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A Stochastic Assessment of Geothermal Potential Based on Seismic and Potential Field Analysis and Hydro-thermal Forward Modeling – an Example from Tuscany (Italy)

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ABSTRACT

We present a stochastic approach for estimating geothermal and hydraulic properties in a medium-enthalpy geothermal reservoir Southern Tuscany (Italy) on a regional scale. The approach combines interpretations of different types of geophysical field data geophysical and geological borehole logs and laboratory data with hydro-geothermal numerical simulations. Special attention is paid to quantifying the uncertainties of the derived 3D model. For estimating model uncertainties, distribution functions are derived or estimated for all geophysical properties involved based on borehole measurements, careful seismic velocity analysis and forward modeling.

1. INTRODUCTION

Our study is part of an interdisciplinary effort of developing improved methods for prospecting and assessing potential geothermal reservoirs. Our approach basically consists of the following steps:

1. To derive a geological model of the subsurface based on seismic reflection measurements, including major lithological units and fault zones,
2. to determine seismic velocities of the geological units by careful seismic reflection velocity analysis in order to obtain an indicator of lithology,
3. to evaluate the seismic model by gravimetric forward modeling, thereby determining the density contrasts between the geological units as further lithological constraints,
4. to attribute thermal and hydraulic parameters derived from laboratory measurements of rock samples to the corresponding lithological units and
5. to estimate the hydro-thermal regime by hydro-thermal forward modeling and inversion, thereby iteratively correcting the initial model parameters in order to fit available temperature and heat flow data.

In the whole procedure increased attention is paid to quantifying the uncertainties of the 3D model at each step of its derivation. For estimating model uncertainties, distribution functions are derived or estimated for all geophysical properties involved based on borehole measurements, careful seismic velocity analysis and gravimetric and hydro-thermal forward modeling. The uncertainty values are then transferred to the geothermal assessment by repeating the hydrothermal computations for underground models randomly varied in their properties according to the corresponding parameter uncertainties.

The example case considered in the present article is a medium enthalpy geothermal reservoir in Tuscany that is heated by magmatic activity (e.g. Romanoli et al., 2010). Near surface temperature gradients have been found between 50 and 200°C. The study has been performed in a collaborative way involving working groups from universities and commercial firms. It is presented at the WGC 2015 in two companion papers - Ebigbo et al. and this one – where the present paper focuses on the development of the underground model, while Ebigbo et al. cover the hydro-thermal modeling. In the following chapters we are presenting results derived in steps 1 to 3 of the procedure outlined above.

2. DEVELOPMENT OF A GEOLOGICAL SUBSURFACE MODEL

For developing a structural geological model of the investigation area we could rely on a network of 5 multiply covered seismic reflection profiles, 2 vertical seismic profiles (VSPs) along boreholes and corresponding standard geophysical logs and a Bouguer gravity map. The lengths of the seismic profiles are between 10 and 20 km spanning an area of about 20x15 km. Depth penetration is about 8 km. In order to obtain optimum seismic images the data was very carefully processed in an iterative way. The processing sequence included, in particular, a thorough determination of P-wave velocities at depth for obtaining lithological constraints and near-surface for static corrections. The seismic velocities determined along the profiles could then be compared with the velocities form the VSPs in order to identify lithological units.

An example of a composite seismic section is shown in Figure 1 where reflection amplitudes, indicating structural interfaces, is underlain by seismic velocity (color-coded), correlating with lithology. The seismic velocities found in VSPs for the relevant lithological units are shown in Figure 2. These are carbonates of Ligurian and Tuscan units with P-wave velocities of the order of 3000 to 3500 km/s. These rocks are found in the upper levels of the investigation area showing thicknesses up to 2.5 km. Beneath these layers anhydrites of the so-called Burano formation are found showing P-wave velocities of 6-6.5 km/s that represent the maximum observed in both profile and borehole data. The third type of lithology is represented by rocks of the Farma formation, consisting of metamorphic phyllites as known from drill cores. The velocities are still high, about 5 km/s, but visibly lower than the Burano velocities. The color distribution in Figure 1 shows that the Farma layer is underlain by a high velocity layer followed by a heterogeneous sequence with velocities locally decreasing and again increasing with depth. This interlayering can be interpreted tentatively as an alternation of stacked Burano and Farma layers. However, this interlayering is not observed everywhere in the investigation area that has undergone a complex tectonic development. The basic structure of the resulting 3D geological underground model can be seen in Figure 3. Its dominant tectonic feature is a major fault along which the interlayered units were displaced in the km-range. The (meta-) sedimentary sequences are underlain by a major regional reflection structure, the so-called K-Horizon, that was already observed along the CROP03 and CROP18 deep reflection profiles (Pialli et al., 1998; Brogi et al., 2005). It has tentatively been associated with the brittle-ductile transition zone and might represent the top of a granitic intrusion. However, in our investigation area no seismic velocities could be determined for the layer underneath the K-Horizon. Therefore, addressing its geological nature remains speculative.

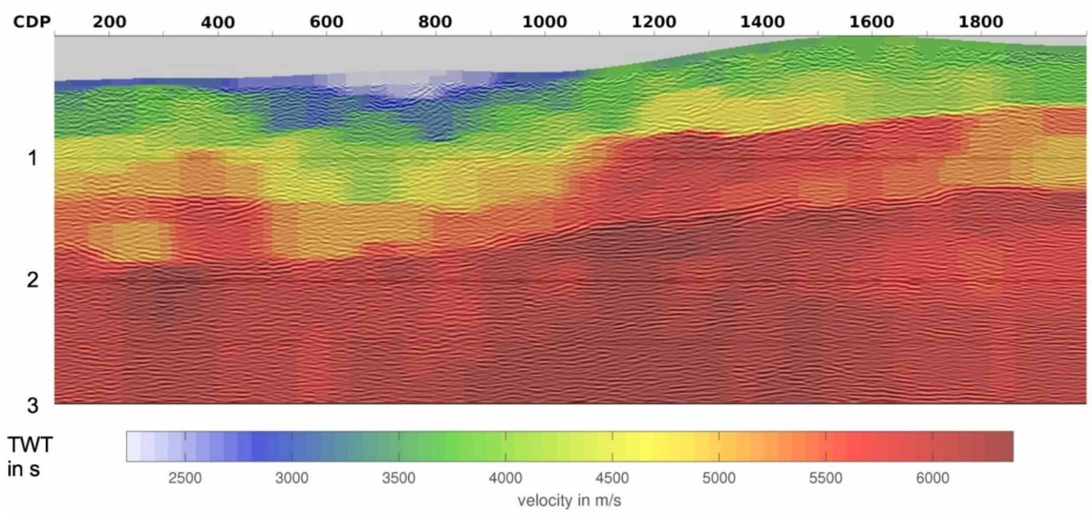

Figure 1: Example of a composite seismic reflection profile (migrated DMO-stack) with underlying interval P-wave velocities derived from NMO-velocity analysis.

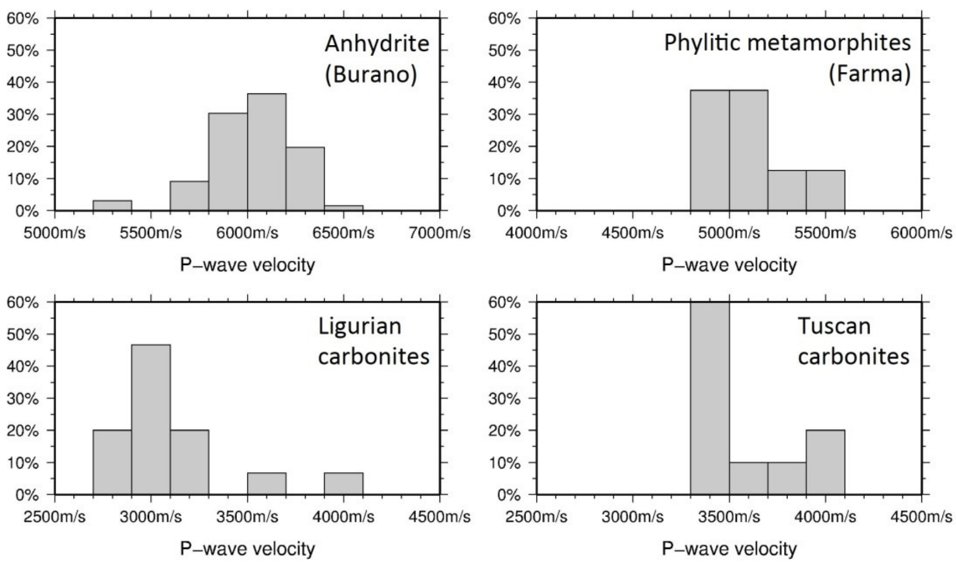

Figure 2: Histograms of P-wave velocities found by vertical seismic profiling in two boreholes of the investigation area, to be compared with the velocities found in situ by seismic reflection velocity analysis (Figure 1).

The uppermost Burano layer represents the potential geothermal reservoir. It is suspected to be hydraulically much more permeable than the other (meta-) sedimentary layers because fractures widened by solution processes may provide significant fluid pathways.

3. ESTIMATING SEISMIC MODEL UNCERTAINTIES

Since seismic wave velocity is the major source of information on lithology on a regional scale an assessment of its uncertainty is fundamental for model development. There are basically two sources of uncertainties that need to be considered:

(1) There is a spatial variability (fluctuation) in the seismic velocity of each lithologically uniform layer. This fluctuation may be caused by spatial variation in petrological composition and fracture density, also variation in the degree of metamorphosis or seismic anisotropy may play a role. This sort of seismic velocity variation can be recognized and quantified by the histograms

of the VSP results (Figure 2). They can also be associated with the lateral velocity variation along the layers visible in Figure 1. This geologically caused spatial velocity fluctuation is of the order of ±10%.

(2) The accuracy of reflection-based seismic velocity analysis is clearly limited by the lengths of the applied geophone spreads, by the complexity of geological structure and by the signal-to-noise ratio. This effect is demonstrated in Figure 4. The leftmost figure shows a cut-out of the section of Figure 1. The semblance diagram to the right of this figure shows red spots that indicate which so-called NMO-velocity (normal move-out velocity, horizontal scale) is adequate for the reflecting horizons found at the corresponding reflection times (vertical scale). The NMO-velocity represents a sort of average velocity of the hanging wall from that the velocities of the layers can be computed recursively. It is obvious that the red spots, which represent a measure of the coherency of the seismic arrival analyzed, are of finite width that broadens with depth. Under good conditions the accuracy with which the NMO-velocities can be determined is ±5%, but the accuracy may decrease to ±10% especially at deeper levels. These uncertainties translate directly into depth uncertainties of the corresponding geological interfaces. The right sub-figures of Figure 4 show average depth functions of NMO-velocity and corresponding interval (layer) velocities for the profile segment on the left (black line) and its corresponding uncertainties (grey bars). The red and green lines show two assumed endmember models for comparison: A interlayering of Ligurian/Tuscan and Burano layers (red, minimum endmember) and a homogeneous Burano layer (green, maximum endmember). The figure shows that the lithology can be resolved in terms of seismic velocities only in the upper half of the depth profile.

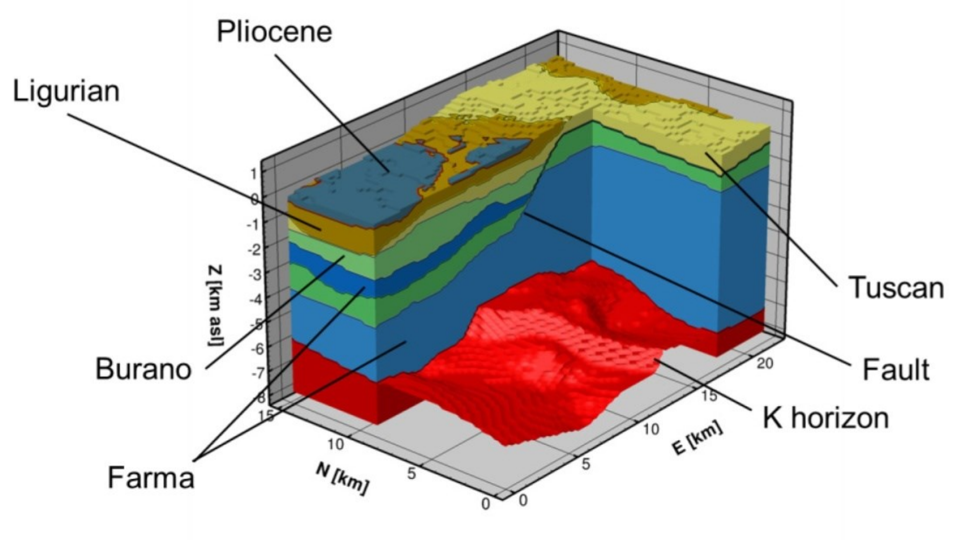

Figure 3: Geological model of the investigation area based on five seismic reflection profiles and seismic interval velocity analysis.

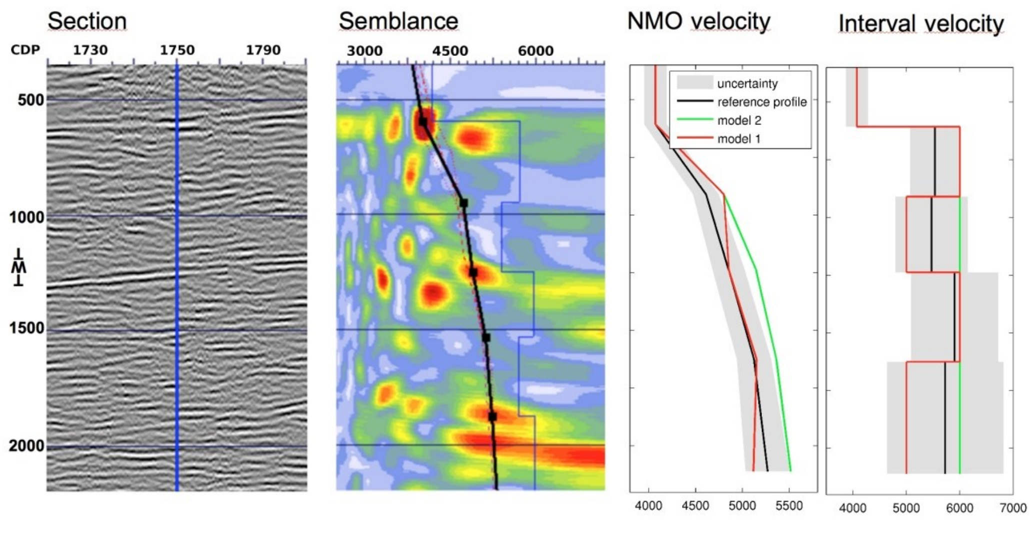

Figure 4: From left to right: (1) cut-out of the section of Figure 1. (2) The semblance diagram to the right of this figure shows red spots that indicate NMO-velocity (normal move-out velocity, horizontal scale) adequate for the reflecting horizons found at the corresponding reflection times (vertical scale). (3) The right sub-figures of Figure 4 show average depth functions of NMO-velocity and corresponding interval (layer) velocities for the profile segment on the left (black line) and its corresponding uncertainties (grey bars). The red and green lines show two assumed endmember models for comparison: An interlayering of Ligurian/Tuscan and Burano layers (red, minimum endmember) and a homogeneous Burano layer (green, maximum endmember).

4. GRAVIMETRIC ASSESSMENT

The seismically determined 3D model was evaluated by forward modeling of the corresponding gravity field. Therefor, a refined topographic correction and regional trend removal were applied. Then constant density values were attributed to each lithological unit. Since the structure of the model is defined by seismic measurements a simple linear inversion could be used to determine the density values of the units involved. The densities of near-surface layers that are known from drill cores were held fixed during the inversion. In this way we could obtain a satisfactory fit of the order of 2 mGal compared to an initial peak-to-peak anomaly size of 15 mGal.

Sensitivity tests showed that a lateral change of bulk density (mass deficit) has to be assumed at the depths beneath the bottom of the Burano for fitting the data. This mass deficit is required east of the fault. It may be realized by a lateral density change within the Farma unit or deeper beneath the K-Horizon (hot granitic intrusion as modeled by Bernabini et al. 1995). Up to this point it can not be clarified which model is to be preferred. The different possible model solutions then enter the thermal computations as endmember models the output of which can then be compared to thermal data in order to differentiate between them.

4. CONCLUSIONS

Seismic reflection imaging and velocity analysis were applied to set up a geological model of the investigation area that is in agreement with borehole measurements and the tectonic history of the area. Seismic velocity analysis helped to identify the lithology of interlayered sequences in areas remote from the drillholes. Additional 3D gravity modeling helped to check the consistency of the 3D underground model that was otherwise constrained only by a wide-mesh network of 5 seismic profiles. The model is subject to uncertainties that lie in the natural fluctuation of seismic velocities of the involved geological formations, in the complexity of the underground and in limitations of the data (signal-noise-ratio) and of the measurement set-up (spread lengths). Both natural fluctuations and measurements uncertainties are of the order of 5-10% in terms of seismic velocity or layer depths, respectively. Based on the lithological constraints thermal properties can be attributed to the layers and hydro-thermal model computations be can be performed for the final assessment considering the statistical uncertainties of the model. These computations, which represent the final steps of the assessment procedure, are explained in the companion paper of Ebigbo et al. (this volume).

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