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Using archaeological models for the inversion of magnetometer data

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The Raganello Archaeological Project, undertaken by the University of Groningen, explores the mountainous area around the basin of the Raganello River in northern Calabria with substantial fieldwalking. The investigations are mainly concerned with the transition from Iron Age settlements to the Greek colonial period and aim to supplement earlier data from large central sites with information about the hinterland. Fieldwalking results are complemented by detailed geophysical investigations using electromagnetic and magnetic susceptibility (van Leusen *et al.* 2014) and magnetometer (Ullrich and de Neef 2010; Armstrong and van Leusen 2012) surveys. Since only a few key-hole excavations are possible as part of this extended project, the information gained from the geophysical data has to be maximised. For the magnetometer data, the aim is to obtain a detailed characterisation of buried features and to test various archaeological models that can describe them.

The shapes, size and position of magnetic anomalies differ from the buried archaeological features that cause them. It is necessary to use modelling and inversion to link the measured magnetometer data to magnetic soil properties. The magnetic inverse problem has no unique solution; there are many different subsoil distributions of magnetic susceptibility and remanence that could create the same magnetic surface data, and given small variations in magnetometer readings ('noise'), an infinite number of matching subsurface models could be found. Inversion of magnetic data, therefore, always has to make some assumptions to reduce the number of possible solutions and the assumptions determine the final results.

Based on the work by Li and Oldenburg (1996), most inversion schemes rely on 'objective functions' that use a particular depth weighting to derive a subsurface magnetic susceptibility distribution to fit the measured data. These schemes therefore have no knowledge of the nature of features that may cause the magnetometer results. By contrast, this project includes *a priori* archaeological information by using models of possible subsurface features and restricts the model parameters to archaeologically plausible limits. The inversion then progresses by adjusting automatically the model parameters (not the subsurface properties directly) until the best possible match with the measurements is achieved. Each of these parameters is changed separately to minimise the deviation from the measurements, since it is virtually impossible to derive a Jacobian inversion matrix for a closed formulation of this forward model. The adjusted model that results from this process depends on the order in which the parameters are adjusted during the inversion as there are many local minima that can trap the process. Several runs with

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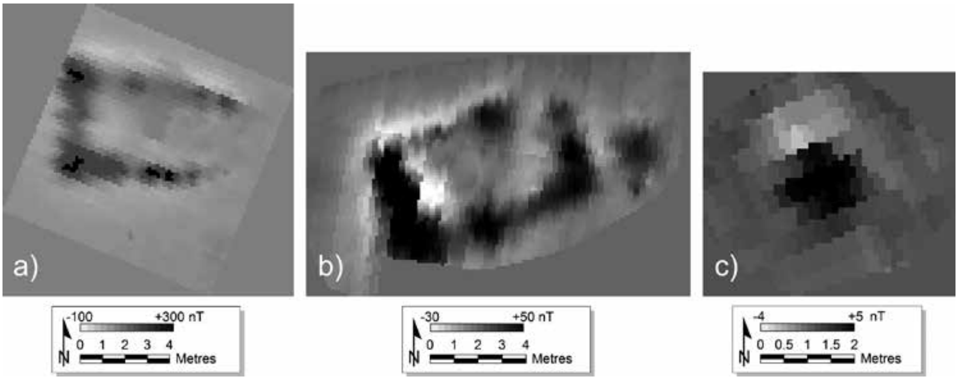

Fig. 1. Fluxgate gradiometer data for three classes of anomalies: (a) U-shaped building, (b) C-shaped building and (c) pit-like anomaly

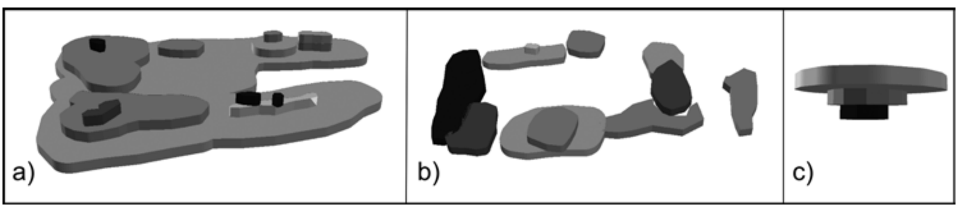

Fig. 2. Geophysically informed polygonal models adjusted through inversion to obtain the best possible match with the magnetometer data (see Fig. 1)

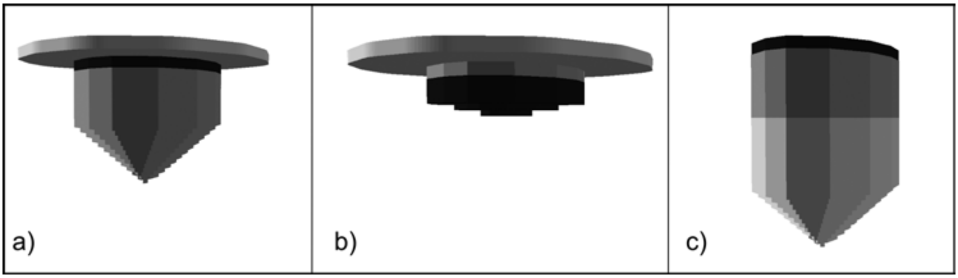

Fig. 3. Archaeologically informed model for the pit in Fig. 1c. The parameters for this model (e.g., thickness of layers, diameter) were adjusted through inversion to obtain the best possible match with the magnetometer data. The three different inversion results (a to c) fit the data nearly equally well

parameters in randomised order are therefore performed to obtain an overview of the possible solutions from which those can be selected that have a good overall fit and are archaeologically plausible. Since it is unlikely that the chosen generalised archaeological models fit the buried features of a site exactly (e.g., slight deviations in angles, depth layering), some mismatch with the actual measurements is to be expected. It is acceptable therefore to assume that remanence is roughly oriented in the direction of the current Earth's magnetic field and that remanent and induced magnetisation can be described together by an apparent magnetic susceptibility that the inversion process determines. The remanence can then be derived by comparison with magnetic susceptibility measurements of actual soil samples.

Two different approaches for designing the parameterised models were tested in this project; they can be referred to as geophysically and archaeologically informed models, respectively. For the first approach an archaeological geophysicist may estimate the approximate shape and location of possible archaeological subsurface features from the anomaly map of the data. The model is constructed from polygons at different depths that are chosen so that they may recreate the measured anomalies. The inversion process then proceeds to adjust three parameters for each polygon: its magnetic susceptibility, its size (expressed as a positive or negative buffer radius around the polygon), and a shift of the buffered polygon along the magnetic north-direction. For the second approach, an archaeological model is designed based on known archaeological structures, for example, a pit with two layers of fill. Parameters are chosen to describe the different aspects of the model (e.g., thickness of layers, diameter, tapering at the bottom) and are varied in the inversion to achieve a good fit with the measurement data.

For the Raganello Archaeological Project, detailed magnetometer surveys were undertaken with handheld magnetometers over anomalies of particular interest. For some sites, this was followed by trial-trenching and magnetic susceptibility sampling. From these results, three classes of anomalies were selected for the test of the inversion methodology: (a) U-shaped buildings, (b) C-shaped buildings and (c) pit-like anomalies (Fig. 1). Following the first approach, polygonal models were designed to reproduce the measured magnetometer data and their parameters were adjusted through the inversion process resulting in subsurface features that matched the measurements well (Fig. 2). After inversion the size of the deeper polygons was often considerably larger than initially estimated, which may be due to destruction layers at the base of the archaeological features. In most cases, the inversion shifted the polygons slightly north, thereby accounting for the fact that a buried feature lies to the north of the peak of its anomaly. Hence, the resulting polygons were better approximations of the buried features than the initial interpretation diagrams. When adjusting the polygon parameters in different order, models were calculated that looked considerably different but fitted the data nearly equally well. In particular, the contribution of the lower layers was dissimilar between the various runs of the inversion.

For the second approach, parameterised models of archaeological features were created. For example, a pit was described by a spread-out plough layer, followed by top and bottom layers of different magnetic susceptibilities with a tapering at the bottom. The inversion then progressed to optimise the parameters of these models, including thickness, radius and magnetic susceptibility. The various runs of the inversion resulted in considerably different models (Fig. 3). This is attributed to the strong decrease of the magnetic signal with depth so that variations in deeper layers have little effect on the overall magnetic anomalies.

Both model-based inversion approaches produce results that contribute to a better understanding of the features that cause the measured magnetic anomalies. Although the inherent non-uniqueness of magnetic inversion cannot be overcome, using archaeologically informed constraints allows feature interpretations to be created with a greater level of confidence.

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