THE NEED FOR GEOLOGICAL AND PETROPHYSICAL CONSTRAINTS IN GEOPHYSICAL INVERSIONS

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INTRODUCTION

Taking a broad view, inversion can be regarded as the extraction of information about attributes of the Earth (model) from measured data. This includes endeavouring to characterise all possible Earth variants which are consistent with the data.

In practice in exploration, a much narrower view is often adopted: inversion is generally understood as a computational process used to find one model which satisfies a geophysical data set. If geophysics alone is able to directly detect and unambiguously delineate mineralisation, inversion of geophysical data in isolation may be effective. However, geophysics is increasingly deployed as a mapping tool first and foremost, to deliver an improved geological “map” of the area of interest.

Geophysics cannot map geology directly; rather it maps variations in rock properties. There are usually an infinite number of rock property models satisfying the geophysical data acceptably well, owing to the limitations imposed by physics, logistics, and experimental error. Therefore inversion must be guided or constrained by geological and petrophysical information in order to reject models which are inconsistent with what is already known about the geology.

One valid response to this issue of non-uniqueness is to endeavour to characterise the entire suite of possible models in statistical fashion, e.g. Bosch et al (2001), Minsley (2011). Probabilistic approaches to constrained inversion are computationally onerous and are themselves subject to uncertainties. Philosophically, there is also a limit as to the utility of probability-based decision-making in exploration, an endeavour driven by possibility. Nonetheless, deterministic methodologies which rely on a single model carry additional risk.

In this brief note our aims are threefold: to describe our view of inversion as a component of integrated Earth modelling; to summarise geological and petrophysical constraint options; and to explain the advantages of inverting on a geological model rather than a pure property model.

INVERSION AS A COMPONENT OF EARTH MODELLING

Whether deployed for direct targeting or for mapping, the purpose of geophysics is to improve understanding of some portion of the Earth. Our understanding is normally captured in a model which, ideally, is a compilation of all relevant information, shared across all disciplines (McGaughey, 2006). Inversion plays an important role in defining model features which are, or are not, compatible with the geophysical data. Therefore inversion can be regarded as a component in an overarching Earth modelling effort. One implication of this standpoint is that inversion itself can be viewed as a sequence of recursive steps, not necessarily a single stage process. Thus a conventional “unconstrained” inversion might be completed as a first step.

Geological models are comprised of surfaces, mainly litho-stratigraphic contacts and structures, which divide the ground into rock type domains. Geological models are categorical, insofar as each sub-surface domain is assigned to a rock type.

In petrophysical (or property) models the sub-surface is divided into cells, to which are assigned one or more physical properties. Cell boundaries are often artificial, i.e. bear no relation to geological contacts and structures.

Models for geophysical inversion must be petrophysical, and can also be geological. Inverting on geological models delivers flexibility and control not available with pure property models (Fullagar & Pears, 2007; see below). In particular, geological models permit *geometry inversion*, to alter the shape of boundaries, as well as *property inversion*.

The place of geometry and property inversion within the realm of geological modelling options is illustrated schematically in Figure 1.

GEOLOGICALLY- AND PETROPHYSICALLY-CONSTRAINED INVERSION

Geologically-constrained inversion is defined here as inversion explicitly or implicitly constrained by geological observations of lithology, stratigraphy, or surfaces (be they contacts, structures, or others such as alteration fronts). Traditionally, the model being constrained is usually a petrophysical model, i.e. a mapping of geology into physical properties without preservation of rock type. Nonetheless, the intent is to preserve or favour certain geological characteristics.

Petrophysically-constrained inversion is defined here as inversion of geophysical data which honours petrophysical measurements, either explicitly, or (geo)statistically, or both. The intent of petrophysical constraints is to deliver models which reproduce individual measurements or statistical distributions for particular geological domains. Constraining statistical distributions within rock type domains is not feasible for pure property models.

TYPES OF GEOLOGICAL CONSTRAINTS

Constraints can be imposed on geological contacts, rock types, and structures. Constraints are either “hard”, if honouring direct observations, or “soft”, if favouring or penalising certain types of changes during inversion.

For geometry inversion on geological models, formation boundaries can be fixed where pierced by drill holes (Figure 2) or where well defined by seismic. Geological logs also impose restrictions (“bounds”) on permissible contact geometries (Figure 3). Boundaries are prevented from crossing one another or from erupting through the ground surface. To avoid development of discontinuities, changes to the boundary are usually suppressed, via weighting, within a neighbourhood centred on each pierce point.

In algorithms which permit reassignment of rock type in boundary cells, e.g. Lane et al (2007), conditions can be imposed according to stratigraphic relationships, as well as volume and shape of lithological domains.

Inversions can also be constrained by structural measurements (Figure 4). Weighting schemes have been developed to impose preferred dip, strike, or structural axis orientation on petrophysical models, e.g. Lelievre & Oldenburg (2009), Davis et al (2012). The LCI and SCI algorithms of Viezzoli et al (2008) favour laterally continuous (layered) models. More generally, the assumption of coincidence of petrophysical gradients provides a convenient basis for joint inversion of disparate data sets, e.g. Gallardo et al (2012).

Weighting can be applied to favour certain characteristics, e.g. preferred source depths, shapes, and orientations (e.g. Chasseriau & Chouteau, 2003).

Deviations of cell properties from the starting (or “reference”) model values, assigned according to rock type, can be minimised (Li & Oldenburg, 1996, 1998).

TYPES OF PETROPHYSICAL CONSTRAINTS

The most common petrophysical constraints are upper and lower property bounds, applied to all model cells or to subsets of cells, e.g. those belonging to a particular geological unit.

The spatial distribution of physical properties is always conditioned during property inversion. Smoothness (strictly, “smallness”) is imposed commonly, (e.g. Li & Oldenburg, 1996, 1998). Alternatively, stronger contrasts can be introduced if compact sources are favoured (Portniaguine & Zhdanov, 2002).

Downhole or drill core property measurements can be expressed in the model as fixed property cells. Ideally, the value assigned to each cell should take account of the difference in volume (or “support”) between core samples and model cell. Upscaling is a familiar consideration in mining geostatistics, but the assumption of additivity is untenable for some petrophysical properties, e.g. conductivity (Close et al., 2001).

As for pierce points, a neighbourhood of influence is defined around each fixed cell to suppress rapid model changes in close proximity.

If property measurements are available in sufficient numbers over a representative volume, statistical and geostatistical conditioning of the sub-surface property distribution becomes viable (Figure 5). Integration of geophysical inversion and geostatistical modelling is well advanced in the context of petroleum exploration and production, e.g. Dubrule (2003), but is still a rarity in the mining arena.

When petrophysical data density is adequate for property modelling, the remote geophysical data may not have the resolution to refine the model internally. However, geophysical inversion could still provide a (coarse) check on both the accuracy of the property values (suitably upscaled) and the adequacy of the modelled volume (Figure 6).

Lithology, or at least rock class, can be inferred from inverted properties, using either supervised (e.g. Perron et al, 2012) or unsupervised (Sun & Li, 2011; Hodgkinson et al, 2012) methods. Thus petrophysical models can be transformed into “inverted geology”.

ADVANTAGES OF INVERTING A GEOLOGICAL MODEL

Geological models permit geometry inversion as well as property inversion. Programs capable of geometry inversion can also perform property inversion, either simultaneously, e.g. Bosch et al (2006), or sequentially, e.g. Fullagar et al (2004).

For property inversion on a geological model, the rock type attribute provides added flexibility and control. For example, the properties of entire homogeneous units can be optimised by inverting their respective properties; homogeneous unit inversion is fast, even for large models, because only a handful of parameters are involved.

The advantages of inverting on a geological model are summarised below:

- Natural driver for integration
- Simplifies interpretation of property model
- Fast optimisation of homogeneous properties
- Greater control, e.g. restriction of changes to particular geological units
- Incorporation of magnetic remanence according to geological unit
- Assignment of statistical distributions according to rock type
- Geometry inversion as well as property inversion
- Restriction of changes to particular geological boundaries

The perceived disadvantages of inverting on a geological model are as follows:

- time required to construct model at the outset (though normally it either exists or not)
- time required to simplify an existing geological model, e.g. increase cell size to reduce run time and/or demand on memory
- time required to compile and analyse physical property data.

However, it could be argued that the “additional” time is really just the “normal” time required for interpretation.

Importantly, inverting on a geological model does not restrict the inversion options. If little or nothing is known about the geology, conventional “unconstrained” property inversion can be performed on a geological model comprised of a single rock type.

HOWMANY CONSTRAINTS MAKE A DIFFERENCE?

There is no dogmatic answer to this question. For example, knowing (after collecting hundreds of geochemical samples with a 2m auger) that the basement depth is greater than 2m over the entire area is of probably of minimal benefit. On the other hand, if one of the 2m holes reaches basement, its significance could be enormous. This point is illustrated via constrained and unconstrained inversion of regional gravity data from northwest Queensland (Figure 7).

A single property constraint could have major implications in terms of the volume of the causative body. Likewise, a single remanence determination could materially alter a magnetic interpretation, if regarded as representative of the entirety of the source.

OPPORTUNITIES AND ROADBLOCKS FOR GEOLOGICALLY- AND PETROPHYSICALLY-CONSTRAINED INVERSION

Roadblocks:

- inversion still a black box?
- geological model construction and manipulation
- lack of petrophysical data
- time allocated for interpretation
- consultants and contractors at arms length?
- model appraisal and risk assessment
- upscaling
- workflows

Opportunities:

- faster processors in parallel deliver shorter run times
- massive amounts of memory facilitate inversion of larger and/or more detailed models
- lithological inversion
- efficient joint inversion by exploiting common geology
- incorporation of constraints from seismic
- contribute to resource modelling
- inversion software integrated with geological modelling packages
- inversion by geologists?

CONCLUSIONS

Inversion can be regarded as one component of an Earth modelling system, to advance interpretation of the sub-surface. The immediate aim of inversion is to improve a starting model in order to achieve a satisfactory fit to geophysical data. Owing to the limitations imposed by physics, logistics, and experimental error, there are usually an infinite number models which are acceptable in terms of data fit. Of these, the models which conflict with what is already known about the geology and petrophysics of the area must be rejected. Hence the need for geological and petrophysical constraints.

Most 3D geophysical inversion models are purely petrophysical, i.e. comprised of cells attributed with physical properties only. Geological models, on the other hand, are comprised of surfaces which enclose rock type domains. If inversion is performed on a geological model rather than a pure property model, a richer set of options is available, both for inversion style and for constraints. In particular, geometry inversion can be applied to modify geological boundaries, or the variability of a property within a domain can be controlled to conform to a prescribed probability distribution.

In both petrophysical and geological models, bounds can be imposed on individual cells, with very tight bounds assigned to cells enclosing property measurements on core or downhole. In terms of geological constraints, deviation from a “reference” model can be minimised, and a structural grain can be imposed. However, petrophysical constraints which are specific to a rock type, e.g. remanent magnetisation parameters, cannot be easily applied to pure property models.

A wide range options is already available for constrained inversion, and there is great scope for further developments. A number of opportunities and challenges has been identified. Arguably the key challenge is to develop workflows and supporting utilities to expedite interpretation utilising constrained inversion, and hence to derive maximum benefit from the geophysical data.

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Prominent Hill gravity inversion is included as an example by kind permission of OZ Minerals. **TBC**

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Figure captions:

Figure 1a: Schematic of modelling options for geological surfaces.

Figure 1b: Schematic of modelling options for petrophysical data.

Figure 2: Constrained geometry inversion of susceptible orebody, illustrating geological non-uniqueness. (a) Geologically modelled sulphide boundary, with drill holes traced in red; (b) Modified shape after geometry inversion, constrained by the drill hole pierce points, to improve the fit to magnetic data.

Figure 3: Drill hole pierce point and bound constraints at a geological contact (after Fullagar et al, 2008).

Figure 4: Non-uniqueness of magnetisation inversion. Three magnetic slabs with different magnetisation produce the same TMI anomaly (after Clark et al, 1992). The ambiguity can be resolved if the geological dip is known.

Figure 5: VPmg stochastic inversion of gravity over a limestone unit. (a) *a priori* density distribution in the limestone; (b) density histogram after inversion; (c) inverted density distribution in the limestone.

Figure 6: Prominent Hill density modelling. (a) Selected drill holes, coloured by core density; (b) Section 555535mE through density model based on core measurements; (c) Section 555535mE through density model after constrained gravity inversion.

Figure 7: Gravity inversion of Boulia 1:250,000 sheet, Queensland. (a) Boulia free-air gravity, with locations of water bores (black) and diamond drill holes (red) superimposed. (b) Comparison of inferred basement surface after constrained (red) and unconstrained (green) geometry inversion. Starting model for the constrained inversion incorporated insights from magnetic data (in terms of both lithology and depth) plus measured basement depths from two drill holes. (after Fullagar et al, 2008).