Research Article

A Methodology for Assessing the Favourability of Geopressured-Geothermal Systems in Sedimentary Basin Plays: A Case Study in Abruzzo (Italy)

Alessandro Santilano, Eugenio Trumpy, Gianluca Gola, Assunta Donato, Davide Scrocca, Federica Ferrarini, Francesco Brozzetti, Rita de Nardis, Giusy Lavecchia, and Adele Manzella

1 CNR, Institute of Geosciences and Earth Resources (IGG), Via Moruzzi 1, 56124 Pisa, Italy
2 CNR, Institute of Environmental Geology and Geoengineering (IGAG), P.le Aldo Moro 5, 00185 Roma, Italy
3 CRUST, DiSPUTer, Università "G. d’Annunzio", Via dei Vestini 31, 66013 Chieti Scalo, Italy
4 DPC, Dipartimento della Protezione Civile, Via Vitorchiano, 4, 00189 Rome, Italy

Correspondence should be addressed to Alessandro Santilano; alessandro.santilano@igg.cnr.it

Received 24 April 2018; Revised 29 September 2018; Accepted 8 October 2018; Published 4 March 2019

Guest Editor: Matteo Lupi

Copyright © 2019 Alessandro Santilano et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

We exploit the concept of the geothermal favourability, widely used for hydrothermal and EGS systems, to present an innovative methodology for assessing geopressured-geothermal resources occurring in terrigenous units in sedimentary basin plays. Geopressured-geothermal systems (hereafter also referred to as "geopressed") are an unconventional resource for power trigeneration. They exploit three forms of energy: (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 geopressed regimes. This resource is of particular interest for trigeneration to the most promising areas throughout a systematic data integration. The research was developed within the framework of the Geothermal Atlas of Southern Italy Project [1].

1. Introduction

Geothermal exploration is a complex, time-consuming, and expensive activity. Integrating geological, geochemical, and geophysical data can speed up exploration stages. Very few reference studies are available regarding the assessment at regional scale of geopressed-geothermal resources, which industrial interest is recently increasing worldwide.

We present a new methodology to assess the favourability of geopressed-geothermal systems occurring in terrigenous units in sedimentary basin plays. The aim is to drive effective exploration to the most promising areas throughout a systematic data integration. The research was developed within the framework of the Geothermal Atlas of Southern Italy Project [1].

Geopressed-geothermal systems (hereafter also referred to as "geopressed") are an unconventional resource for power trigeneration. They exploit three forms of energy [2]: (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 geopressed 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.

The USA focused on geopressed systems from the 1970s to the 1990s above all for industry and produced extensive knowledge of the geopressed system of the Gulf of Mexico (e.g., [3, 4]). Such industrial interest has recently been renewed with projects aimed at demonstrating their commercial feasibility, as in Louisiana [5]. With regard to Europe, Hungary has been developing geopressed projects [6] while cogeneration plants for the direct use of geothermal heat and dissolved methane are in operation. Previous works have described the prospective factors for the assessment of geopressed systems (e.g., [7]), mainly aimed at the Gulf of Mexico. Italy has also been involved in some works, for example Alimonti and Gnoni [8] presented a study on the heat recovery from depleted wells in a well-known geopressed field in the Po Plain (Northern Italy).

In the recent scientific literature, the geothermal favourability concept has been widely proposed in order to study geothermal systems, focusing on hydrothermal and enhanced geothermal systems (EGS). Various approaches have been exploited in order to quantitatively integrate different sources of data, usually organized in information layers in a GIS environment [9–18]. The favourability consists in a semiquantitative data integration for identifying prospective areas to be further investigated for the appraisal of the geothermal potential.

Our methodology is based on the integration of layers of evidence by Index Overlay. Data analysis by the Index Overlay method has been widely proposed in literature (e.g., [9, 16]) for the assessment of other types of geothermal systems. We provide a novel tool for assessing geopressed resources that considers specific prospective factors. We applied our methodology to the foredeep-foreland domains of the Apennines thrust belt in the Abruzzo region (central Italy). This is one of the first attempts to assess geopressed systems at the regional scale in Italy. Favourability maps were computed in order to assess the geopressed 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 [19–21] and in a gas (methane)-prone area, characterized by low geothermal gradients.

We analysed hundreds of deep hydrocarbon wells, and we carried out geological modelling and coupled thermo-fluid dynamic numerical simulations. Information on the pressure regimes and on the chemistry of the system was also obtained. The final favourability map for the Abruzzo region was computed which provides a ranking of the most prospective areas.

Once having described the general approach, the article focuses on the application to the test site in Abruzzo in order to better explicate the various steps of the methodology. Finally, the obtained maps are analysed and discussed.

2. Geopressed-Geothermal Systems: State of the Art and Prospective Factors

A geopressed-geothermal system is constituted by a hydrothermal reservoir with a higher pore pressure than the hydrostatic reference and contains dissolved gaseous hydrocarbons. The first patent for exploiting this resource was filed in 1966 [22]. The trigeneration of energy derives from the abnormal formation pressure, the occurrence of dissolved methane, and the heat transferred by the fluid. Due to various technical problems (e.g., the sustainability of the exploitation), geopressed systems are still considered unconventional, i.e., requiring technological development. Figure 1 shows the classic flow diagram for trigeneration as proposed by Hughes [23].

The literature contains a few studies regarding the exploration of this resource worldwide (e.g., [24]) and several works from related congresses, held in the USA, and technical reports (e.g., [7, 25–28]). The most studied geopressed systems are located onshore of the Gulf of Mexico, particularly in Texas and Louisiana. In the USA, following the oil crisis in the 1970s, the DOE (Department of Energy) funded two important research programs [27]. Numerous abandoned hydrocarbon wells were tested, and new wells were drilled in prospective areas. The most important productive well was the “Pleasant Bayou 2” located in Texas, a test site in which the technical feasibility of power production was demonstrated [29].

The concomitant occurrence of hydrothermal resources and hydrocarbons, in abnormal pressure regimes, makes the genesis of geopressed systems particular to specific geological environments. The play concept [30–32] is of primary importance in the favourability assessment.
The continuous burial of an enormous amount of organic matter is key to the formation of hydrocarbons. In geopressed systems, the methane exploited is mainly in solution in the hydrothermal fluid, and the gas/water ratio and the methane solubility are fundamental. The P/T and salinity conditions of the fluid strongly influence the solubility of methane; i.e., the amount of exploitable gas for a certain flow rate of the fluid. The methane solubility is directly proportional to the pressure and temperature and inversely proportional to the salinity of the fluid [36].

Geothermal exploration, in particular for power production, searches for the hottest hydrothermal resource and highest geothermal gradients. In the case of geopressed systems, the geological conditions that usually facilitate their development are unfavourable to high-geothermal gradients, such as those in volcanic or intrusive geothermal plays. For example, fast sedimentation environments are related to a decrease in the thermal gradient. The thermal regime is, however, a fundamental factor in deriving the economic value of the geopressed resource, since thermal energy plays a major role in trigeneration.

Permeability is another key factor. In geopressed systems, the lithology and the primary permeability play important roles, characterizing (i) the clayey seals, with a low permeability that favours the development of overpressed regimes, and (ii) the productive intervals, usually in sandy formations. The structural setting is a key factor in the evolution of such systems, for example, the possibility of characterizing permeable and nonpermeable faults as well as growth faults.

### 3. Methodology

GIS spatial analysis for mapping the geothermal potential or favourable areas has been extensively used following different approaches in order to speed up the exploration stages [9–18, 37, 38].

In cases of abundant data availability, the spatial layers in a GIS environment can be treated on the basis of statistical estimations. Otherwise, the processing of layers can rely on the knowledge of experts. The first case is known as the data-driven method, while the second is referred to as the knowledge-driven method [39].

In many cases, the information available makes it impossible to carry out a probabilistic analysis. We therefore applied a knowledge-driven method using the Index Overlay (IO) technique to combine geological, geophysical, and geochemical information. The IO is a simple and flexible way to linearly integrate different spatial information ensuring a common scale of value. The resulting map is obtained from (1), where \( F \) is the favourability for each pixel, \( W_i \) is the weight for the \( i \)th map, and \( S_{ij} \) is the score for the \( j \)th class of the \( i \)th map [39]:

\[
F = \frac{\sum_{i=1}^{n} S_{ij} W_i}{\sum_{i=1}^{n} W_i}.
\]
The workflow setup for the computation of the favourability map is organized into three stages, as shown in Figure 2. 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 geopressed-geothermal reservoir, (iii) depth of the top and base of basin deposits, (iv) isobaths of the target temperature, (v–vi) temperature at the Earth’s surface and at the top of the basement underlying the reservoir, (vii) digital elevation model. (viii) formation pressure, and (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 described in Section 2. The methodology includes the following layers: (i) the effective geopressed 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 geopressed systems as a result of the last stage of the workflow. The layers are in turn scored and weighted following the Index Overlay method ((1)). 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 2). The weights, classes, and scores were set based on generic features of terrigenous sedimentary basins.

In this work, all the computations were performed in the Open Source Quantum GIS environment exploiting SAGA and GRASS GIS tools [40]. The resolution of the combined maps is the same, with the grid nodes of each layer overlapping.

3.1. Effective Geopressed-Geothermal Reservoir. The effective reservoir concept was initially proposed in Trumpy et al. [9] for hydrothermal conventional systems in carbonates. Here, we adapted the idea of “effective” reservoir in order to develop a new concept for geopressed systems in sedimentary basin plays: the geopressed-geothermal effective reservoir. This layer of evidence is intended to assess only that part of a geopressed reservoir with a temperature suitable for geothermal exploitation. In this paper, a threshold value of 90°C was set as target, considering the technology of a conventional power production plant. The threshold temperature is chosen accordingly to the aim of exploration (e.g., power production, and direct use of heat). Basically, the idea is to disregard those sectors of reservoir that are colder than the threshold temperature. The layer is computed by means of a layer intersection between the depth of the

![Flow diagram](image_url)

**Figure 2:** Flow diagram for computing the geothermal-geopressed favourability in basin plays.
Table 2: Scores (S) of classes and weights (W) for layers of evidence, used in the favourability analysis.

| Layer of evidence               | Weight (W) | Unit                             | 5 (very high) | 4 (high) | 3 (medium) | 2 (low) | 1 (very low) |
|---------------------------------|------------|----------------------------------|----------------|----------|------------|---------|--------------|
| Geopressed effective reservoir  | 0.4        | m b.g.l. (depth of the top)      | 0–1500         |          |            |         |              |
| Geochemistry                    | 0.1        | Clear indications of CH₄-saturated waters |                | Clear indications of CH₄-saturated waters |    |              |
| Pressure regime                 | 0.3        | Bar/100 m (pressure gradient)    | >18.82         | 18.82–18.82 | 12.52–15.82 | 10.52–12.52 | 0–10.52     |
| Thermal regime                  | 0.1        | °C/1000 m (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       |
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. The choice of limit values (Table 2) was driven by economic considerations regarding geothermal drilling, based on worldwide studies [41, 42]. For example, the lowest class is for a drilling depth of higher than 4500 meters. The effective geopressed reservoir is the layer with the highest weight in the Index Overlay calculus for the reservoir (Figure 3(a)) show a near horizontal WSW-ENE ridge (Gran Sasso and Majella) and later (Late Pliocene–Early Pleistocene) of the Apennines and peri-Adriatic foothills [43–52].

3.4. Deposit Thickness. The deposit thickness takes into account the role of the compaction disequilibrium for the genesis of overpressure regimes. The importance of a larger thickness of the (effective) reservoir can influence the quality of the resource in terms not only of pressure but also of temperature. In fact, assuming that the thermal gradient is not driven by pure convection, higher temperatures can be reached at larger depths.

This layer of evidence is obtained by simply classifying the thickness of the deposits of the studied basin. The classes (Table 2) were set based on knowledge-driven considerations related to the thicknesses of basin deposits worldwide. The weight is 0.1 by 1.

3.5. 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 occurrences of CH₄ in reservoir. Due to the vertical and horizontal variability of the CH₄ content, the spatial mapping of this layer is extremely difficult.

The score is simply classified according to the occurrence or not of clear indications of CH₄-saturated and oversaturated water, 5th and 1st classes, respectively (see Table 2). The weight of the layer of evidence is 0.1.

4. Geological–Structural Setting of Eastern Abruzzo (Italy)

The study area is located in the central-eastern sector of the Italian Apennines (inset in Figure 3(a)), which experienced several deformation events in response to the late Neogene tectonic convergence between the European and African plates. The outcropping tectonic units (Figure 3(a)) derived from the deformation of both shallow-water limestones (carbonate platform domains) and deeper-water carbonate (slope and pelagic basin domains) successions deposited on the southern Neotethyan passive margin ([43] and references therein). Since the very late Messinian, these successions were affected by eastward-directed fold and thrusting which led, initially, to the growth of the main Apenninic ridges (Gran Sasso and Majella) and later (Late Pliocene–Early Pleistocene) of the Apennines and peri-Adriatic foothills [43–52].

The contractional deformation [53–55] piled the Apenninic thrust units onto the Adriatic foreland (Triassic–Early Miocene) consistently with an overall in-sequence regional propagating model [44, 56, 57] (Figure 3(b)). From the Late Pliocene–Early Pleistocene, the western Abruzzo chain area was affected by an extensional tectonic regime which was responsible for the formation of an articulated system of normal faults [58, 59] and associated Quaternary continental basins (Figure 3(a)).

The study area (Figure 3) also includes the Neogene-Quaternary Abruzzo foredeep and the adjacent Adriatic foreland [60–62]. From a structural point of view, the foredeep can be subdivided into two sectors. The western sector is characterized by outcrops of syn-orogenetic turbiditic successions of the upper Laga (Late Messinian) and Cellino (Zanclean) Formations. The eastern sector is dominated, at the surface, by late-orogenic shelf clays, evolving upward to coastal sands of the Late Pliocene-Pleistocene age (Mutignano Fm [63, 64]).

Active deformation characterizes the eastern foredeep sector, which since early Pleistocene times has been undergoing eastward overthrusting above the Adriatic foreland [65, 66]. Instrumental seismicity and borehole breakouts (Figure 3(a)) show a near horizontal WSW-ENE
Figure 3: (a) Simplified geological-structural map of the study area with the main lithological units and tectonic structures. All information was derived from geological maps on a 1:100,000 [92] and 1:50,000 [93] scale and from [68]. Tectonic structures were mainly derived from CNR [76]. Key: (1) continental deposits (Quaternary), (2) marly and clayey deposits of the Mutignano Fm and equivalent units (Late Pliocene–Early Pleistocene), (3) arenaceous and pelitic deposits of the Laga (A) and Cellino Fms and equivalent deposits (Late Messinian–Early Pliocene), (4) slope-to-basin and basinal carbonate deposits (Late Triassic–Miocene), (5) platform carbonate deposits (Late Triassic–Miocene), (6) undifferentiated deposits pertaining to the allochthonous Molise Nappe (Upper Cretaceous–Upper Miocene), (7) main thrusts ((a) outcropping, (b) inferred or buried), (8) normal faults ((a) outcropping, (b) inferred or buried), (9) boundary of the allochthonous Molise Nappe, CoS = coastal anticline, (10) direction of the minimum horizontal stress (SHmin) referring to a selection of A and B quality borehole breakout data as reported in [94], and (11) P-axes from a compilation of focal mechanisms taken from the RCMT and TDM catalogue [95] plus other focal solutions deduced from specific papers (e.g., [96]) for the Italian earthquakes with Mw > 4.0 occurring between 1968 and May 2016. BCS = Bellante–Cellino structure. The black dotted box includes the sector investigated for favourability assessment. (b) Interpretative geological section (trace in (a)) showing the main thrusts deforming the carbonate and foredeep deposits of the outer Abruzzo region. The outcropping successions and their thickness were constrained with information from geological cartography [92, 93]. The thicknesses of the Mezo-Cenozoic carbonate deposits in the Adriatic foreland were extracted from [78], while most of the data concerning the depth of the base of Pliocene deposits come from the present study (see Subsection 5.1). Key: (1) Late Triassic dolostone and evaporites, (2) Jurassic–Cretaceous to Middle Miocene undifferentiated carbonates, (3) Late Miocene (upper Messinian) foredeep deposits (Laga Fm), (4) Lower Pliocene foredeep deposits, (5) Upper Pliocene foredeep and Quaternary marine deposits, (6) thrusts ((a) outcropping, (b) buried), (7) hypothesized faults ((a) reverse, (b) normal). BP = base of the Pliocene foredeep deposits (see Subsection 5.1).
compressional deformation, on average characterized by a low seismic budget (~0.3 mm/year) [67].

The lower Pliocene succession (Cellino Fm and equivalent units) is particularly important for our study, since it is the possible overpressured target. Its stratigraphic range spans from the Sphaeroidinellopsis sp. to the G. punctulata biozones [64, 68]. Its succession is up to 2 km thick and consists of several alternations of poorly cemented arenaceous bodies and thick pelitic units. On the whole, this succession is sandwiched in between the post- evaporitic pelites of the topmost Laga Fm and the thick package of clays of the lower Mutignano Fm.

Thrust and folds, affecting the Laga and Cellino deposits, are well documented in the subsurface of the Abruzzo peri-Stratigraphic context. Two main buried structural trends are defined in the literature, referred to as the “Bellante-Cellino structure” (BCS) and the “Coastal anticline” (CoS), from west to east (Figure 3(a); [46, 60–62, 69]). Between the BCS and the CoS, the upper Pliocene sedimentary wedge reaches a maximum thickness of 2000 m and is slightly folded. The Pleistocene succession is only slightly deformed in an E-dipping, low-angle monocline. East of the leading edge of the Apennine outer thrust, the Adriatic foreland is characterized by a west-dipping low-angle regional monocline, affected by minor normal faulting, due to flexural retreat, on which the Plio-Pleistocene siliciclastic succession lies conformably above the Mezo-Cenozoic carbonates [70].

The foredeep-foreland system of the Abruzzo region belongs to the Adriatic petroleum province [19–21], 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 [19, 69].

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. [71] shows values mainly in the range of 40–50 mW/m² in the study area, with a positive anomaly in the south-eastern offshore part (up to 80 mW/m²). This pattern is expected in areas experiencing a very high sedimentation rate. The thermal gradient values are in the range of 30–40°C/km regarding the onshore areas, as shown in the Italian geothermal ranking by Cataldi et al. [72].

5. Source of Data from the Abruzzo Case Study

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) [73]. For each well, we gathered, from the BDNG, detailed information sheets related to headings (e.g., well name, coordinates), fluid geochemistry, temperature, formation tests, lithology, stratigraphy and ages, drilling (e.g., deviation), and occurrence of formation fluids (water, hydrocarbons).

We have also checked the original master logs, provided by the Italian Ministry of Economic Development [74], in order to support the additional analysis of selected wells, e.g., homogenization of stratigraphic information, and assessment of the validity of the pressure measurements from formation tests (as described in the next subsections).

Beside the well logs and data from the scientific literature, we carried out a geological modelling and 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.

5.1. Geological Data and Modelling. We reconstructed the base of the Pliocene foredeep deposits (hereafter BP) in the study area by exploiting and integrating datasets from the literature (Figure 4) and the abovementioned BDNG. This involved identifying the lowermost position of the base of Pliocene foredeep deposits, disregarding the local interposition of tectonic slices which could have piled up and thickened the foredeep succession. These particular settings were especially investigated in the northern Abruzzo (offshore) and in the southern Abruzzo (onshore) sectors. In the former, the compressive deformation also affected the foredeep deposits (see cross section in Figure 3(b)) from the uppermost Early Pliocene to the Early Pleistocene (moving from west to east). In the latter, minor slices of the Molise Allochthonous units have been sandwiched between lower-middle Pliocene deposits [75]. In both cases, the lowermost contacts (both stratigraphic or tectonic) were considered.

We first extracted information on the depth of BP from the stratigraphy reported in the wells drilled for petroleum exploration [74] and organized in the BDNG (Figure 4(a)). More than 180 wells were found to clearly intercept this level. Most (about 170) reported the stratigraphic contact of the lower Pliocene successions (conformable or unconformable) above terms belonging to the diagenetic regime of the Pliocene succession [76]. In both cases, we achieved our final target by converting all data into isobaths using published average velocities for the Pliocene and Pleistocene units (e.g., [44]). A recent interpretation of the M13–14 CROP seismic line [78], which crosses the Adriatic offshore, was also considered (section trace in Figure 4(a)).

We achieved our final target by converting all data into feature datasets (point and lines) in order to process them into a common georeferenced framework in a GIS environment. Finally, we integrated all the collected data and converted them into point features which were interpolated.
through an inverse distance weighting (IDW) method, using local barriers represented by the main tectonic structures reported for the study area and/or hypothesized from lateral discontinuities observed in the in-well stratigraphy.

A 3D surface with 1000 m pixel resolution was obtained and is shown in the new map of the base of Pliocene in the Abruzzo outer sector (Figure 4(d)).

5.2. Pressure Data. The pressure conditions in the periadriatic FTB-foredeep-foreland system are well known, above all in the northern sector. Carlin and Dainelli [79] reviewed pressure well data in order to define the various pressure systems in the Adriatic foredeep. Abnormal pressure regimes occur mainly in the Pliocene basin deposits, whereas the underlying carbonates are mainly in hydrostatic conditions.

The authors defined three pressure regions in the Plio-Pleistocene succession, from the innermost: (i) inner thrust, (ii) deformation front, and (iii) undeformed foredeep. The compaction disequilibrium is the major cause for overpressures, coupled with a minor contribution of tectonics. The top of the geopressed zone corresponds to the base of the Pleistocene, which led us to target the Pliocene basin deposits as also highlighted by the temperature analysis. Our study area was only partially covered by Carlin and Dainelli [79] in their analysis. Thus, a careful analysis of the pressure well data was performed here in order to estimate the pressure gradients along available wells and to obtain first-order information on the pressure conditions.

The dataset is composed of hundreds of drill stem tests (DSTs) and some repeat formation tests (RFTs). Each test

Figure 4: Three main databases (a, b, c) used for the reconstruction of the new map of the base of Pliocene deposits (d) in the outer sector of the Abruzzo region. (a) In-well BP depth as reported in the wells drilled for petroleum exploration [73, 74]; the trace of the seismic line M13–14 CROP is reported in brown from [78]. (b) Isobaths of the BP with main tectonic structures. (c) Map of the isobaths of the BP redrawn from [77]. (d) New map of the BP deposits as reconstructed for the study area. The tectonic structures and the colour-scale legend of isobaths are the same as in (b). The dotted black box includes the sector investigated for the favourableness assessment.
is described with additional information such as the measured (MD) and true vertical (TVD) depths, lithology, stratigraphy, type of fluid, measured pressure, and above all the duration of all the phases of the tests. In fact, we considered the stabilized pressures measured after a greater shut-in time than the flowing periods. The tests were grouped according to the geological unit tested belonging to Mezo-Cenozoic carbonates or Plio-Pleistocene basin deposits.

In Figure 5, the complete dataset is summarized in a depth vs pressure plot. The pressure data are plotted and classified on the basis of the geological unit. The analysis highlights mainly hydrostatic pressure conditions for the carbonate basin as well as for the Pleistocene sediments, whereas abnormal pressure regimes occur in the Pliocene deposits, in some cases approaching lithostatic conditions (the epochs refer to the GSA scale v4.0 from [80]).

A pressure gradient was estimated for each well in the targeted Pliocene interval. We firstly selected those wells with more than one pressure value in the Pliocene succession in order to compute the pressure gradient by linear regression. In some sectors, where only one pressure value was available in the Pliocene succession along a well, we extrapolated the pressure at the top of Pliocene from the surface assuming a hydrostatic regime in the overlying Pleistocene. The pressure at the top of Pliocene from the surface were previously evaluated in order to correct the deposits. We also considered six pressure pro

![Figure 5: Depth vs pressure plot for the well dataset from the BDNG [73, 74] in the studied area.](image)

5.3. **Thermal Data and Modelling.** In order to evaluate the regional thermal structure of the study area, we solved the mathematical model for geothermal heat and mass transfer.

The bottom-hole temperatures (BHTs), measured in the deep hydrocarbon exploratory wells, were used as control points in order to compare the numerical results with the borehole data (Figure 7(b)). The thermal effects due to the drilling had been previously evaluated in order to correct the BHT data [81, 82]. Although the corrected BHTs had a mean error of the order of ±10%, they were suitable for highlighting the main regional thermal structure.

The sets of partial differential equations which describe the principles of conservation of mass, momentum, and energy are approximated through the finite element method in the COMSOL Multiphysics environment [83, 84]. The steady-state solution was evaluated within a numerical domain of 130 × 100 × 20 km³ accounting for the whole regional thermal structure of the Abruzzo-Molise outer sector. The tetrahedral mesh-grid counts >3.6·10⁶ nodes and the length of tetrahedron edges vary from a minimum of 100 m to a maximum of 1000 m, allowing the numerical mesh to fit the spatial variations of the boundary surfaces. The regional fluid circulation occurs within the permeable Mezo-Cenozoic carbonate units, and in the eastern Abruzzo geological framework, the Plio-Pleistocene foredeep deposits act as the cap-rock of the deep-seated low-temperature hydrothermal system, almost throughout the entire investigated area. The carbonate units outcropping in the Apennine chain represent the main recharge areas of the regional reservoir.

The geometrical model considers three main lithothermal units, from the top to the bottom: (i) the impervious sedimentary cover unit acting as a cap-rock, (ii) the tectonically thickened carbonate units hosting the main regional reservoir, and (iii) the basement unit. Each lithothermal unit is composed of different rocks with similar thermal and hydraulic properties. The rocks were treated as a homogeneous and downward anisotropic porous material. Mixing laws were applied to estimate the effective thermal and hydraulic properties of the rock-fluid system accounting for the in situ conditions [85]. In the cover and basement domains, a purely conductive heat transport takes place, while in the carbonate reservoir, the regional hydraulic gradient and the thermal convection affect the temperature distribution by mass and energy transport. The buried upper and basal boundaries of the reservoir are set impermeable to fluid flow, allowing only conductive heat transfer.

Accounting for the recharge zones, we applied a stress boundary condition where the reservoir units crop out (Figure 7(a)). As the reservoir is assumed to be fully saturated, the pressure on those boundaries is set as equal to...
Table 3: Pressure measurements in wells. The ID refers to the location in Figure 6. The type of pressure test is reported plus information on measured depth (MD) lithology, age, and the geological unit.

| ID | X WGS84 UTM33N | Y WGS84 UTM33N | Name       | Test | *MD (m) | Pressure (bar) | Lithology** | Age**          | Geological unit* |
|----|----------------|----------------|------------|------|---------|---------------|-------------|----------------|------------------|
| 1  | 467486         | 4683474        | Aguglia 1D | RFT  | 1069    | 112           | Sandy stratum in clay | Pleistocene (uncertain) | Basin deposits   |
| 1  | 467486         | 4683474        | Aguglia 1D | RFT  | 1072    | 111           | Sandy stratum in clay | Pleistocene (uncertain) | Basin deposits   |
| 1  | 467486         | 4683474        | Aguglia 1D | RFT  | 1074    | 116           | Sandy stratum in clay | Pleistocene (uncertain) | Basin deposits   |
| 1  | 467486         | 4683474        | Aguglia 1D | RFT  | 1134    | 124           | Interbedded silty-clay and marly-clay | Pleistocene (uncertain) | Basin deposits   |
| 1  | 467486         | 4683474        | Aguglia 1D | RFT  | 1148    | 124           | Interbedded silty-clay and marly-clay | Pleistocene (uncertain) | Basin deposits   |
| 1  | 467486         | 4683474        | Aguglia 1D | RFT  | 1203    | 124           | Conglomerate               | Pleistocene (uncertain) | Basin deposits   |
| 2  | 426176         | 4697027        | Caprara 1  | DST  | 1664    | 211           | Clay and silty clay         | Pliocene            | Basin deposits   |
| 3  | 424550         | 4691862        | Città S. Angelo 1 | DST | 525    | 63            | Clay with thin sandy strata | Pliocene            | Basin deposits   |
| 4  | 406998         | 4712354        | Fino 2     | DST  | 1305    | 135           | Marly clay with interbedded sand | Pliocene            | Basin deposits   |
| 4  | 406998         | 4712354        | Fino 2     | DST  | 1426    | 157           | Marly clay with interbedded sand | Pliocene            | Basin deposits   |
| 5  | 411053         | 4744028        | Fonte Armata 1 | DIR | RFT  | 2602         | Interbedded clay, silt, and sand | Pliocene            | Basin deposits   |
| 5  | 411053         | 4744028        | Fonte Armata 1 | DIR | RFT  | 2608         | Interbedded clay, silt, and sand | Pliocene            | Basin deposits   |
| 5  | 411053         | 4744028        | Fonte Armata 1 | DIR | RFT  | 2612         | Interbedded clay, silt, and sand | Pliocene            | Basin deposits   |
| 5  | 411053         | 4744028        | Fonte Armata 1 | DIR | RFT  | 2612         | Interbedded clay, silt, and sand | Pliocene            | Basin deposits   |
| 5  | 411053         | 4744028        | Fonte Armata 1 | DIR | RFT  | 2613         | Interbedded clay, silt, and sand | Pliocene            | Basin deposits   |
| 5  | 411053         | 4744028        | Fonte Armata 1 | DIR | RFT  | 2613         | Interbedded clay, silt, and sand | Pliocene            | Basin deposits   |
| 6  | 419361         | 4723269        | Fonte Dell’Olmo 1 | DST | 758    | 133           | Clay with interbedded sandy strata | Pliocene            | Basin deposits   |
| 6  | 419361         | 4723269        | Fonte Dell’Olmo 1 | DST | 758    | 133           | Clay with interbedded sandy strata | Pliocene            | Basin deposits   |
| 6  | 419361         | 4723269        | Fonte Dell’Olmo 1 | DST | 758    | 114           | Clay with interbedded sandy strata | Pliocene            | Basin deposits   |
| 6  | 419361         | 4723269        | Fonte Dell’Olmo 1 | DST | 849    | 149           | Clay with interbedded sandy strata | Pliocene            | Basin deposits   |
| 6  | 419361         | 4723269        | Fonte Dell’Olmo 1 | DST | 849    | 146           | Clay with interbedded sandy strata | Pliocene            | Basin deposits   |
| 6  | 419361         | 4723269        | Fonte Dell’Olmo 1 | DST | 1044   | 186           | Clay with interbedded sandy strata | Pliocene            | Basin deposits   |
| 7  | 435683         | 4708320        | Greta 1    | DST  | 2485    | 284           | Silty clay with interbedded sand | Pliocene            | Basin deposits   |
| 8  | 453858         | 4755065        | Milli 1    | DST  | 927     | 97            | Clay with interbedded sandy strata | Pleistocene ***     | Basin deposits   |
| 8  | 453858         | 4755065        | Milli 1    | DST  | 1184    | 130           | Clay with interbedded sandy strata | Pleistocene ***     | Basin deposits   |
| 8  | 453858         | 4755065        | Milli 1    | DST  | 1670    | 210           | Clay with interbedded sandy strata | Pliocene            | Basin deposits   |
| ID | X WGS84 UTM33N | Y WGS84 UTM33N | Name                          | Test  | * MD (m) | Pressure (bar) | Lithology**                        | Age**  | Geological unit* |
|----|----------------|----------------|-------------------------------|-------|----------|----------------|------------------------------------|--------|-----------------|
| 9  | 409409         | 469590         | Montebello di Bertona 1       | DST   | 1248     | 104            | Clay with interbedded sandy strata | Pliocene | Basin deposits  |
| 9  | 409409         | 469590         | Montebello di Bertona 1       | DST   | 1720     | 145            | Interbedded clay and sand          | Pliocene | Basin deposits  |
| 10 | 412573         | 4725288        | Morro D’oro 1                 | DST   | 2664     | 259            | Clay with interbedded sandy strata | Pliocene | Basin deposits  |
| 10 | 412573         | 4725288        | Morro D’oro 1                 | DST   | 3737     | 660            | Clay with interbedded sandy strata | Pliocene | Basin deposits  |
| 11 | 432011         | 4687606        | S. Barbara 1 DIR             | RFT   | 1603     | 157            | Interbedded clay, silt, and sand  | Pleistocene | Basin deposits  |
| 11 | 432011         | 4687606        | S. Barbara 1 DIR             | RFT   | 1607     | 158            | Interbedded clay, silt, and sand  | Pleistocene | Basin deposits  |
| 11 | 432011         | 4687606        | S. Barbara 1 DIR             | RFT   | 1608     | 158            | Clay with interbedded sand        | Pleistocene | Basin deposits  |
| 12 | 476663         | 4654451        | S. Salvo 18                  | DST   | 792      | 85             | Sand with interbedded clayey strata | Pleistocene | Basin deposits  |
| 13 | 460849         | 4652300        | S. Buono 1                   | DST   | 1110     | 140            | Mainly marls                      | n.a.    | Allochthonous    |
| 13 | 460849         | 4652300        | S. Buono 1                   | DST   | 1265     | 170            | Mainly marls                      | n.a.    | Allochthonous    |
| 14 | 401564         | 4737592        | S. Omero W1                  | DST   | 928      | 127            | Sand with interbedded clayey strata | Pliocene | Basin deposits  |
| 14 | 401564         | 4737592        | S. Omero W1                  | DST   | 1066     | 147            | Sand with interbedded clayey strata | Pliocene | Basin deposits  |
| 15 | 425177         | 4695464        | S. Salvatore 1               | DST   | 1745     | 193            | Clay and sand                     | Pliocene | Basin deposits  |
| 16 | 455226         | 4682931        | S. Vito Chietino 1           | DST   | 688      | 61             | Sandy lens in clay                | Pleistocene | Basin deposits  |
| 17 | 402492         | 4729249        | San Silvestro 1              | DST   | 2388     | 255            | Marls with interbedded sand       | Pliocene | Basin deposits  |
| 17 | 402492         | 4729249        | San Silvestro 1              | DST   | 2575     | 305            | Marls with interbedded sand       | Pliocene | Basin deposits  |
| 18 | 418324         | 4726514        | Savini 1                     | RFT   | 1140     | 229            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 18 | 418324         | 4726514        | Savini 1                     | RFT   | 1192     | 240            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 18 | 418324         | 4726514        | Savini 1                     | RFT   | 1253     | 264            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 18 | 418324         | 4726514        | Savini 1                     | RFT   | 1254     | 265            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 18 | 418324         | 4726514        | Savini 1                     | RFT   | 1274     | 271            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 18 | 418324         | 4726514        | Savini 1                     | RFT   | 1298     | 277            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 18 | 418324         | 4726514        | Savini 1                     | RFT   | 1374     | 296            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 980      | 107            | Conglomerate with sand and clay   | Pleistocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1423     | 143            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1424     | 146            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1439     | 143            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1439     | 143            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1439     | 143            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1443     | 143            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1459     | 158            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| 19 | 470602         | 4670874        | Sinello 1                    | RFT   | 1586     | 174            | Clay with interbedded sand        | Pliocene | Basin deposits  |
| ID | X WGS84 UTM33N | Y WGS84 UTM33N | Name       | Test | *MD (m) | Pressure (bar) | Lithology** | Age** | Geological unit** |
|----|----------------|----------------|------------|------|---------|---------------|-------------|-------|------------------|
| 20 | 469004         | 4756682        | Stefania 1 | DST  | 700     | 69            | Clay and sandy clay | Pleistocene | Basin deposits    |
| 21 | 406048         | 4727393        | Villa Torre 1 | DST  | 1452    | 184           | Sand with interbedded clayey strata | Pliocene | Basin deposits    |
| 21 | 406048         | 4727393        | Villa Torre 1 | DST  | 1482    | 184           | Sand with interbedded clayey strata | Pliocene | Basin deposits    |
| 21 | 406048         | 4727393        | Villa Torre 1 | DST  | 2758    | 335           | Sand       | Pliocene | Basin deposits    |
| 22 | 461034         | 4669078        | Villafonsina 3 | DST  | 1436    | 160           | Clay with interbedded sand | Pliocene | Basin deposits    |

*The depth is referred to the recording device or to the top of the tested interval. **The geological model, age, and lithology refer to the tested interval whose depth can be different with the depth of the recording device. ***The Pleistocene can be reported in the logs as Upper Pliocene.
Figure 6: Location of wells with available pressure measurements. The wells were grouped according to the calculated pressure regime. The ID (1–22) of each well corresponds to the ID in Table 3, which reports the main information (from [73, 74]), whereas the wells marked with B are from Carlin and Dainelli [79]. The area in red is the study area for the favourability assessment.

Figure 7: Thermal model. (a) Elevation map of the top of carbonate units hosting the regional reservoir together with the depth (referring to the sea level) of the 90°C isotherm. The gray lines encompass the sector in which the threshold temperature of 90°C is above the base of the Pliocene deposits. The main recharge areas (outcrops of carbonate units) and the deep exploratory wells are also reported. (b) Comparison between the corrected bottom hole temperatures (black square) and the modelled thermal profiles from selected clusters of wells ((a), dashed white lines). The error bar of ±10% is also reported.
the freshwater head calculated with a reference water density of 1000 kg/m$^3$ and the sea level as datum. Regarding the upper and lower thermal boundaries, we defined the mean annual soil temperature and a specific isotherm at a 20 km depth, respectively. The vertical boundaries of the numerical domain do not allow a horizontal flow of fluid and heat.

A good fit between the measured and simulated temperatures was achieved for a basal temperature of 350 °C and an average permeability of the regional carbonate reservoir of $1.6 \cdot 10^{-16}$ m$^2$.

The observed geothermal gradients spanned from 20 to 50°C/km, and the mean value was 28°C/km. The highest and lowest values were observed in the mountainous zones in which the heat advection, controlled by the regional groundwater flow, modifies the conductive thermal structure. Regarding the thermal structure of the study area, we computed the depth (a.s.l.) of the 90°C isotherm (also referred to as z90). The isobaths show two minima (z90 > 5 km) in the south-western corner separated by an upwelling zone (z90 ≈ 2 km). In the mainland, far from the carbonate outcrops, z90 settles around 2.5–2.7 km and deepens toward the offshore sector to 3–3.4 km.

On the basis of the thermal and geological models, the sectors in which z90 is above the base of the Pliocene deposits represent the target areas (Figure 7(a)).

5.4. Geochemistry. In our case study, the geochemical analyses on fluids sampled in wells were used to analyse known methane-prospective areas (corresponding to tectonic elements), whereas a geostatistical analysis was not possible.

Minissale et al. [86, 87] clearly defined multiple sources of gas discharge manifestations in central Italy. Along a transect crossing the Northern Apennine, the inner part of the chain is mostly characterized by CO$_2$-rich emissions, whereas CH$_4$-rich emissions are predominant in the outer part of the Apennines along the Adriatic coast, where the study area is located. The source of CH$_4$ in the Adriatic sector is related to the sedimentary process in the Periadriatic foredeep. In fact, Italy is considered a gas (methane)-prone area, the formation and accumulation of which are strictly related to the tectono-sedimentary evolution and specific areas.

Mattavelli and Novelli [88] identified a narrow area, corresponding to the foredeep of the Apennine belt, where 77% of Italian natural gases were discovered (Figure 8). Here, the synsedimentary tectonics, the highly efficient turbidite systems coupled with subsidence, favoured the generation (and also trapping) of natural gases. Eighty-two per cent of natural gas in this area is biogenic, characterized by almost pure and isotopically light CH$_4$ with C$_2$ (ethane) and other components (<0.5%). The authors found strong evidence for in situ generation of gas, through bacterial or diageneric processes. The gaseous hydrocarbons are mainly stored in Plio-Pleistocene sediments.

We focused on the gas chemistry of sampled fluids in wells. Several chemical analyses of major ions were available for the water samples with complementary notes on the
occurrence of gas (generic) or smell of hydrocarbons. A few were coupled with chemical analyses of well gases. The analyses of well gases sampled in Plio-Pleistocene deposits show an amount of CH$_4$ that is always higher than 97% and CO$_2$ lower than 1%. In addition, tens of wells record exsolved gas traces in the Plio-Pleistocene interval. The same analyses in the underlying carbonates show lower and highly variable amounts of CH$_4$. These gases were sampled in relation to supposed hydrocarbon targets in the carbonates. Figure 8 shows the wells with measured CH$_4$, as well as those with traces of exsolved gas.

An example is given by the well “Montebello di Bertona 1” in which well gases were analysed both in terrigenous sediments and in carbonate successions. The gas sampled in the interbedded shale and sand, Pliocene in age, is composed of 99% of CH$_4$, whereas in the underlying carbonates, CH$_4$ abruptly decreases and CO$_2$ increases to over 50%.

The analyses led us to assume formation water saturated and oversaturated in methane, with a clear indication of the diffuse presence of CH$_4$ in the Plio-Pleistocene deposits, which is locally accumulated. Table 4 summarizes the well gas analyses. We also computed the methane solubility in water by using the empirical method by Price et al. [36] and taking as an example the conditions at depth along the well “Morro D’oro 1” from a test in water with dissolved gas. Considering a formation pressure of 660 bar at 3733 m, a temperature of 90°C, and water salinity of 28.6 g/l, the solubility of methane is 28.75 SCF/Bbl. The solubility we computed is close to the values reported for the geopressed system of the Gulf of Mexico [27, 36].

6. Layers of Evidence

With regard to the Abruzzo case study, in the first stage, a preliminary analysis was carried out in order to identify the areas to be assessed, those strictly related to the concept of sedimentary basin plays. The study area corresponds to the foredeep-foreland domains of the Apennines thrust belt in Abruzzo. The targets are the geopressed resources hosted in the Plio-Pleistocene siliciclastic succession. Basically, the sectors in which the depth of the 90°C isotherm is above the base of the Pliocene deposits represent the target areas.

We then created the layers of evidence by combining different thematic inputs throughout the spatial analyses. These layers of evidence were related to the favourable factors and referred to (see details in Section 3): (i) the effective geopressed-geothermal reservoir, (ii) the thermal regime, (iii) the pressure regime, (iv) the deposit thickness, and the (v) geochemistry.

The five layers of evidence were combined by Index Overlay to produce the final favourability map as a result of the last stage of the workflow. The layers of evidence have been computed with the same spatial resolution, 1 x 1 km, and with the grid nodes of each layer overlapping.

### Table 4: Well gas chemical analyses, in relation to the CH$_4$ and CO$_2$ percentage. The ID refers to the location in Figure 8.

| ID | X WGS84 UTM33N | Y WGS84 UTM33N | Name | MD (m) | Test | Gas analysis CH$_4$ (%) | CO$_2$ (%) | Lithology | Age | Geological unit |
|----|----------------|----------------|------|--------|-----|------------------------|----------|-----------|-----|-----------------|
| a  | 445825         | 4653324        | Bomba 1 | 1222   | DST | 68,91                | 0,73     | Wackestone and packstone | Miocene | Carbonate basement |
| b  | 445031         | 4652621        | Bomba 2 | 1378   | DST | 69,14                | 0,7      | Wackestone and packstone | Miocene | Carbonate basement |
| c  | 410927         | 4685976        | Bonanno 1 | 1680   | DST | 7,5                  | 36       | Limestone | Miocene | Carbonate basement |
| d  | 464912         | 4656839        | Gissi 2 | 1021   | DST | 98,37                | 0,32     | Packstone and marls | Miocene (allochthonous) | Basin deposits |
| e  | 451540         | 4676478        | Lanciano 2 | 2721   | DST | 31,84                | 13       | Wackestone and packstone | Cretaceous | Carbonate basement |
| f  | 409409         | 4695990        | Montebello di Bertona 1 | 1248   | DST | 99,19                | 0,04     | Intercalated shale and sandstone | Pliocene | Basin deposits |
| g  | 449486         | 4661657        | Perano 1 | 979    | DST | 97,4                 | 0,06     | Shale | Pliocene (uncertain) | Basin deposits |
| h  | 457847         | 4673292        | S. Maria 2 | 2194   | DST | 26,67                | 1,83     | Limestone | Cretaceous | Carbonate basement |
| i  | 461034         | 4669078        | Villalfonsina 3 | 1436   | DST | 99,33                | n.a      | Sandy shale | Pliocene | Basin deposits |
| L  | 458910         | 4666716        | Paglieta 3 | 700    | DST | 98,5                 | n.a      | Limestone and marls | Miocene (allochthonous) | Basin deposits |
the Pliocene deposits. The result is a grid layer of a ranked depth of the top of the effective geopressured-geothermal reservoir (Figure 10).

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.

The ranking classes and the weight are listed in Table 2.

6.2. Thermal Regime. In our study, the thermal regime is parameterized by the thermal gradient.

The thermal gradient was computed starting from the average air temperature, which varies on the basis of the topography elevation, and using the layer of the temperature at the top of the carbonate formations. By a raster computation, we obtained an average air temperature for each cell from the digital elevation model (DEM) layer applying a lapse rate of 0.0065 (°C/m) and 0.0045 (°C/m) for positive (i.e., above sea level) and negative (i.e., below sea level) elevations, respectively [89, 90]. A further raster computation then enabled us to define the thermal gradient map (Figure 11). The thermal regime was ranked and weighted as shown in Table 2.

6.3. Pressure Regime. We obtained information of the pressure regions through geostatistical analyses on the pressure gradients computed in the wells reaching the Pliocene succession. A statistical analysis showed only a partial trend along the X and Y coordinates. After various attempts, we have chosen the resulting interpolation obtained with the Universal Kriging algorithm, which guaranteed the least root-mean-square error. The resulting grid layer is shown in Figure 12.

The rank is related to the amount of overpressure that occurs in the Pliocene sedimentary succession.

6.4. Deposit Thickness. This layer of evidence was obtained by simply classifying the thickness of the basin deposits (i.e., the Pliocene bottom depth from the ground level) using the raster recode function (Figure 13). The classes and weights are listed in Table 2.

6.5. Geochemistry. This 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 [88] (Figure 14). We assigned the highest class (5th) to this area, assuming the occurrence of CH4-saturated and oversaturated waters in reservoir. The available geochemical dataset on fluids sampled in wells supports this assumption (see Section 5.4). The dataset was not complete enough to compute geostatistical analysis. The remaining part of the area, not included in this CH4-prospective domain, was ranked with the less favourable class (1st).
7. The Favourability Map of Abruzzo: Results and Discussion

The quantitative integration of data using the Index Overlay method (see Section 6) resulted in the favourability map of a geopressed-geothermal system for the foredeep-foreland basin play of Abruzzo, shown in Figure 15.

The role of the prospective factors at regional scale (Table 1) has been addressed in the five layers of evidence. The geopressed effective reservoir takes into account the depositional environment, the temperature, the depth of the reservoir, and intrinsically the lithology. Pressure and temperature have been considered in the pressure and thermal regime layers of evidence, respectively. The deposit thickness takes into account the depositional environment, the deposition rate, the size of the reservoir, and the lithology. The geochemistry layer provides information on the occurrence of dissolved gaseous hydrocarbons.

A point that deserves a clarification is the use or not of the faults as permeability indicator. The main limit of its use in the favourability computation is the possible hydraulic behaviour of the faulted volume of rocks. A fault can act as a permeability barrier or can enhance the permeability. At regional scale, it is not accurate and reliable to assign a favourable value around a fault trace. At local (i.e., exploration licence) or well scale, the detailed geophysical and geological studies allow the understanding of the hydraulic feature of a fault. We decided to disregard this contribution in our computation at regional scale, but we consider the structural setting a key information to be addressed during a local exploration project.

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 km² and runs parallel to the shoreline along a
NW-SE direction, both offshore 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.

We assigned the highest weight in the Index Overlay computation to the effective reservoir layer of evidence (0.4; see Table 2) because it takes into account (i) the minimum temperature requirement for the exploitation, (ii) the financial factors related to the depth of the drilling target, and (iii) the occurrence of a potential reservoir. Since the subsurface temperature is usually close or lower than the average continental reference in the study area, the depth of the top of the effective reservoir belongs mostly to the medium and low favourable classes with scores of 3 and 2, respectively. This means that in the best scenario, wells should reach a 2.5–3 km depth to exploit 90°C.

The second most weighted layer of evidence (0.3; see Table 2) is the pressure regime. Our study area is mostly characterized by high to very high favourable classes (4 and 5 scores) with hard geopressured gradients in the Pliocene succession, locally approaching the lithostatic reference. We consider this layer of evidence as a useful first-order approximation of pressure regions. However, due to the low number of pressure data, the spatial analysis cannot be used to evaluate a precise value at depth of the formation pressure. As expected, the most abnormal pressure regime occurs along the deformation front subparallel to the coast. The inner sector (westwards) shows hydrostatic to soft geopressed regimes, whereas the undeformed foredeep (eastwards) shows soft to hard geopressed regimes. The results of our analysis are in good agreement with the pressure regions identified by Carlin and Dainelli [79] for the northern sectors of the Adriatic Sea.
Although temperature is embedded in the concept of the effective reservoir, which considers the 90°C isotherm, we included a layer of evidence exclusively related to the thermal regime, with a weight of 0.1 by 1. We thus included information on the occurrence of positive thermal anomalies. As expected, most of the study area shows low values of geothermal gradient except for the southern part, where higher values belonging to the 3rd class were found. Here, the deep water rising toward the groundwater base level can affect the conductive thermal gradient within the impermeable cover.

The layer of evidence related to the deposit thickness shows higher values, up to the 4th class, only in a small sector located in the deformation front along the northern coastal zone. The weight assigned is the same as the thermal regime, i.e., 0.1 by 1. We chose a weight value lower than the effective reservoir and pressure regime because this layer is mainly related to geological conditions that can indirectly favour the presence of geopressed resources and less direct information is provided, such as the possible extent at depth of reservoirs. We stress that the deposit thickness is correlated with the deposition rate, but it is also controlled by tectonics in the study area.

The aim of this study was to assess the geopressed resources occurring in terrigenous sedimentary basin plays, as they favour the generation of overpressure and above all widespread dissolved gaseous hydrocarbons. The importance of methane is already embedded in this focus. Furthermore, we assumed that there are methane-saturated waters in the CH₄-prospective area [88] corresponding to the foredeep domain, after a duly analysis, assigning the highest class (5th). In our case study, the geochemical dataset was too poor to rank the area accordingly and the assigned weight is 0.1 by 1.
The procedure can be improved with a quantitative ranking of the layer of evidence regarding the geochemistry (e.g., percentage of methane in free gases, methane solubility) by using geostatistical tools.

From a practical point of view, the map can be considered constrained where direct data along deep wells are available. For this reason, we provide the final favourability map coupled with the well locations. Moreover, to further assess and exploit the geopressed resources in the study area, it should be considered that the favourable part located in the offshore is limited by technical (even if the sea floor of the Adriatic Sea is really shallow) and nontechnical (e.g., legal regulations) barriers.

7.1. Sensitivity Analysis. In order to verify the stability of the resulting favourability map and the reliability of our knowledge-driven choices, we have computed a sensitivity analysis in which the influence of input variations is evaluated on the outcomes.

A deterministic sensitivity analysis was computed as follows:

(i) The favourability map of the Abruzzo (Figure 15) is set as reference outcome \( \text{out}_{\text{ref}} \) as well as the weights \( W_{i,\text{ref}} \) of each layer of evidence.

(ii) The weight of the first layer of evidence \( W_{i,1} \) was perturbed in the range 0.1–0.9 while homogenously distributing the remaining weight to the other layers (being the sum of the weights equal to 1). The procedure is repeated for each layer of evidence. For each scenario, a favourability map \( \text{out}_n \) was computed by IO (see (1)). We stress that the classes of each layer of evidence are kept equal to the reference scenario.

(iii) The percentage change in the output \( \Delta \text{out} \) of each scenario is computed for each pixel with respect to the reference map.
(iv) The percentage change in the weight ($\Delta W_i$) of each scenario is computed with respect to the reference weights ($W_{i,\text{ref}}$).

(v) The sensitivity $s$ for each scenario is computed pixel by pixel as the ratio between percentage changes in the output and weights, as follows:

$$s = \frac{\Delta \text{out}}{\Delta W_i}$$

The results are summarized in Figure 16. We show the sensitivity maps evaluated for each layer of evidence with weights varying from 0.1 to 0.9 with a step of 0.2.

The comparison among the various sensitivity maps highlights a larger sensitivity to the geopressured effective reservoir and the pressure regime layers of evidence. The main variations of the sensitivity index mimic the spatial distribution of the pressure regime, highlighting a very important role of this layer. This behaviour is expected because among the most weighted layers, the pressure regime shows the largest spatial variability; on the contrary, the effective reservoir is almost homogenous.

Conversely, our reference map is slightly sensitive to the perturbation on the thermal regime, geochemistry, and the deposits thickness layers, except for a few restricted areas. Particularly, the sector in the southwestern corner of the map shows larger sensitivity. This response corresponds to an area at the contact of outcropping carbonates where very high thermal gradients are modelled. This computation appears to be a local artefact, due to the fact that the thickness of the impermeable cover is really short and the resulting thermal gradients were extremely high.

8. Conclusions

This paper is intended to be a practical analytical framework for the systematic integration of the relevant data required to
assess the geopressed-geothermal resources. The approach described can be considered valid and applicable at a global scale as the whole procedure is based on generic features of terrigenous sedimentary basins and was further tested on the Abruzzo case study.

The main results of this study can be summarized as follows:

(i) We propose a novel integrated methodology aimed at assessing and mapping the favourability of geopressed resources in sedimentary basin plays worldwide. We used a consolidated system of weighting and scoring in a GIS environment, the Index Overlay, to analyse various prospective parameters.

(ii) We identified five layers of evidence that describe the prospective factors needed for assessing such unconventional resources: (i) the effective geopressed-geothermal reservoir, (ii) the thermal regime, (iii) the pressure regime, (iv) the deposit thickness, and (v) the geochemistry. The effective geopressed-geothermal reservoir is a concept that can be of help for the industrial exploration. The depth of its top is a key parameter, easy to map.

(iii) Regarding the Abruzzo case study, an updated dataset of subsurface data was organized and important outcomes are now available such as the 3D geological model, including an up-to-date base of Pliocene deposits, and the study on the pressure and thermal regimes.

(iv) 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.

Figure 15: Favourability map of the geopressed-geothermal system for Abruzzo.
only for hydrocarbons. In order to provide a quantitative estimation of the resources required for industrial projects, detailed exploration activities at the local scale (research permits) are required.

**Data Availability**

(1) The official geological maps for the study area are available at the following links: (i) ISPRA, 2017a. Geological maps of Italy, scale 1 : 100.000 (sheets 133, 134, 140, 141, 146, 147,148, 152, 153, 154), Istituto Superiore per la Protezione e la Ricerca Ambientale. http://193.206.192 .231/carta_geologica_italia/default.htm; (ii) ISPRA, 2017b. Geological maps of Italy, scale 1 : 50.000, sheet 339. Istituto Superiore per la Protezione e la Ricerca Ambientale. http://www.isprambiente.gov.it/Media/carg/339_TERAMO/Foglio .html. (2) The master logs of the deep hydrocarbon wells analysed in this work are available at ViDEPI project website. Visibilità dei dati afferenti all’attività di esplorazione petrolifera in Italia (Visibility of data related to the hydrocarbon exploration in Italy). http://unmig.sviluppo economico.gov.it/videpi/pozzi/pozzi.asp. (3) The deep hydrocarbon well data are organized in the following database: Trumpy, E., Manzella, A., 2017. Geothopica and the interactive analysis and visualization of the updated Italian National Geothermal Database, International Journal of Applied Earth Observation and Geoinformation, 54, 28–37. 10.1016/j.jag.2016.09.004. Available at: http://geothopica.igg.cnr.it/. (4) Information on the pressure regimes in the Northern Adriatic Foredeep was obtained from Carlin, S., Dainelli, J., 1998. Pressure regimes and pressure systems in the Adriatic foredeep (Italy). In: Law, B.E., Ulmishek, G.F., Slavin, V.I. eds. Abnormal pressures in hydrocarbons environments. AAPG Memoir, 70, 145–160. (5) This work was carried out within the framework of the Geothermal Atlas of Southern Italy Project. Thematic maps produced in the frame of the Project are available at http://atlante.igg.cnr.it/index.php/prodotti/mappe.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.
Acknowledgments

This work was carried out within the framework of the Geothermal Atlas of Southern Italy Project, funded by the Italian National Research Council. The Project is aimed at verifying, locating, and generating an updated atlas of geothermal resources usable for the production of geothermal energy in the southern regions of Italy.

References

[1] Geothermal Atlas for Southern Italy Project website, "Progetto Atlante Geotermico del Mezzogiorno. CNR per il mezzogiorno," January 2018 http://atlante.igg.cnr.it/.

[2] R. H. Wallace Jr., T. F. Kraemer, R. E. Taylor, and J. B. Wesselman, “Assessment of geopressed-geothermal resources in the Northern Gulf of Mexico basin,” in Assessment of Geothermal Resources of the United States – 1978, United States Geological Survey Circular, L. J. P. Muller, Ed., pp. 132–155, U.S. Geological Survey, 1979No. 790.

[3] R. G. Loucks, D. L. Richmann, and K. L. Millken, Factors Controlling Reservoir Quality in Tertiary Sandstones and Their Significance to Geopressed Geothermal Production. Report of Investigation No. 111, Bureau of Economic Geology, University of Texas, 1981.

[4] J. S. Griggs, “A re-evaluation of geopressed-geothermal aquifers as an energy resource,” Proceedings Thirtieth Workshop on Geothermal Reservoir Engineering, Stanford University, 2005, Stanford, California, January–February 2005, 2005SGP-TR-176.

[5] DOE (United States Department of Energy), Geothermal Energy Production with Co-produced and Geopressed Resources, DOE/GO-10210-3004, 2010.

[6] M. Árpási, Á. Lorberer, and S. Pap, “High pressure and temperature (geopressed) geothermal reservoirs in Hungary,” in Proceedings of World Geothermal Congress 2000, Kyushu - Tohoku (Japan), 2000.

[7] D. G. Bebout, B. R. Weise, A. R. Gregory, and M. B. Edwards, Wilcox Sandstone Reservoirs in the Deep Subsurface along the Texas Gulf Coast: Their Potential for Production of Geopressed Geothermal Energy. Report of Investigation, No. 117, Bureau of Economic Geology, 1982.

[8] C. Alimonti and A. A. Gnoni, “Harnessing the fluids heat to improve mature oil field: the Villfortuna–Trecreate case study,” Journal of Petroleum Science and Engineering, vol. 125, pp. 256–262, 2015.

[9] E. Trumpol, A. Donato, G. Gianelli et al., “Data integration and favourability maps for exploring geothermal systems in Sicily, Southern Italy,” Geothermics, vol. 56, pp. 1–16, 2015.

[10] R. M. Prol-Ledesma, “Evaluation of the reconnaissance results in geothermal exploration using GIS,” Geothermics, vol. 29, no. 1, pp. 83–103, 2000.

[11] M. F. Coolbaugh, J. V. Taranik, G. L. Raines et al., “A geothermal GIS for Nevada: defining regional controls and favorable exploration terrains for extensional geothermal systems,” Transactions-Geothermal Resources Council, vol. 26, pp. 485–490, 2002.

[12] M. Coolbaugh, R. Zehner, C. Kreemer et al., Geothermal Potential Map of the Great Basin, Western United States, Nevada Bureau of Mines and Geology, 2005.

[13] Y. Noorollahi, R. Itoi, H. Fujii, and T. Tanaka, “GIS model for geothermal resource exploration in Akita and Iwate prefectures northern Japan,” Computational Geosciences, vol. 33, no. 8, pp. 1008–1021, 2007.

[14] Y. Noorollahi, R. Itoi, H. Fujii, and T. Tanaka, “GIS integration model for geothermal exploration and well sitting,” Geothermics, vol. 37, no. 2, pp. 107–131, 2008.

[15] H. Yousefi, Y. Noorollahi, S. Ehara et al., “Developing the geothermal resources map of Iran,” Geothermics, vol. 39, no. 2, pp. 140–151, 2010.

[16] N. Tufekci, M. Luti Suzen, and N. Gulec, “GIS based geothermal potential assessment: a case study from Western Anatolia, Turkey,” Energy, vol. 35, no. 1, pp. 246–261, 2010.

[17] M. K. Moghaddam, Y. Noorollahi, F. Samadzadegan, M. A. Sharifi, and R. Itoi, “Spatial data analysis for exploration of regional scale geothermal resources,” Journal of Volcanology and Geothermal Research, vol. 266, pp. 69–83, 2013.

[18] M. K. Moghaddam, F. Samadzadegan, Y. Noorollahi, M. A. Sharifi, and R. Itoi, “Spatial analysis and multi-criteria decision making for regional-scale geothermal favorability map,” Geothermics, vol. 50, pp. 189–201, 2014.

[19] L. Mattavelli, L. Novelli, and L. Anelli, “Occurrence of hydrocarbons in the Adriatic basin,” Spec. Publ. EAPG (European Association of Petroleum Geoscientists), vol. 1, pp. 369–380, 1991.

[20] P. Casero and S. Bigi, “Structural setting of the Adriatic basin and the main related petroleum exploration plays,” Marine and Petroleum Geology, vol. 42, pp. 135–147, 2013.

[21] F. Cazzini, O. D. Zotto, M. Ghielmi, P. Ronchi, and P. Scotti, “Oil and gas in the Adriatic foreland, Italy,” Journal of Petroleum Geology, vol. 38, no. 3, pp. 255–279, 2015.

[22] C. E. Hotman, “Method for producing a source of energy from an overpressured formation,” 1966, United States Patent Office 3258069.

[23] E. E. Hughes, “Gas/geothermal hybrid experiment,” in DOE/GRI Industry Meeting March 4-5, 1986, Review of Geopressed-Geothermal and Co-production Research, H. F. Coffier and R. W. Howell, Eds., Idaho National Engineering Laboratory (INEL), 1987.

[24] S. K. Garg, T. D. Riney, and R. H. Wallace Jr, “Brine and gas recovery from geopressed systems,” Geothermics, vol. 15, no. 1, pp. 23–48, 1986.

[25] W. J. Bernard, “Reservoir mechanics of geopressed aquifers,” in Proceeding of the First Geopressed Geothermal Energy Conference, Austin, Texas, 1975.

[26] S. D. S. R. Karamchetty, H. M. Liebowitz, and J. M. Oliver, “Geopressed-geothermal: a multi-energy resource,” in Proceedings of Fifth Conference Geopressed–Geothermal Energy, U.S. Gulf Coast, October 1981.

[27] C. J. John, G. Maciasz, and B. J. Harder, Geopressured-geothermal: a multi-energy resource, Geothermal Resources Council Transactions, vol. 14, no. 1, pp. 537–545, 1990.

[28] J. Negus de Wys and M. Dorfman, “The geopressed-geothermal resource: transition to commercialization,” Geothermal Resources Journal, vol. 1, pp. 83–103, 2000.

[29] T. D. Riney, Pleasant Bayou Geopressed-Geothermal Reservoir Analysis-January 1991. Topical Report, performed for the Center for Energy Studies (University of Texas at Austin) Under U.S. Department of Energy Cooperative, 1991, Agreement No.DE-FC07-85NV10412.
V. Scisciani and R. Montefalcone, "Evolution neogenico-quaternaria del fronte della catena centro-appenninica: vincoli dal bilanciamento sequenziale di una sezione geologica regionale," Bollettino della Società Geologica Italiana, vol. 124, pp. 579–599, 2005.

D. Scrocca, "Thrust front segmentation induced by differential slab retreat in the Apennines (Italy)," Terra Nova, vol. 18, no. 2, pp. 154–161, 2006.

E. Patacca and P. Scandone, "Geology of the southern Apennines," Bollettino della Società Geologica Italiana, vol. 7, Spec. Issue, pp. 75–119, 2007.

R. Fantoni and R. Franciosi, "Tectono-sedimentary setting of the Po Plain and Adriatic foreland," Rendiconti Lincei, vol. 21, Supplement 1, pp. 197–209, 2010.

L. Vezzani, A. Festa, and F. Ghisetti, "Geology and tectonic evolution of the Central-Southern Apennines, Italy," p. 469, 2010, GSA Special Papers.

A. Artoni, "The Pliocene-Pleistocene stratigraphic and tectonic evolution of the central sector of the Western Periadriatic Basin of Italy," Marine and Petroleum Geology, vol. 42, pp. 82–106, 2013.

S. Bigi, A. Conti, P. Casero, L. Ruggiero, R. Recanati, and L. Lipparini, "Geological model of the central Periadriatic basin (Apennines, Italy)," Marine and Petroleum Geology, vol. 42, pp. 107–121, 2013.

G. Lavecchia, F. Brozzetti, M. Barchi, M. Menichetti, and J. V. A. Keller, "Seismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformations and related stress fields," GSA Bulletin, vol. 106, no. 9, pp. 1107–1120, 1994.

R. W. H. Butler, S. Mazzoli, S. Corrado et al., "Applying thick-skinned tectonic models to the Apennine thrust belt of Italy—limitations and implications," Thrust Tectonics and Hydrocarbon Systems, K. R. McClay, Ed., vol. 82, pp. 647–667, AAPG Memoir, 2004.

E. Patacca, P. Scandone, E. di Luzzio, G. P. Cavinato, and M. Parotto, "Structural architecture of the central Apennines: interpretation of the CROP 11 seismic profile from the Adriatic coast to the orographic divide," Tectonics, vol. 27, no. 3, 2008.

G. Lavecchia, G. Minelli, and G. Pialli, "The Umbria-Marche arcuate fold belt (Italy)," Tectonophysics, vol. 146, no. 1–4, pp. 125–137, 1988.

E. Patacca and P. Scandone, "The Plio-Pleistocene thrust belt-foredeep system in the southern Apennines and Sicily (Italy)," in Special volume of the Italian geological society for the 32 th IGC, Florence, 2004.

M. A. Romano, R. De Nardis, M. Garbin et al., "Temporary seismic monitoring of the sulmona area (Abruzzo, Italy): a quality study of microearthquake locations," Natural Hazards and Earth System Sciences, vol. 13, no. 11, pp. 2727–2744, 2013.

G. Lavecchia, G. M. Adinolfi, R. de Nardis et al., "Multidisciplinary inferences on a newly recognized active east-dipping extensional system in Central Italy," Terra Nova, vol. 29, no. 1, pp. 77–89, 2017.

U. Crescenti, C. D'Amato, A. Balduzzi, and M. Tonna, "Il Plio-Pleistocene del sottosuolo abruzzese–marchigiano tra Ascoli Piceno e Pescara," Geologica Romana, vol. 19, pp. 63–84, 1980.

R. Casnedi, "L’avanfossa abruzzese fra i fiumi Vomano e Pescara nel Pliocene inferiore: rapporti tra sedimentazione e tectonica," Studi Geologici Camerti, vol. Spec. 2, pp. 375–379, 1991.
Ombrina-Rospo Plateau (Apulian Platform): evolution of a carbonate platform and its margins during the Jurassic and Cretaceous,” Marine and Petroleum Geology, vol. 42, pp. 4–29, 2013.

[79] S. Carlin and J. Dainelli, “Pressure regimes and pressure systems in the Adriatic foredeep (Italy),” in Abnormal Pressures in Hydrocarbons Environments, B. E. Law, G. F. Ulmishek, and V. I. Slavin, Eds., vol. 70 of AAPG Memoir, , pp. 145–160, AAPG, 1998.

[80] J. D. Walker, J. W. Geissman, S. A. Bowring, and L. E. Babcock, “Geologic time scale v. 4.0,” Geological Society of America, 2012.

[81] V. Pasquale, P. Chiozzi, G. Gola, and M. Verdoya, “Depth–time correction of petroleum bottom-hole temperatures in the Po Plain, Italy,” Geophysics, vol. 73, no. 6, pp. E187–E196, 2008.

[82] G. Gola, A. Manzella, E. Trumpy, D. Montanari, and J. D. Van Wees, “Deep-seated geothermal resource assessment of the VIGOR project regions, Italy,” in Proceedings of the European geothermal congress 2013, Pisa, Italy, June 2013.

[83] R. Castaldo, G. Gola, A. Santiliano et al., “The role of thermo-rheological properties of the crust beneath Ischia Island (Southern Italy) in the modulation of the ground deformation pattern,” Journal of Volcanology and Geothermal Research, vol. 344, pp. 154–173, 2017.

[84] D. Montanari, A. Minissale, M. Dovieri et al., “Geothermal resources within carbonate reservoirs in western Sicily (Italy): a review,” Earth-Science Reviews, vol. 169, pp. 180–201, 2017.

[85] V. Pasquale, G. Gola, P. Chiozzi, and M. Verdoya, “Thermophysical properties of the Po Basin rocks,” Geophysical Journal International, vol. 186, no. 1, pp. 69–81, 2011.

[86] A. Minissale, W. C. Evans, G. Magro, and O. Vaselli, “Multiple source components in gas manifestations from north-central Italy,” Chemical Geology, vol. 142, no. 3-4, pp. 175–192, 1997.

[87] A. Minissale, G. Magro, O. Martelli, O. Vaselli, and G. F. Tassi, “Fluid geochemical transect in the Northern Apennines (central-northern Italy): fluid genesis and migration and tectonic implications,” Tectonophysics, vol. 319, no. 3, pp. 199–222, 2000.

[88] L. Mattavelli and L. Novelli, “Geochemistry and habitat of natural gases in Italy,” Advances in Organic Geochemistry, vol. 13, no. 1-3, pp. 1–13, 1988.

[89] A. Giorgetti, “Climatological analysis of the Adriatic Sea thermohaline characteristic,” Bollettino Di Geofisica Teorica Ed Applicata, vol. 40, pp. 53–73, 1999.

[90] I. I. Mokhov and M. G. Akperov, “Tropospheric lapse rate and its relation to surface temperature from reanalysis data,” Izvestiya, Atmospheric and Oceanic Physics, vol. 42, no. 4, pp. 430–438, 2006.

[91] R. Fortuna and A. Jelacic, “The geopressured-geothermal research program: an overview,” in Proceeding of the natural gas R & D contractors review meeting, Morgantown WV, April 1989.

[92] ISPRA, Geological Maps of Italy, Scale 1:100.000 (Sheets 133, 134, 140, 141, 146, 147,148, 152, 153, 154), Istituto Superiore per la Protezione e la Ricerca Ambientale, 2017, http://193.206.192.231/carta_geologica_italia/default.htm.

[93] ISPRA, Geological Maps of Italy, Scale 1:50.000, Sheet 339, Istituto Superiore per la Protezione e la Ricerca Ambientale, 2017, http://www.isprambiente.gov.it/Media/carg/339_TERAMO/Foglio.html.
P. Montone and M. T. Mariucci, “The new release of the Italian contemporary stress map,” Geophysical Journal International, vol. 205, no. 3, pp. 1525–1531, 2016.

INGV Catalogs and databases website, February 2018 http://istituto.ingv.it/it/archivi-e-banche-dati.

A. Frepoli and A. Amato, “Contemporaneous extension and compression in the Northern Apennines from earthquake faultplane solutions,” Geophysical Journal International, vol. 129, no. 2, pp. 368–388, 1997.

UNMIG Website, Ufficio nazionale minerario per gli idrocarburi e le georisorse (National Mining Office for hydrocarbons and Georesources), Italian Ministry of Economic Development, May 2017 http://unmig.mise.gov.it/.
