical of pressure diffusion in porous media; that is to say in the form of $\sqrt{t}$ where t is time. Therefore, the lateral extents $LX_c(t)$ of the planes P1 and P2 are forced to evolve from an initial value LX_{min} to a threshold value at the end of the studied period ($t = t_{max}$), i.e. $LX = LX_c(t_{max})$, as described by the equation

$$LX_c(t) = \sqrt{LX_{min}^2 + \frac{(LX^2 - LX_{min}^2)t}{t_{max}}} \tag{1}$$

In addition to Okada's five original input parameters, we introduced three more: the width W of P2 (corresponding to the width of the confining layer influenced by the upright pressure change), the proportion $\delta = 0.90$ of total load/opening applied into the fracture zone P1 (the remaining $1 - \delta$ being applied to the roof P2) and finally the storativity S described above. For each time step the amplitude of dislocation, which is the displacement between the walls of each plane, is determined from an incremental water volume that is stored in the fault zone since pumps were shut down. This volume $\Delta V(t)$ is defined as:

$$\Delta V(t) = \Delta h_{F32}(t) \times A \times S \tag{2}$$

where $\Delta h_{F32}(t)$ stands for pressure head in borehole F32 and S is the fault zone's storativity. A is the fault zone's area projected on a horizontal plane. Hence, the amplitude of tensile dislocation $\Delta\Omega_1$ and $\Delta\Omega_2$ which represent the opening of P1 and P2 respectively at each time step are given by:

$$\Delta\Omega_1(t) = \frac{\delta \times \Delta V(t)}{LX_c(t) \times LR} \tag{3}$$

and

$$\Delta\Omega_2(t) = \frac{(1 - \delta) \times \Delta V(t)}{LX_c(t) \times W}. \tag{4}$$

Besides storativity that we try to constrain, our Okada-based model has the advantage of necessitating only one other mechanical parameter: Poisson's ratio. It is obvious that at the site scale, we expect heterogeneities due to differences in rock nature and weathering to induce a significant spatial variability of this parameter. Besides, it is complicated to have a grasp of this geomechanical property from the field. Nonetheless, we did dispose of seismic data from a borehole located a few meters from F32. From transversal and longitudinal wave velocities along the borehole, we estimated a Poisson ratio of 0.27.

References

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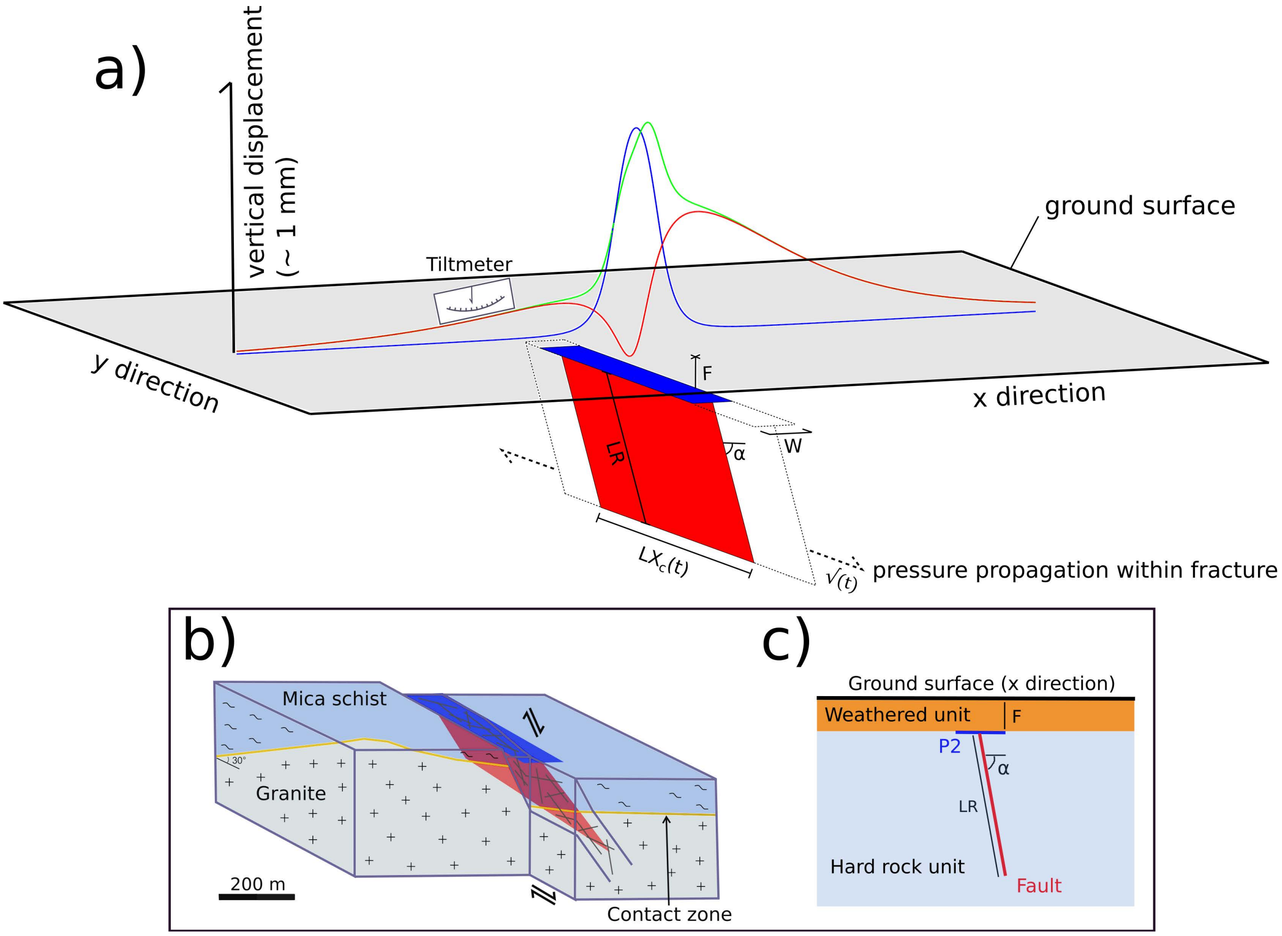

Figure S1. Diagram illustrating the Okada-based model used in this study: a) Vertical displacement at the ground surface is obtained by superimposing the analytical solution of *Okada* [1985] for two different dislocation planes (red and blue surfaces). The red plane represents a sub-vertical fault zone and the blue plane mimics the effect of vertical pressure applied on the aquifer's confining unit. The associated vertical displacements on a surface cross-section are shown by the red and blue curves respectively, along with the summed contribution of both planes in green (displacement are largely exaggerated). Tilt can be recovered anywhere by taking the local gradient of vertical displacement: in this case along the x direction ; b) Bloc diagram of Ploemeur's aquifer and location of modeled fracture planes ; c) Side view of panel a.