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Seismic and Electromagnetic Study of Reservoir Properties for Geothermal Applications

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ABSTRACT

Joint reflection seismic, resistivity and multi-fold ground-penetrating radar (MFGPR) study of reservoir analogues allows extracting information about cross-property relations of interest in the characterization and monitoring of deep geothermal resources. In particular, a link between resistivity and velocity of seismic waves can be established though porosity. MFGPR is further used as a structural and physical properties validation tool, as it provides ultra-high resolution images of the rock volume, including networks of joints and fractures, estimates of electromagnetic impedance and detailed mapping of variations in electromagnetic properties that affect amplitude and velocity and are highlighted by the attributes of the radar trace. Comparison between experimental results, theoretical and empirical cross-property relations connecting electrical conductivity to elastic moduli and velocities of rocks shows that combined methods provide enhanced assessment of reservoir characteristics, with particular reference to porosity. We test the method on a Tertiary limestone outcrop.

1. INTRODUCTION

Reservoir analogues can be used for the experimental study of petrophysical properties of rock masses and for their correlation with the response obtained by geophysical methods. The combined geophysical and petrophysical analysis can improve the knowledge of subsurface fractured and porous systems, the calibration of geophysical data and the numerical simulation of mass and heat transfer in better constrained reservoir models. This is of particular interest in the case of geothermal systems, where a detailed preliminary assessment of reservoir characteristics is required to reduce risks and costs of exploratory and production/injection drilling.

Several authors (see e.g. Zeng et al., 2004; Corbeanu et al., 2002; Hammon et al., 2002; Novakovic et al., 2002; Szerbiak et al., 2001) have recently applied ground-penetrating radar (GPR) to characterize reservoirs through the study of data obtained from outcrops and boreholes. Their results show that GPR is suited to provide insight into the internal architecture of reservoir rocks and can produce 3-D deterministic representations of subsurface features controlling fluid flow (Zeng et al., 2004).

Nonetheless, GPR cannot be applied to a full reservoir characterization, even at depths corresponding to the most favorable geothermal gradient conditions, due to the limits of penetration of radio waves in geological materials. Borehole surveys in dry crystalline rocks obtain maximum penetration values not exceeding 150 m (see e.g. Hollender et al. 1999) and such figures can be considered adequate for geothermal system characterization only in limited volumes. Moreover, fluids characterizing geothermal reservoirs can increase conductivity and relevant attenuation of electromagnetic waves by orders of magnitude, thus imposing further constraints on the volumes accessible to GPR characterization.

The problem can be tackled from a different perspective, by considering the information attainable by other geophysical methods, which can achieve penetration in the order of kilometers, and by using cross-property rock physics relations to establish links and obtain a multi-parameter characterization of the subsurface volume.

Resistivity obtained from magnetotelluric methods (see e.g. Suparno et al., 2005) is a common source of information about geothermal fields, due to the limited cost and large investigation depth. On the other hand, the inherent non-uniqueness in data inversion does not allow reliable reconstructions of subsurface conditions unless complementary data are available to constrain the subsurface model and focus the search of the global minimum of the objective function in more restricted regions.

Seismic reflection data can provide unrivalled imaging and characterization of subsurface volumes to depths of several kilometers. The principal limit in their application is the cost of data acquisition and processing that, in the case of large 3-D datasets, cannot be considered affordable in the framework of geothermal projects, where the budget is normally a fraction of that allowed to hydrocarbon exploration. Recent studies however prove their effectiveness and the considerable value they can add to the knowledge of complex geothermal systems (see e.g. Cameli et al., 2000; Cappetti et al., 2005; Fiordelisi et al., 2005; Mazzotti et al., 2002).

In this study we perform a reconstruction of reservoir analogue architecture and characteristics through MFGPR data. The multi-fold method is applied to calculate velocity and attenuation of radio waves as well as to enhance subsurface images in complex structural settings, such as densely fractured rock masses of interest in reservoir studies.

We further analyze the results of seismic waves velocity analysis and resistivity inversion to verify possible links through cross-property relations (Carcione et al., 2007; Mukerji et al., 2009).

The integration of geophysical data provides detailed models of reservoir characteristics that are validated by direct inspection of outcrop and borehole data.

2. METHODS

We use surface multi-fold and borehole (tomographic) ground-penetrating radar (GPR) to study a Tertiary limestone outcrop located in a quarry in NE Italy and belonging to the Peri-Adriatic carbonatic platform. The GPR dataset are integrated by resistivity measurements (2-D tomography) and multi-component seismic measurements to obtain seismic waves velocities. Theoretical and empirical cross-property relations are used to verify the links

2.1 Surface and borehole ground-penetrating radar

The method is based on propagation of electromagnetic waves in the radio frequency range and on the measurement of amplitude and arrival time of waves travelling along direct, reflected, refracted and diffracted paths.

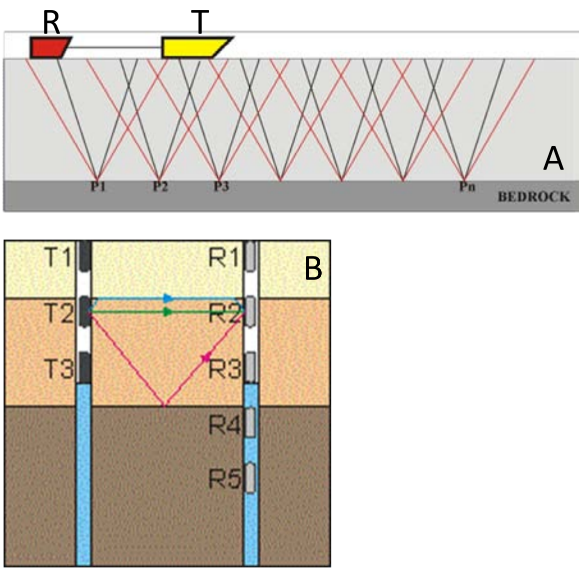

Figure 1: A) surface multi-fold ground-penetrating radar and B) cross-well tomography ground-penetrating radar data acquisition schemes used in the present work.

We use 250 and 500 MHz antennas for surface acquisition, 100 MHz ones for cross-well tomography. Surface data acquisition is performed on 5 cm in-line and 25 cm cross-line grids, minimum fold 1200% with offset range between 40 and 200 cm. Data processing focuses on resolution enhancement, depth imaging, velocity and attenuation analysis, instantaneous attributes calculation (see e.g. Yilmaz, Guangyou and Pipan, 2003). Cross-well tomography data are obtained from two wells with the following parameters:

Borehole-1 (B-1): Azimuth=84°, Dip=50°, Depth= 15.5m;

Borehole-2 (B-2): Azimuth=260°, Dip=68°, Depth= 20m;

Transmitter depth spacing increment: 50 cm;

Receiver depth spacing increment: 10 cm;

Data are inverted by using a 2-D ray based algorithm (Cai and McMechan, 1999).

2.2 Resistivity

2-D electrical tomography (see e.g. Dahlin, 1996) is performed with a multi-electrode (16) system by exploiting a Wenner-Schlumberger data-acquisition scheme and least-squares inversion algorithm (Loke and Barker, 1996).

2.3 Seismics

Seismic data (P waves) are obtained for velocity analysis purposes by performing transmission (from vertical to horizontal rock face) and reflection/refraction data acquisition across the volumes surveyed by means of GPR techniques. Seismic source is a 2.5 Kg hammer striking a 5 Kg tungsten-chromium steel plate; 24 vertical geophones, 10 Hz natural frequency, are used for seismic wavefield sampling with 50 cm geophone spacing and maximum 20 m offset.

2.4 Cross-property relations

A number of models and cross-property relations are proposed in literature to establish links between properties of materials measurable by geophysical methods (e.g. Archie, 1942; Carcione et al., 2007; Sen et al., 1981) . Porosity is a crucial parameter to establish relations between electric conductivity and seismic velocity (Carcione et al., 2007). Complex permittivity can be determined from volume fractions of components in composite materials (such as rocks and sediments) and eventually expressed as a function of porosity. Porosity measurements are performed in laboratory on samples from the study outcrops and boreholes. We use the complex refractive index method (CRIM, see ref. above) to calculate the permittivity of limestone partially saturated by water according to

$$\varepsilon = \left(\sum_{i=1}^{3} \gamma_i \sqrt{\varepsilon_i} \right)^2 \qquad (1)$$

Where ε_i is the permittivity of the i-th component (in our case, limestone, water, air) and γ_i is the volume fraction of the i-th phase. The CRIM value is compared with the result of radar measurements. P-wave velocity and conductivity values obtained from seismic and resistivity surveys are compared with Gassman-based relations (Carcione, 2007).

3. RESULTS

Figure 2 shows an example of 3-D GPR imaging of a limestone outcrop. A selection of in-line and cross-line data is extracted from the volume to highlight the main structural features of the rock mass. The main stratigraphic joints (J-K) are sub-parallel and exhibit maximum 20% dips. Two stratigraphic contacts characterized by lower reflectivity (α,π) show up in the intermediate sector and are recognized at the rock face. The lens bounded by the latter reflectors is imaged with centimeter accuracy in the GPR volume. The shallow part of the volume is characterized by sub-vertical fractures: the main ones are interpreted in red in Fig.2B. Fracture density shows lateral and vertical variations that affect the radar wave velocity.

Attribute analysis can be applied to GPR data volume to improve interpretation of subtle features and, in particular, of discontinuities in stratigraphic joints. This is of particular interest in the case of reservoir characterization, due to the influence of fracture systems on fluid flow within the reservoir. Figure 3 shows an example of attribute analysis performed on layered limestone (250 MHz data). Images in Figs.3A/B/C correspond to reflection amplitude, response frequency and instantaneous phase respectively. The response Frequency is the value of the instantaneous frequency where the envelope attains its maximum value. One value is obtained for each energy lobe and is returned as a constant for the entire time width of the energy lobe from trough to trough. This is a measure of the dominant frequency of the waveform contained within the envelope and is useful in measuring dominant frequency variations from energy lobe to energy lobe. It is independent of energy and phase (Bodine, 1984). The main radar reflectors corresponding to stratigraphic units identified at the rock face are highlighted in the instantaneous phase section (Fig.3C). Two main normal faults are interpreted (f1, f2) that intersect all the interpreted joints and exhibit measurable slip with maximum values not exceeding 30 cm. The instantaneous phase section allows straightforward interpretation of joints and identification of fractures and bends.

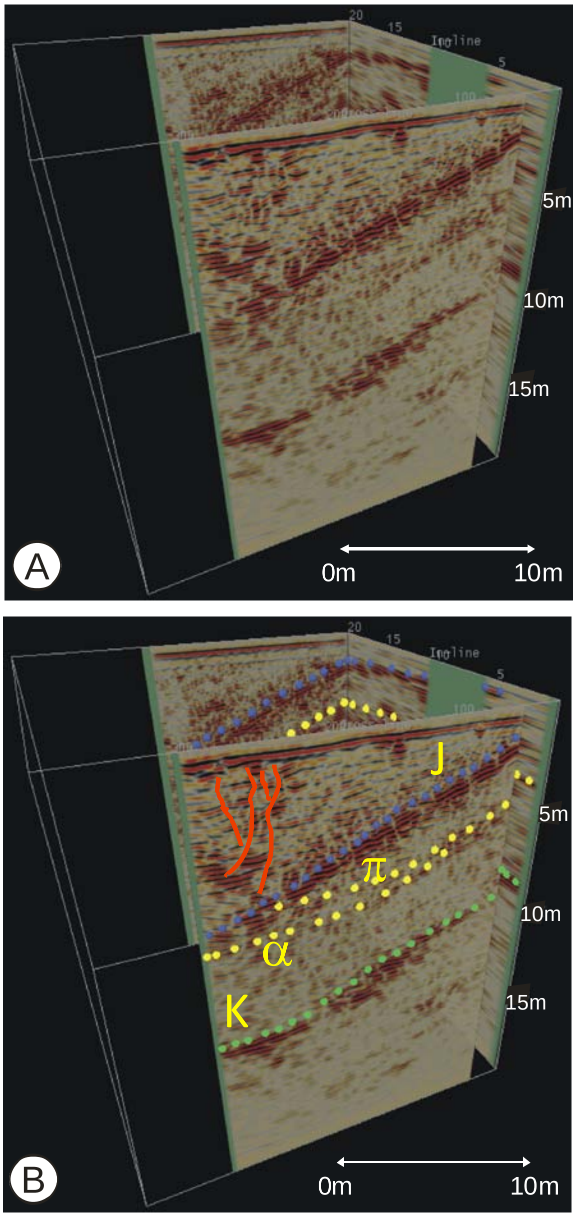

Figure 2: Example of 3-D multi-fold GPR data volume from the area of study (NE-Italy): A) in-line and cross-line selection (250 MHz data); B) interpreted data (stratigraphic joints as dotted lines, fractures as continuous red lines).

The cross-well tomographic data acquisition scheme reported in Fig.1B allowed measurements of velocity and attenuation that integrate the images obtained from surface techniques and the corresponding measurements performed

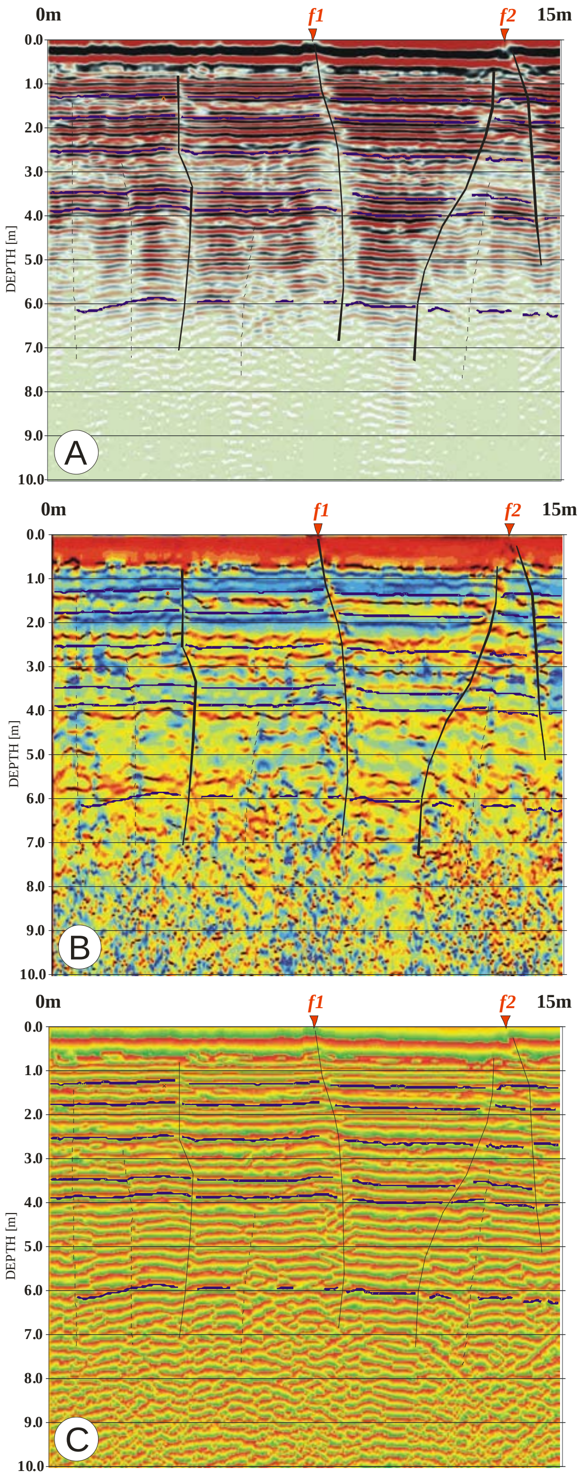

Figure 3: Example of attribute display of multi-fold GPR data from the area of study (NE-Italy): A) reflection amplitude (conventional GPR section, 250 MHz data); B) response frequency; C) instantaneous phase (see text for details).

on multi-fold records.

Figure 4 shows an example of application of borehole techniques to the study area. Amplitude and traveltime picking are performed on the original GPR transmission data (100 MHz) shown in Fig.4A. Bottom-hole separation between the two wells is less than 20 m and data exhibit excellent S/N ratio on the whole distance range. Poor angular coverage prevents from obtaining reliable data in the region adjacent to both wells. A detailed reconstruction of the attenuation (B) and velocity (C) characteristics is obtained in the central sector. In particular, maximum attenuation values and minimum velocity are observed in the deep central region (below 5 m, measured along B1). This is consistent with an increment in water saturation of the porous limestone. Velocity values range between 9.0 and 11.4 cm/ns and match those calculated for the measured porosity range from the CRIM model.

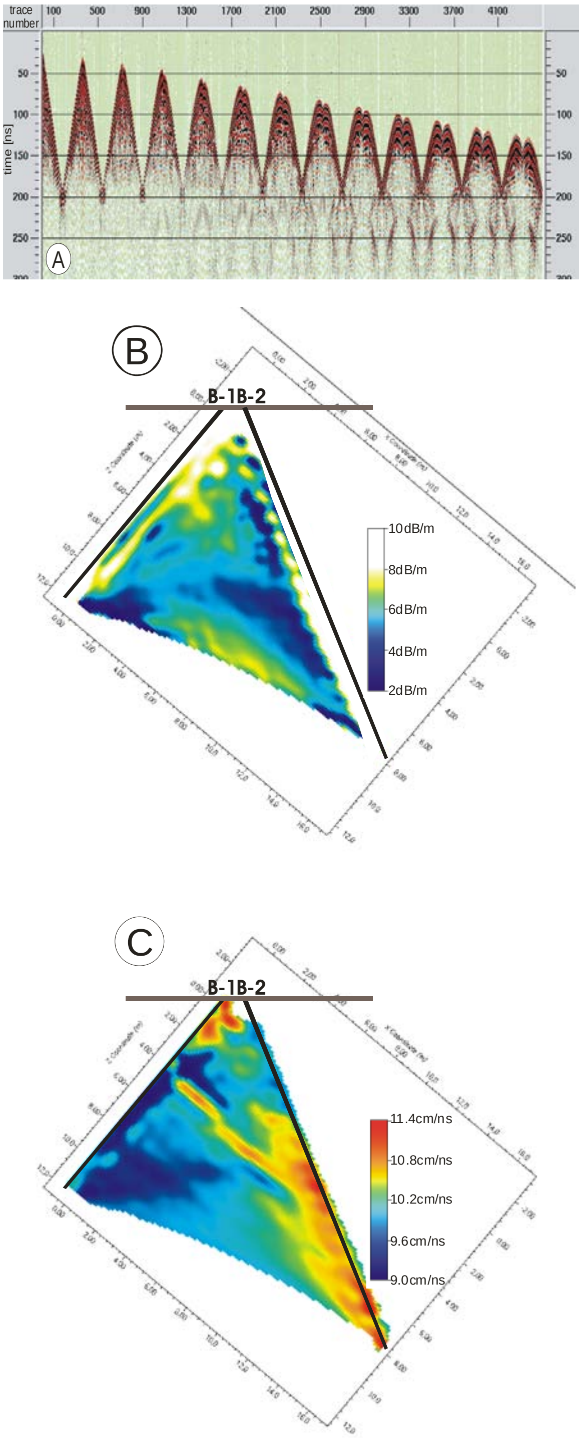

Figure 4: Example of GPR cross-well tomography from the area of study (NE-Italy): A) GPR transmission records (100 MHz data); B) Amplitude inversion; C) traveltime inversion (see text for details).

Traveltime picking and inversion (Fig.4C) highlights localized velocity contrasts. Lithology changes in the study rock volume are related to different type and content in fossils and such variations strongly affect the development of vuggy porosity which in turn reflects on water content.

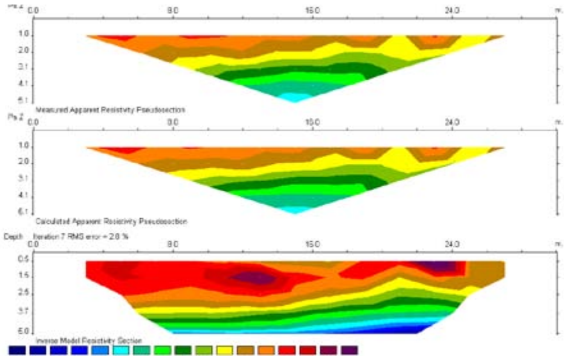

Figure 5: Example of 2-D electrical tomography from the area of study: color coded resistivity value (bottom) range from 1.6*10^2 (blue) to 2.6*10^3 (dark brown) Ωm.

Resistivity measurements performed by means of 2-D tomographic surveys give values compatible with the attenuation observed on radar data. The comparison with P-wave seismic velocities on the other hand does not provide a clear correlation with the values predicted by Gassman/CRIM relations for different rock types.

4. CONCLUSION

Subsurface models obtained from geophysical data integration can open the route to major advancements in geothermal systems exploration through considerable reduction of uncertainty in the assessment of reservoir properties. In particular, enhanced knowledge of structure and features controlling fluid flow can help in evaluating the potential of the geothermal system in the exploratory phase and in constraining subsurface models during the production phase to attain sustainable heat extraction rates. The study of reservoir analogues can help in interpreting the geophysical data at larger depths while the correlation of different physical properties can help filling the gaps deriving from incomplete or missing data from the areas of interest. Discrepancies between theoretical cross-property relations and field results obtained in the present study require further laboratory analysis in order to study the effects of the different components (solid, fluids) on the electromagnetic and elastic properties of the rock type of interest (Tertiary limestone).

5. ACKNOWLEDGMENTS

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