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Resistivity imaging of Pleistocene alluvial aquifers in a contractional tectonic setting: A case history from the Po plain (Northern Italy)

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ABSTRACT

In this work we present the hydrogeophysical imaging of a key sector of the Quaternary Po foreland basin (northern Italy), focussing on the reconstruction of clastic aquifers and aquitards in a complex tectono-sedimentary subsurface architecture. The study area includes the relic reliefs of Casalpusterlengo and Zorlesco, two smooth morphological features involving uplifted and gently folded Pleistocene marine to alluvial sediments, plausibly linked to the buried Northern Apennines thrust and fold belt. The geophysical data include 35 Direct Current Vertical Electrical Soundings collected over a 37 km^2 wide area, acquired with Schlumberger array and maximum half-spacing of 500 m. 1-D resistivity-depth profiles were computed for each VES. An integrated hydrostratigraphic approach was applied, to constrain the interpretation of the geophysical data along several cross-sections, including the comparison of resistivity soundings to stratigraphic logs, borehole electric logs and the pore-water properties.

The resistivity interfaces, traceable with the same laterally continuous vertical polarity, were used to develop an electrostratigraphic model in order to portray the stacking of electrostratigraphic units down to 200 m below ground surface. Their vertical associations show a general upward increase of electrical resistivity. This assemblage mimics the regional coarsening upwards depositional trend, from the conductive units of the Plio-Pleistocene marine-to-transitional depositional systems to the resistive units of the Middle–Late Pleistocene fluvial and alluvial plain depositional systems. Middle Pleistocene depositional systems host an alternation of North-dipping, high-to-intermediate permeability aquifer systems (70–180 Ωm, thickness of 5–70 m) separated by low permeability aquitards (20–50 Ωm, thickness up to 40 m). These units pinch out against the Casalpusterlengo and Zorlesco relic reliefs, where they cover the uplifted and folded regional aquitard (20–50 Ωm) formed by Pliocene-Lower Pleistocene clays to sandy silts with gravel lenses in agreement with borehole data. In the deepest part of the local stratigraphy, a broad low-resistivity anomaly (<10 Ωm) was clearly mapped through the study area. By comparison with electrical borehole logs in deep oil-wells, it could be interpreted as the fresh–saltwater interface due to the presence of connate waters and brines hosted by the marine-to-transitional shales.

1. Introduction

Hydrogeophysical exploration of sedimentary basins is a common tool for hydrostratigraphic and hydrogeological studies (Binley et al., 2010; Bridge and Hyndman, 2004; Hubbard and Rubin, 2005). During the last decade, geo-electrical investigation of alluvial basins has shown the importance of the integration of geoelectrical methods with the (hydro)-stratigraphic reconstruction in order to obtain more realistic and reliable geophysical images of clastic aquifers, aquitards and aquicludes.

Until now, the investigation has mainly focussed on multiple-scale geoelectrical imaging of the most common sedimentary units encountered in alluvial hydrostratigraphy, like meandering rivers or braided rivers (Baines et al., 2002; Bersezio et al., 2007; Bowling et al., 2005, 2007; Bratus and Santarato, 2009; Mele, 2009; Mele et al., 2012; Sinha et al., 2012; Yadav et al., 2010). These results encouraged a new effort to use geoelectrical methods to investigate the regional architecture of alluvial hydrostratigraphy in a complex tectono-sedimentary setting. This attempt was made in the Lodi alluvial plain, south of Milan, in the central part of the Quaternary Po foreland basin (Northern Italy; Fig. 1A). The hydrostratigraphic structure of this sector of the Po basin formed during and after Plio-Pleistocene thrust-folding and uplift of Middle *pro parte* (p.p.)–Upper Pleistocene alluvial terraces (aquifer systems) sitting above Upper Pliocene–Middle p.p. Pleistocene marine to littoral sediments (aquitard and aquiclude systems) at the deep intersection between the Alps and Apennines mountain belts. Within this large scale framework, mapping the heterogeneity at a detailed

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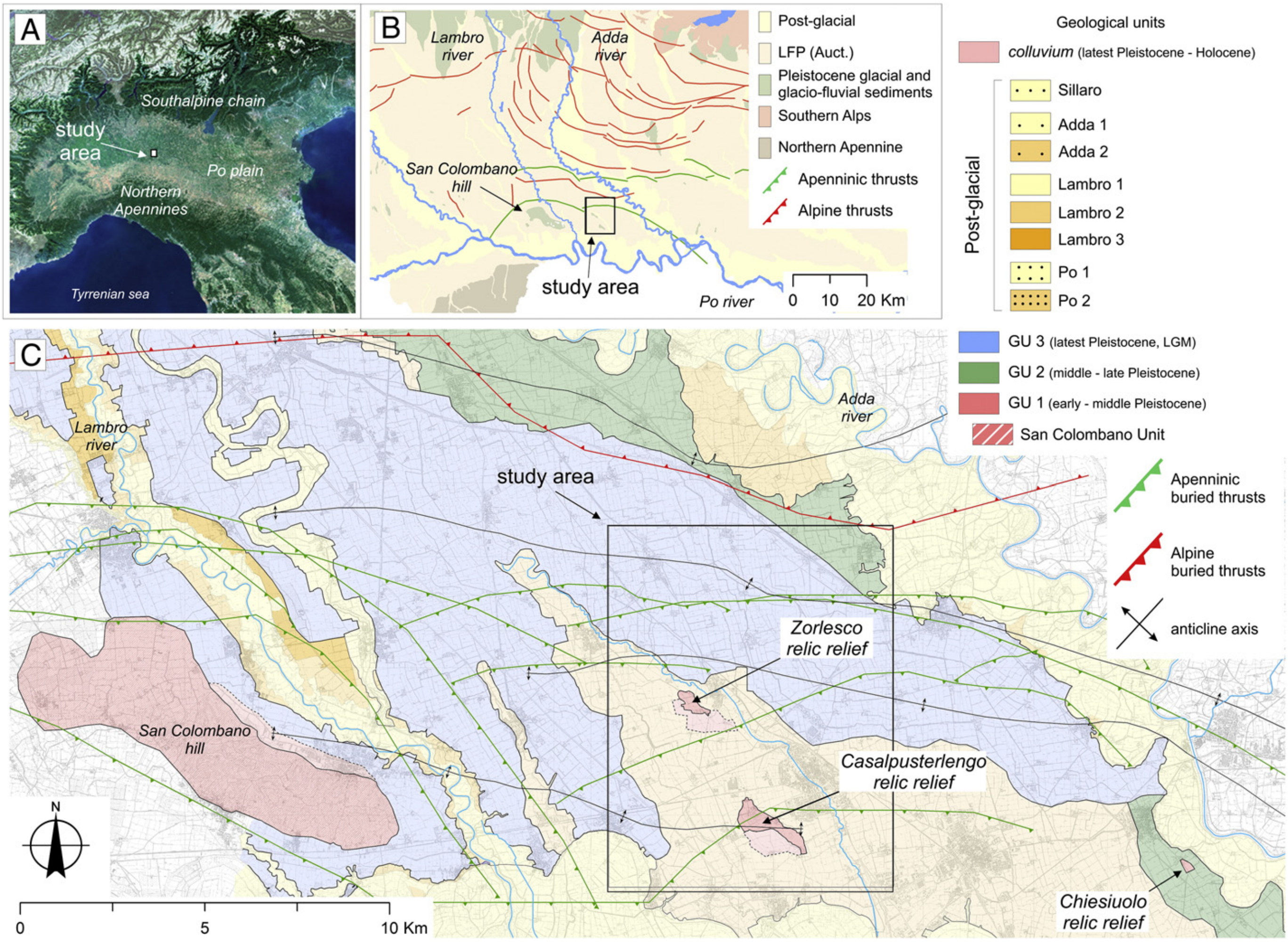

Fig. 1. A) Location of the study area in the Quaternary Po alluvial plain (Northern Italy); B) Main tectonic and geological features at the Alps–Apennines intersection; C) Geological map of the Southern Lodi plain (modified after Baio et al., 2009) showing the position of the study area, the Casalpusterlengo, Zorlesco and Chiesiolo relic reliefs, the San Colombano hill and the main tectonic features.

scale is limited by the uncertainties in the correlation of sparse well log data.

In this work, direct current (DC) resistivity methods were used to yield maps of the subsurface electrical resistivity. In clay-poor alluvial permeable sediments, current flow is primarily related to electrolytic conduction, and strongly depends upon the connected porosity, the litho-textural assemblage and the pore-space structure. On the other hand, current flow in clay-rich aquitards and aquicludes is characterized by surface conduction produced at shale–grain interfaces by the excess negative charges of clay particles forming an electrical double layer (Keller and Frischknecht, 1966; Reynolds, 2011; Schön, 2004; Telford et al., 1990): the great specific surface produces smaller electrical resistivity than for clay-free sediments. Moreover, the mutual dependence of electrical resistivity and hydraulic conductivity on the pore-space structure, the shale distribution and the pore water electrical properties (Keller and Frischknecht, 1966; Reynolds, 2011; Schön, 2004; Telford et al., 1990) permits the existence of a relationship between electrical resistivity and hydraulic conductivity, so that geophysical imaging can be used as a *proxy* to map subsurface hydraulic conductivity structure.

Following this premise, the goal of this paper is the application of a methodological approach based on the acquisition of DC data to yield an hydrogeophysical image of (1) the shape and stacking of the hydrostratigraphic units (Maxey, 1964), (2) the heterogeneity of hydraulic properties and the aquifers connectivity and (3) the relationship of these physical and geometrical properties with the fresh–saltwater interface. The results obtained in the complex tectono-sedimentary setting of the Lodi area provide suggestions about the general applicability of the applied methodology to hydrostratigraphic characterization of alluvial foreland basins.

At this purpose, 35 DC Vertical Electrical Soundings (VESs) were collected over a 37 km^2 wide area (Figs. 1; 2) and 1-D resistivity inverse modeling was used to define a high-resolution electrostratigraphic model. The concept of "electro-stratigraphic units" (EsUs), as it was redefined by Mele et al. (2012), was adopted to link the vertical and lateral heterogeneities of electrical properties to hydrostratigraphic heterogeneity (external shape, size, lateral continuity and connectivity of sedimentary bodies; textures and fine-to-coarse grained sediments ratios; facies associations and internal structure of the sedimentary bodies; distribution of diagenetic vs. pedogenetic features). Calibration to stratigraphic logs and borehole electric logs allowed correlation of the electrostratigraphic image to the stratigraphy of alluvial units and their marine substratum.

2. Geology and hydrostratigraphy of the southern Lodi plain

In the Southern Lodi plain (Fig. 1B), the deposition of the Plio-Quaternary marine to continental systems was strongly controlled by