The geothermal favourability of geopressured-geothermal systems: a case study in Italy

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ABSTRACT

We present an innovative methodology to assess geopressured-geothermal resources occurring in terrigenous units in sedimentary basin plays. This kind of resource is considered unconventional due to economic and technical barriers, but is particularly of interest for the possibility either to improve the economic feasibility of an industrial geothermal project or to deploy the uneconomic/depleted abandoned hydrocarbon wells. This paper is intended to be a practical analytical framework for the systematic integration of the relevant data required to assess these resources. For this purpose, innovative parameters were also implemented in the methodology. The final result is the favourability map for identifying prospective areas to be further investigated for the appraisal of the geopressured-geothermal potential. We applied our methodology to the foredeep-foreland domains of the Apennines thrust belt (Abruzzo region, central Italy). We analysed hundreds of deep hydrocarbon wells in order to create 3D geological and thermo-fluid dynamic models at a regional scale as well as to obtain information on the pressure regimes and on the chemistry of the system. The final favourability map for the Abruzzo case study is a first attempt at ranking these kinds of unconventional geothermal resources in a region that has been historically explored and exploited mostly for hydrocarbons.

1. INTRODUCTION

Geopressured-geothermal systems (or “geopressured”) are an unconventional resource for power trigeneration. They exploit three forms of energy (Wallace et al., 1979): (i) chemical energy from the combustion of hydrocarbons, (ii) thermal energy from hydrothermal fluids, and (iii) kinetic energy from well-head overpressure due to abnormal geopressured regimes. This resource is of particular interest due to the possibility of improving the economic feasibility of an industrial geothermal project or of uneconomic/depleted hydrocarbon wells.

Very few reference studies are published in the peer-review literature regarding the assessment at regional scale of geopressured-geothermal resources (e.g. Garg et al., 1986), which industrial interest is recently increasing worldwide. Several works are available from related congresses, held in the USA, and technical reports (e.g. John et al., 1998).

The research was carried out in the framework of the Geothermal Atlas of Southern Italy Project (http://atlante.igg.cnr.it). The project is aimed at developing methodologies for assessing various types of conventional and unconventional geothermal systems by mean of systematic data integration. This paper present a new methodology to assess the favourability of geopressured-geothermal systems occurring in terrigenous units in sedimentary basin plays.

Our methodology is based on the integration of layers of evidence by Index Overlay exploiting the concept of the geothermal favourability (e.g. Tufekci et al., 2010; Trumpy et al., 2015). We provide a novel tool for assessing geopressured resources that considers specific prospective factors.

A first-order assessment of the Bradanic foredeep, the adjacent Adriatic foreland and the Sicilian FTB was carried out in the frame of the Geothermal Atlas of Southern Italy Project (Project volume and Atlas in prep). We selected a wide prospective area along the foredeep-foreland domains of the Apennines thrust belt in the Abruzzo region (central Italy) to test our methodology. This is one of the first attempts to assess geopressured systems at the regional scale in Italy. Favourability maps were computed in order to assess the geopressured resources that would be suitable for power production.

The Abruzzo case study is also important due to the possibility of developing geothermal projects in a region belonging to the Adriatic petroleum province (Mattavelli et al., 1991; Cazzini et al., 2015) and in a gas (methane)-prone area, characterized by low geothermal gradients.

The detailed results of this research were recently published in Santilano et al., (2019).

2. METHDOLOGY

We exploited GIS spatial analysis for mapping the favourable areas. The information available makes it impossible to carry out a statistical analysis. We therefore applied a knowledge-driven method using the Index Overlay (IO) technique to combine geological, geophysical and geochemical information. The resulting map is obtained from equation [1], where F is the favourability for each pixel, W_i is the weight for the ith map, and S_{ij} is the score for the jth class of the ith map (Bonham-Carter, 1994):

$$F = \frac{\sum_{i=1}^{n} S_{ij} W_i}{\sum_{i=1}^{n} W_i} \qquad [1]$$

The workflow set up for the computation of the favourability map is organized into three stages:

- Play analysis (area selection)

- Layers of Evidence building

- Favourability computation (IO)

It starts with a preliminary geological analysis of the play. Indeed, the methodology focuses on the sedimentary terrigenous basin plays and the study area should be selected accordingly.

The second stage of computation requires the collection and processing of geological, well logs, geochemical and geophysical datasets. The following thematic inputs are properly set up: i-ii) depth of the top and base of the geopressured-geothermal reservoir; iii) depth of the top and base of basin deposits; iv) isobaths of the target temperature; v-vi) temperature at Earth's surface and at the top of the basement underlying the reservoir; vii) digital elevation model; viii) formation pressure; ix) fluid and gas geochemistry. The thematic inputs are combined by means of GIS spatial analysis tools to obtain the layers of evidence. The layers of evidence are the spatial representation of the main prospective parameters for mapping geopressured resources. The methodology includes the following layers: i) the effective geopressured reservoir, ii) the thermal regime, iii) the pressure regime, iv) the deposit thickness and v) the geochemistry.

The five layers of evidence are combined to produce the final favourability map for geopressured systems as a result of the last stage of the workflow. The layers are in turn scored and weighted following the Index Overlay method. The classification for each layer of evidence consists of identifying five ranges of score values (classes). The classes are scored from 1 to 5, "very low" (less favourable area) to "very high" (most promising area) respectively. In order to combine the layers of evidence, each was weighted with values whose sum is equal to 1 (Table 1). The weights, classes and scores were set based on generic features of terrigenous sedimentary basins.

Table 1: Scores (S) of classes and weights (W) for layers of evidence, used in the favourability analysis (from Santilano et al., 2019).

Layer of evidence	Weight (W)	Unit	Score (S) favourability				
			5 (very high)	4 (high)	3 (medium)	2 (low)	1 (very low)
Geopressured effective reservoir	0,4	m b.g.l. (Depth of the top)	0-1500	1500-2500	2500-3500	3500-4500	>4500
Geochemistry	0,1	ND	Clear indications of CH_4-saturated waters				No indications of CH_4-saturated waters
Pressure regime	0,3	Bar/100m (Pressure gradient)	>18,82	15,82-18,82	12,52-15,82	10,52-12,52	0-10,52
Thermal regime	0,1	°C/1000m (Geothermal gradient)	>50	40-50	30-40	15-30	0-15
Deposits thickness	0,1	m	>8000	6000-8000	4000-6000	2000-4000	0-2000

2.1 Effective geopressured-geothermal reservoir

The effective reservoir concept was initially proposed in Trumpy et al. 2015 for hydrothermal conventional systems in carbonates. Here, we have adapted the idea to develop a new concept for geopressured systems in sedimentary basin plays: the geopressured-geothermal effective reservoir. This layer of evidence is intended to assess only that part of a geopressured reservoir with a temperature suitable for geothermal exploitation. The layer is computed by means of a layer intersection between the depth of the 90°C isotherm and the base of the reservoir. Where the isotherm is deeper than the base of the reservoir, i.e. no effective reservoir occurs, the corresponding areas are neglected from the computation and considered as not favourable. Conversely, if the 90°C isotherm rests above the base, an effective reservoir is identified and the depth of the top is recorded in this layer of evidence. The result is a grid layer of a ranked depth of the top of the effective geopressured-geothermal reservoir.

The ranking classes (Score, S) are related to the depth to be drilled in order to reach the top of the effective reservoir: the shallower the top, the higher the favourability (Table1). The concept of the Effective geopressured-geothermal reservoir is properly described in Santilano et al., 2019.

2.2 Thermal regime

In our study, the thermal regime is parametrized by the thermal gradient. Thus, higher thermal gradients imply shallower high temperatures. The method to compute the thermal gradient is dependent upon the kind of available datasets. The thermal gradient is ranked following the range presented in Table 1, whereas the weight assigned for this layer of evidence is 0,1 by 1.

2.3 Pressure regime

We propose to produce a map of the pressure gradient in the targeted interval through geostatistical analyses of pressure data (e.g. drill steam tests) along wells. The limits of the classes (see Table 1) are in part based on the hydrostatic, soft and hard geopressured regimes as proposed by Loucks et al. (1981), with additional classes such as a “near-lithostatic” class (most favourable one).

2.4 Deposit thickness

The deposit thickness takes into account the role of the compaction disequilibrium for the genesis of overpressure regimes.

This layer of evidence, is obtained by simply classifying the thickness of the deposits of the studied basin. The classes (Table 1) were set based on knowledge-driven considerations related to the thicknesses of basin deposits worldwide.

2.5 Geochemistry

The decision to focus on terrigenous sedimentary basin plays is driven by the possible assumption that their formation waters are saturated in methane. This layer of evidence is aimed at ranking the study area according to the evidences of the occurrence of CH_4 in reservoir. The score is simply classified according to the occurrence or not of clear indications of CH_4-saturated and oversaturated water (see Table 1). The weight of the layer of evidence is 0.1.

3. THE GEOLOGICAL SETTING OF ABRUZZO

The study area is located in the central-eastern sector of the Italian Apennines (Figure 1), which experienced several deformation events in response to the late Neogene tectonic convergence between the European and African plates (Bally et al., 1986; Scrocca, 2006; Vezzani et al., 2010).

The study area includes the Neogene-Quaternary Abruzzo foredeep and the adjacent Adriatic foreland. Active deformation characterizes the eastern foredeep sector, which since early Pleistocene times has been undergoing eastward overthrusting above the Adriatic foreland (Lavecchia et al., 2007).

The lower Pliocene succession (Cellino Fm and equivalent units) is particularly important for our study, since it is the possible overpressured target. Its succession is up to 2 km thick and consists of several alternations of poorly-cemented arenaceous bodies and thick pelitic units.

The foredeep-foreland system of the Abruzzo region belongs to the Adriatic petroleum province, where many exploration plays and productive oil and gas fields have been in operation. Different kinds of plays occur both in siliciclastic basinal and carbonate platform systems. Gas-fields are present in the Plio-Pleistocene turbiditic sequences in channelized or deep-sea fan deposits (Mattavelli et al., 1991; Casnedi, 1983).

With regards to the geothermal resources, the geological conditions of the study area do not favour the development of high temperature systems. Mezo-Cenozoic carbonates represent the regional scale reservoir for hydrothermal resources. The heat flow map of Italy by Della Vedova et al. (2000) shows values mainly in the range of 40-50 mW/m^2 in the study area. This pattern is expected in areas experiencing a very high sedimentation rate. The geothermal gradient values are in the range of 30-40 °C/km regarding the on-shore areas, as shown in the Italian geothermal ranking by Cataldi et al. (1995).

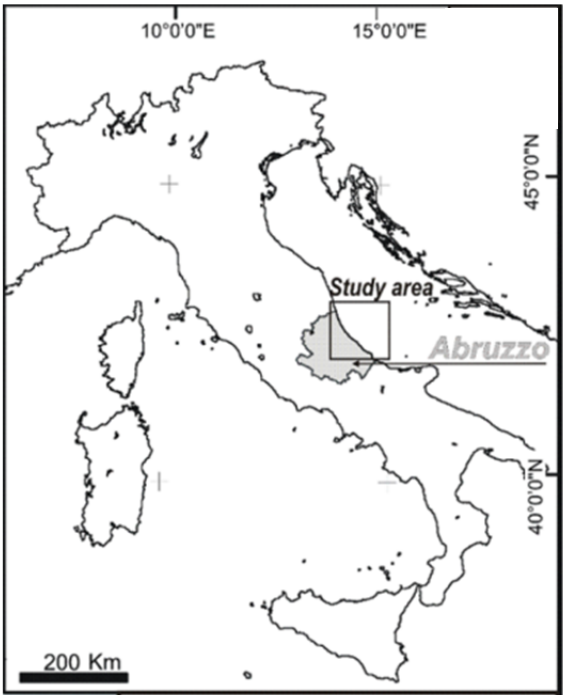

Figure 1: Location of the study area

4. ABRUZZO CASE STUDY: LAYER OF EVIDENCE AND FAVOURABILITY MAP

The favourability computation of the geopressured-geothermal system of Abruzzo was based on a critical review of a large dataset. The main focus was the analysis of about 200 deep hydrocarbon wells, extracted from the Italian National Geothermal Database (BDNG) (Trumpy and Manzella, 2017; VIDEPI Project website http://unmig.sviluppoeconomico.gov.it/videpi/pozzi/pozzi.asp).

Beside the well logs and data from the scientific literature, we carried out a 3D geological modelling and 3D coupled thermo-fluid dynamic numerical simulations in order to provide a reliable temperature distribution at depth. Indeed, we used as input for building the layers of evidence both measured data and modelled data.

The study area corresponds to the foredeep-foreland domains of the Apennines thrust belt in Abruzzo. The targets are the geopressured resources hosted in the Plio-Pleistocene siliciclastic succession.

4.1 Layers of evidence

The five layers of evidence were combined by Index Overlay to produce the final favourability map. The spatial resolution was 1 x 1 km, with the grid nodes of each layer overlapping.

The concept of the effective geopressured-geothermal reservoir is described in Section 2. In this paper a threshold value of 90°C was set considering the geothermal power production purposes. The effective geopressured-geothermal reservoir layer was built by applying a layer intersection between the depth of the 90°C isotherm and the bottom surface of the Pliocene deposits. The result is a grid layer of a ranked depth of the top of the effective geopressured-geothermal reservoir. Where the isotherm is deeper than the base of the Pliocene deposits, i.e. no effective reservoir occurs, the corresponding areas are neglected from the computation

Regarding the pressure, we analysed a dataset of hundreds of drill stem tests (DSTs) and some repeat formation tests (RFTs). The analysis highlights mainly hydrostatic pressure conditions for the carbonate basement as well as for the Pleistocene sediments, whereas abnormal pressure regimes occur in the Pliocene deposits, in some cases approaching lithostatic conditions (Figure 2).

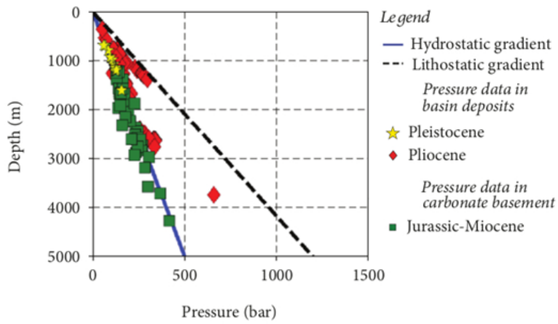

Figure 2: Depth vs Pressure plot for the well dataset (from Santilano et al., 2019).

We obtained information of the pressure regions through geostatistical analyses (Universal Kriging algorithm) on the pressure gradients computed in the wells reaching the Pliocene succession. The rank is related to the amount of overpressure that occurs in the Pliocene sedimentary succession.

Regarding the thermal regime, we parameterized and ranked it by the thermal gradient.

The deposit thickness layer of evidence was obtained by simply classifying the thickness of the basin deposits (i.e., the Pliocene bottom depth from the ground level).

The geochemical layer of evidence, for the Abruzzo case study, is essentially based on the ranking of the methane-prospective area, corresponding to the foredeep domain, proposed by Mattavelli and Novelli (1988). We assigned the highest class (5th) to this area, assuming the occurrence of CH_4-saturated and oversaturated waters in reservoir, after a careful analysis of the well chemical data.

4.2 The favourability map of Abruzzo for the geopressured-geothermal resources

The quantitative integration of data using the Index Overlay method resulted in the favourability map of a geopressured-geothermal system for the foredeep-foreland basin play of Abruzzo, shown in Figure 3.

The study area was mostly ranked from not- to low/medium favourable, with one exception corresponding to a wide continuous prospective sector in the centre. The most favourable sector, with a rank up to the 4th class, extends for less than 1000 km^2, and runs parallel to the shoreline along a NW-SE direction, both in the off and onshore. The 5th class (very favourable) was not retrieved. The cells of the grid that have been ranked (from 1st to 5th class) are those where the effective reservoir was detected, otherwise the cells were not considered favourable.

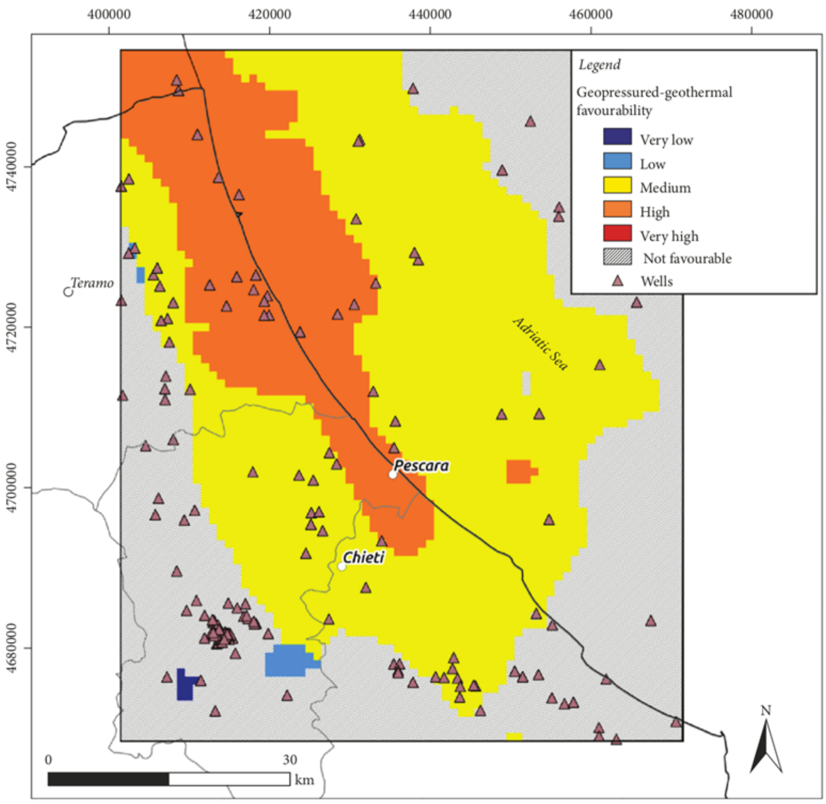

Figure 3: Favourability map of the geopressured-geothermal system for Abruzzo (from Santilano et al., 2019).

5. CONCLUSIONS

This work is intended to be a practical analytical framework for the systematic integration of the relevant data required to assess the geopressured-geothermal resources. The approach described can be considered valid and applicable at a global scale as the whole procedure is based on generic features.

The final favourability map for the Abruzzo case study is a first attempt at ranking these kinds of unconventional geothermal resources in a region that has been historically explored and exploited only for hydrocarbons.

The detailed results of this research were recently published in Santilano et al., (2019), to whom the reader is referred.

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