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Prospecting for clay minerals within volcanic successions: Application of electrical resistivity tomography to characterise bentonite deposits in northern Sardinia (Italy)

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ABSTRACT

Electrical resistivity tomography (ERT) is applied to prospect for and characterise a bentonitic clay deposit in northern Sardinia. Sardinian bentonites derived from the hydrothermal alteration of thick successions of pyroclastic flows and epiclastites are associated with the Oligo-Miocene calc-alkaline volcanic cycle. The alteration of these rocks is generally controlled by faults that control the local circulation of hydrothermal fluids. Two-dimensional ERT investigations were performed close to a faulted area to define the location, thickness and lateral continuity of the clayey body, and determine how it relates to faulting and stratigraphy. A line-based three-dimensional ERT data acquisition was carried out in a selected area to estimate the available clay reserves. The reliability of these resistivity models was assessed by comparison with local borehole data. Finally, the interpretation of the ERT results was optimised through synthetic modelling of the electrical resistivity imaging technique. The results define the extent and geometry of the bentonitic deposit with good accuracy and outline the scenarios where the ERT method may provide optimal results when prospecting for clay deposits.

1. Introduction

Clay mineral deposits are commonly linked to the hydrothermal alteration of volcanic precursors (Inoue, 1995). Within volcanic successions, the interplay between faults and lithology controls the geometry and composition of these clayey deposits, as bedform deposits can develop when a poorly welded, permeable pyroclastic flow is sandwiched between less permeable rocks (Oggiano and Mameli, 2012). Alternatively, vertical or funnel-shaped deposits may form in poorly permeable precursors along the damage zone of regional-scale faults.

The exploration and evaluation of clay reserves are generally achieved through conventional methods, including structural and stratigraphic studies, drilling investigations and trenches. Despite the high costs, these methods can fail in predicting the actual three-dimensional (3D) structure of a deposit, in terms of both geometry and composition, if heterogeneities in the precursor rock and structural complications are not taken into account (Wardrop, 1999).

Geophysical methods, when guided by previous geological and structural surveys, can provide valuable information for mineral prospecting and on the geometric characteristics of mineralised bodies (e.g., thickness, lateral extent, depth). In particular, geoelectrical resistivity methods have been successfully applied to identify and characterise conductive clay bodies (Bazin and Pfaffhuber, 2013; Ferguson et al., 1999; Giao et al., 2003; Sinha, 1980). However, the effectiveness of these techniques depends on the high resistivity contrast between the mineralised body and its host rock. The electrical resistivity of clays is generally lower than that of several host lithotypes (Parasnis, 1973), and ranges from 1 to 100 Ω m (Loke, 1999; Reynolds, 1997), depending on the clay mineral content, porosity, dissolved cations content and water saturation. Bentonitic deposits may have resistivity values as low as 4 Ω m due to the high cation exchange capacity of smectite group minerals (Kaufhold and Penner, 2006). Given this high resistivity contrast, electrical resistivity tomography (ERT) can be a powerful tool in imaging clay bodies for mineral prospecting.

A key advantage in ERT surveying is the automated multielectrode system (Dahlin, 2001), which allows two-dimensional (2D) resistivity models of the subsurface to be created; additional benefits include low costs, the absence of destructivity and rapid acquisition. However, in heterogeneous structures, the influence of the boundary conditions in close proximity to the survey lines violates the 2D assumption, which can cause significant inaccuracies in the resulting 2D resistivity models (Bentley and Gharibi, 2004; Chambers et al., 2002; Sjodahl et al., 2006). Thus, 3D ERT surveys are indispensable in investigating complex three-dimensional structures and estimating the volume of materials that can be potentially extracted in quarries or mines (Aizebeokhai and Olayinka, 2011; Chambers et al., 2006; Chambers et al., 2013; Neyamadpour et al., 2009).

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A complete 3D survey requires electrodes to be placed in the form of a 2D surface grid, with measurements made throughout the grid. However, a more cost-effective strategy is usually adopted wherein 3D data sets are collated from independent, parallel 2D survey lines, and sometimes also from orthogonal crosslines (Rucker et al., 2009). This strategy reduces the cost of a 3D survey, and also allows 2D inversions of each individual line to be performed for quality control (Loke et al., 2013).

In this paper, we present 2D and 3D ERT surveys performed on a selected area in northern Sardinia that provide strong evidence for the existence of bentonite deposits (Figs. 1, 2). The 3D ERT data acquisition was obtained from measurement in a single direction, along several series of parallel 2D electrical lines.

The aims of this work are: (i) to ascertain the occurrence of an economic mineralised body and define its spatial pattern; ii) to assess the reliability of the ERT method in estimating available clay reserves compared with drilling investigations; and iii) to tune a synthetic modelling of the electrical resistivity imaging technique to identify the major shortcomings of this approach in optimising the interpretation of field surveys.

2. Study area and geological setting

The area of interest for this clay mineral prospecting exercise is located in northern Sardinia. It consists of a pyroclastic succession, with minor intercalations of lacustrine tuffites (Cerri and Oggiano, 2002) related to the Oligo-Miocene calc-alkaline volcanic cycle (Fig. 1). The volcanic succession is well exposed at the junction between a ENE trending strike-slip basin (the Chilivani-Berchidda Basin; Fig. 1) and the Logudoro Basin. The latter basin is a half-graben that interrupts the former basin and is bounded by N–S to NNW–SSE normal faults (Oggiano et al., 1995). Two fault arrays, each roughly parallel to the border faults of the two basins, crosscut the volcanic rocks. In northern Sardinia, the faults pertaining to these same arrays acted as preferential paths for hydrothermal fluids, responsible for various types of alteration and epithermal mineralisation at the expense of the Tertiary volcanic succession (Mameli, 2001; Oggiano and Mameli, 2012; Sinisi et al., 2012).

The stratigraphy of the study area (Fig. 2) consists of the following units, from the bottom to top (numbers refer to the stratigraphy in Fig. 2):

- finely laminated tuffites with advanced diagenesis, characterised by alternating dark ash laminae and thin, pumice-rich layers of lacustrine origin (12);
- weakly welded and roughly bedded tuff, derived from a subaerial pyroclastic fall (10);
- a strongly welded pyroclastic flow (upper ignimbrite) with vitroclastic texture and a thickness of 15–25 m (9);
- a moderately welded pyroclastic flow of undetermined thickness due to surface erosion (8).

These Tertiary volcanic rocks are covered by blackish-brown smectite-rich vertisoils, encompassing gravels and boulder of glassy ignimbrites (2) that form a thick slope of debris (1) near the fault scarps.

The main structures of the area are: (i) a sinistral E–W strike-slip fault with a normal component, which downthrows the welded ignimbrite on the northern block; (ii) a N–S trending normal fault responsible for the relative uplift of the western block; and (iii) a normal fault oriented NE–SW, which further downthrows the southern block, allowing the preservation of the moderately welded pyroclastic flow (Fig. 2).

The more porous and permeable unit, the weakly welded pyroclastic fall, is exposed in an erosive window below the upper ignimbrite at a site located 1 km south of the E–W strike-slip fault. The state of the

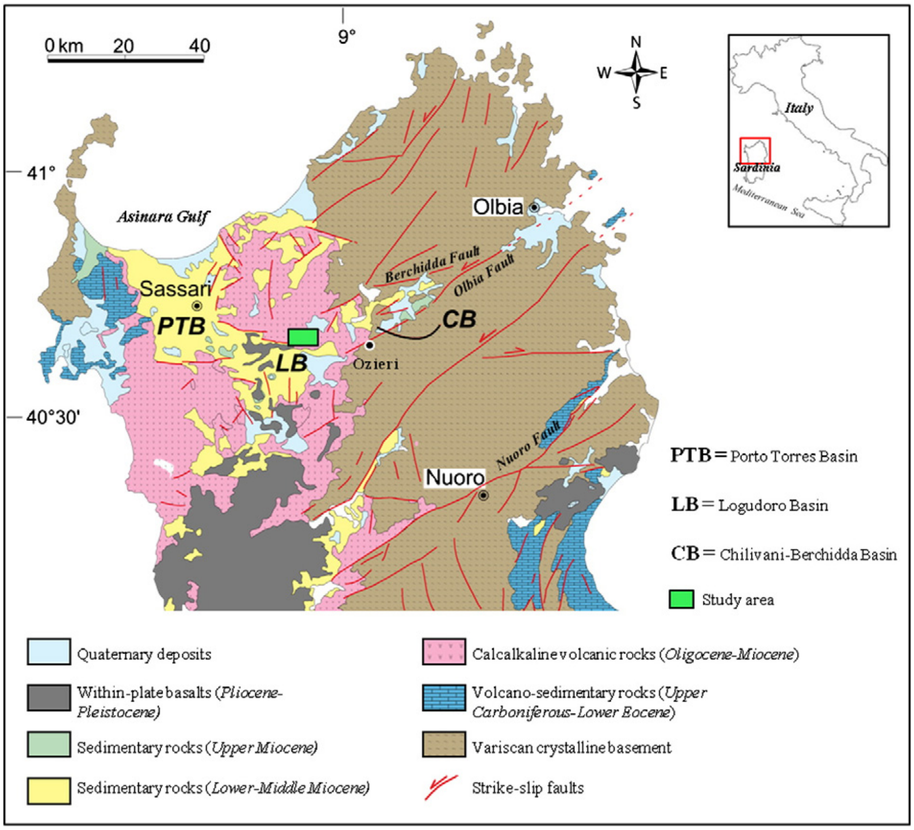

Fig. 1. Geological map of northern Sardinia, with the study area highlighted by the green rectangle (modified from Funedda et al., 2000).