Ecole Doctorale des Sciences Fondamentales

Title of the thesis: Realistic modelling and joint inversion of deformation and temporal changes of gravity signal

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Summary :

In order to detect magma transfers, the deformation of volcanoes is routinely monitored by InSAR at mots active volcanoes. Deformation sources can be diverse, ranging from magmas to hydrothermal fluids or gases (Battaglia et al., Geophysics, 2008). Magma, hydrothermal fluids, volcanic gases having different densities, measurement and interpretation of temporal variations of gravity can be used to discriminate the nature of the sources of unrest. The objective of this project is to develop and test a quantitative method for the joint analysis of deformation and gravity in order to provide estimates of the nature, position and geometry of the sources of volcanic activity using realistic source and crustal models.
Most joint analyses of the temporal variations of gravity and deformation are based on analytical solutions where the crust is assumed to be an infinite, elastic and homogeneous half-space. Nevertheless, numerical models of deformation and gravity (Currenti et al., GJI, 2017, Charcot et al., G3, 2007) show that neglecting topographies or heterogeneities of mechanical properties can lead to misinterpretations. In most models, the sources are assumed to be reservoir type, which is a limitation since during eruptions, the magma is often transported in fractures.
In this thesis project, we propose to conduct models with numerical methods based on a fictitious domain approach (Bodart et al., SIAM, J. Sci. Comp., 2016) in order to model fracture or reservoir sources located in a heterogeneous, truly three-dimensional environment. The fictitious domain method we use is currently able to compute the stresses and strains of a heterogeneous elastic medium. We will have to adapt it to the modeling of gravity signals, following the approach indicated by Bonafede and Mazzanti (JVGR, 1998). To characterize the sources, these models will have to be combined with inversions. We will compare two inversion methods, a near-neighbor type inversion (Sambridge et al., JGI, 1999a and 1999b) and a Marcov Chain Monte Carlo type inversion.
This approach will be applied to the reinterpretation of the 1998 eruption of the Piton de la Fournaise volcano, as well as to the eruptions that occurred in June, July and August 2019. Measurement campaigns will also be carried out in order to either repeat the network set up in May 2019 or to conduct measurements on another volcano. At Piton de la

Fournaise, the eruptions are associated with variations in the volume of the summit reservoir that are difficult to detect, either by the great depth of the storage system or by the strong compressibility of the magma in the reservoir. The eruption of March 1998 is interesting in several respects. It occurred after a 5-year quiescence and could be associated with the transmission of a large mass of magma in a crustal reservoir. Microgravity and GPS surveys were conducted before and after the eruption, which was also captured by InSAR (Fukushima et al., JGR, 2010). The micro-gravimetric signal was analysed (Bonvalot et al., JGR, 2008) using an analytical model that assumes that the sources are fractures (Okabe, Geophysics, 1979) and point reservoirs. This model is combined with inversions based on genetic algorithms (Goldberg, Adison-Wesley, eds, 1989). The authors showed that the eruption was associated with a dyke, as well as an addition of mass at sea level, which could be related to the addition of new magma. Due to point source approximation, this mass is of unknown density. In order to make these results more robust and to determine the respective densities of the bodies in place, and the amount of exsolved volatiles, we will jointly invert the gravimetric, GPS and InSAR data. In 2019, the problem is different. Each eruption is associated with a single dyke. The 3 eruptions resulted in a net summit uplift, while the gravimetric signal does not indicate a summit recharge. This paradox will have to be analyzed.

This research is innovative because there is no numerical model to date adapted to gravity inversions and fracture deformations in heterogeneous 3D environments. A fortiori, no numerical model of this type has been used in inversions. The temporal measurement of the gravity signal is more and more widespread, either during gravity measurement campaigns (Mt. St. Helens, Battaglia et al., AGU, 2015), or by continuous gravity stations, such as those of Etna (Carbone et al., Sci. Rep., 2015; Carbone et al., Frontiers in Earth Science, 2020) or Kilauea (Poland and Carbon, JGR, 2016). Finally, new, more portable instruments are being developed, suggesting the future possibility of more frequent reiterations and denser networks, as they are simpler to measure from a logistical point of view (Carbone et al., Frontiers in Earth Science, 2020). These denser measurements will require more precise analysis.