Abstract

The efficient use of geothermal systems, the sequestration of CO_2 to mitigate climate change, and the prevention of seawater intrusion in coastal aquifers are only some examples that demonstrate the need for novel technologies to monitor subsurface processes from the surface. A main challenge is to assure optimal performance of such technologies at different temporal and spatial scales. Plane-wave electromagnetic (EM) methods are sensitive to subsurface electrical conductivity and consequently to fluid conductivity, fracture connectivity, temperature, and rock mineralogy. These methods have governing equations that are the same over a large range of frequencies, thus allowing to study in an analogous manner processes on scales ranging from few meters close to the surface down to several hundreds of kilometers depth. Unfortunately, they suffer from a significant resolution loss with depth due to the diffusive nature of the electromagnetic fields. Therefore, estimations of subsurface models that use these methods should incorporate a priori information to better constrain the models, and provide appropriate measures of model uncertainty.

During my thesis, I have developed approaches to improve the static and dynamic characterization of the subsurface with plane-wave EM methods. In the first part of this thesis, I present a two-dimensional deterministic approach to perform time-lapse inversion of plane-wave EM data. The strategy is based on the incorporation of prior information into the inversion algorithm regarding the expected temporal changes in electrical conductivity. This is done by incorporating a flexible stochastic regularization and constraints regarding the expected ranges of the changes by using Lagrange multipliers. I use non-l_2 norms to penalize the model update in order to obtain sharp transitions between regions that experience temporal changes and regions that do not. I also incorporate a time-lapse differencing strategy to remove systematic errors in the time-lapse inversion. This work presents improvements in the characterization of temporal changes with respect to the classical approach of performing separate inversions and computing differences between the models.

In the second part of this thesis, I adopt a Bayesian framework and use Markov chain Monte Carlo (MCMC) simulations to quantify model parameter uncertainty in plane-wave EM inversion. For this purpose, I present a two-dimensional pixel-based probabilistic inversion strategy for separate and joint inversions of plane-wave EM and electrical resistivity tomography (ERT) data. I compare the uncertainties of the model parameters when considering different types of prior information on the model structure and different likelihood functions to describe the data errors. The results indicate that model regularization is necessary when dealing with a large number of model parameters because it helps to accelerate the convergence of the chains and leads to more realistic models. These constraints also lead to smaller uncertainty estimates, which imply posterior distributions that do not include the true underlying model in regions where the method has limited sensitivity. This situation can be improved by combining plane-wave EM methods with complimentary geophysical methods such as ERT. In addition, I show

that an appropriate regularization weight and the standard deviation of the data errors can be retrieved by the MCMC inversion.

Finally, I evaluate the possibility of characterizing the three-dimensional distribution of an injected water plume by performing three-dimensional time-lapse MCMC inversion of plane-wave EM data. Since MCMC inversion involves a significant computational burden in high parameter dimensions, I propose a model reduction strategy where the coefficients of a Legendre moment decomposition of the injected water plume and its location are estimated. For this purpose, a base resistivity model is needed which is obtained prior to the time-lapse experiment. A synthetic test shows that the methodology works well when the base resistivity model is correctly characterized. The methodology is also applied to an injection experiment performed in a geothermal system in Australia, and compared to a three-dimensional time-lapse inversion performed within a deterministic framework. The MCMC inversion better constrains the water plumes due to the larger amount of prior information that is included in the algorithm. The conductivity changes needed to explain the time-lapse data are much larger than what is physically possible based on present day understandings. This issue may be related to the base resistivity model used, therefore indicating that more efforts should be given to obtain high-quality base models prior to dynamic experiments.

The studies described herein give clear evidence that plane-wave EM methods are useful to characterize and monitor the subsurface at a wide range of scales. The presented approaches contribute to an improved appraisal of the obtained models, both in terms of the incorporation of prior information in the algorithms and the posterior uncertainty quantification. In addition, the developed strategies can be applied to other geophysical methods, and offer great flexibility to incorporate additional information when available.