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Joint inversion of seismic travel times and gravity data on 3D unstructured grids with application to mineral exploration

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A single Earth model consistent with multiple geophysical datasets (from different surveys) is more likely to represent the true subsurface than a model consistent with only a single type of data. This is especially true if the surveys sense different aspects of the subsurface and therefore provide complimentary information. For example, surface gravity measurements can provide good lateral resolution but not depth resolution, and borehole-borehole or surface-borehole seismic data can provide good vertical resolution but not lateral resolution.

Seismic methods continue to receive interest for use in mineral exploration due to the much higher resolution potential of seismic data compared to the techniques traditionally used, namely gravity, magnetics, resistivity and electromagnetics. However, the complicated geology often encountered in hard-rock exploration can make data processing and interpretation difficult. Inverting seismic data jointly with a complimentary dataset can help overcome these difficulties and facilitate the construction of a common Earth model. We consider the joint inversion of seismic travel times and gravity data.

Over the last several decades there has been a fair amount of study into inversion of seismic and gravity data via joint or cooperative methodologies. However, many questions still remain including how to best link the physical properties involved and what the most appropriate approaches are for specific scenarios. The underlying physical properties, seismic velocity and density, are often closely correlated due to the physical relationship between them. In an exploration context, physical property measurements on rock samples are common and an empirical or statistical relationship can be developed based on that information. When an empirical relationship is available, the joint inverse problem is relatively simple and several authors have demonstrated methods for its solution. There has been less development of joint inversion methods for use when such a relationship is not available or can not be prescribed.

In our joint inversion approach, we discretise the subsurface on an unstructured tetrahedral 3D grid, which, compared to rectilinear discretisation, allows 1) efficient generation of complicated subsurface geometries when such information is known a priori, and 2) can significantly reduce the problem size. The Fast Marching Method is used for the first arrival travel time forward solution and the gravity solution can be calculated using an analytic response for tetrahedra or via a finite element solution to Poisson's equation. When an empirical relationship between physical properties can be developed, our inversion approach can enforce that relationship to some degree commensurate with our confidence in the relationship. In the absence of an empirical relationship, we employ a correlation measure to encourage the properties to maintain a general linear or log-linear relationship. Again, the strength of this correlation constraint can be adjusted based on our confidence in the underlying assumption. In a further extension, we apply an additional fuzzy c-mean measure to encourage the recovered physical property distributions to cluster following the characteristics of the joint physical property distributions determined a priori. If such a priori information is not available, suitable cluster locations can be estimated through an iterative strategy.

Rather than moving to a computationally intensive statistical sampling methodology, we work in a deterministic framework, where well-behaved functions are minimized via a descent search. After some instructional mathematical preliminaries, we present our methods on synthetic and real data scenarios from the Voisey's Bay massive sulphide deposit in Labrador, Canada.