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Data integration and favourability maps for exploring geothermal systems in Sicily, southern Italy

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ABSTRACT

This paper describes a data integration tool used to identify potentially undiscovered geothermal resources in the island of Sicily. The factors facilitating the recovery of exploitable geothermal energy were defined, and their spatial correlation established by Geographic Information System (GIS) models.

By prioritizing favourable conditions using an Index Overly method, "favourability" maps of Sicily were obtained. The maps considered both geological and economic aspects, and energy recovery was considered for current technologies. Our approach and maps are useful for developing and planning local or national energy policies including geothermal energy.

1. Introduction

Italy is a geothermal country: the fifth geothermal power producer in the world (Bertani, 2012), the first to produce geothermal electricity at an industrial scale, and a high exploiter of geothermal heat. Geothermal energy provides a significant contribution to renewable energy sources (RES) in Italy; however its future potential still needs to be fully assessed. Along with its high potential, geothermal energy is ideally suited to baseload operations which intermittent resources are unable to provide on an economic basis.

Geothermal energy is seldom considered in energy planning at national and regional levels in Italy and, due to relative lack of specific incentives and rather difficult and lengthy regulations. New geothermal projects, both for demonstration and research, are very difficult to establish in Italy. A fundamental aspect of any energy policy is the certainty around assessment of the nation's natural energy resources, including geothermal. Therefore, a key requirement for further exploiting geothermal energy by increasing the number of projects as well as the variety of uses is to clearly identify and rank resources and opportunities.

This paper provides a practical analytical framework for the systematic capture of information relevant to the assessment of geothermal resources of Sicily, one of the largest islands of southern Italy.

Geothermal assessments follow a broad search for the existing data provided by a number of sources. In Italy, the most relevant existing information regarding geothermal resources includes deep temperature data from oil and gas exploration boreholes as well as physical and chemical information from wells and natural thermal springs.

Data analysed in this study includes geothermal data gathered in the 1980s from an inventory of geothermal resources in Italy (ENEL et al., 1988), which are organized in the National Geothermal Database, and managed by the Italian National Research Council. The database was then complemented with hydrocarbon well the Italian Ministry of Economic Development. In spite of data improvements, information remains unevenly distributed and only covering a small area of Italy. In areas lacking boreholes and thermal springs, other indirect information can be taken into account from geological/volcanological, geochemical and geophysical surveys in order to assess and rank the geothermal potential of areas of interest. This useful, but scattered information regarding underground conditions was retrieved from public reports, scientific papers, and other databases established for various uses.

The approach described here and applied to Sicily is aimed at organizing and integrating subsurface data, and at providing a methodology to establish a hierarchy of geothermal areas based on their potential for conventional power production, where conventional refers to exploitation of moderate to high-enthalpy geothermal resources with natural permeability as opposed to enhanced geothermal systems (EGS). We introduce here the terminology of "favourability" maps, previously adopted by

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similar studies (e.g., Prol-Ledesma, 2000; Coolbaugh et al., 2002; Noorollahi et al., 2007; Yousefi et al., 2010; Tufekci et al., 2010).

By upgrading and updating the last geothermal ranking for Sicily carried out at a national scale in the 1980s (ENEL et al., 1988; Cataldi et al., 1995), we believe that our work is important for the exploration of potentially concealed geothermal resources. Besides mapping known geothermal systems and contributing to reduced exploration risk, we have made the first step towards a more detailed and systematic resource reporting system in Italy. A reporting method is the basis for the portfolio management of geothermal resources and the selection of specific locations for geothermal power production projects.

In this paper we describe our approach, discuss the information used and provide the results obtained in mainland Sicily. Small volcanic islands of Sicily and their geothermal systems are not taken into account in this paper.

2. Data integration for mapping favourable geothermal areas and space data model tools

Geographical Information System (GIS) software provides tools for the spatial analysis of multiple parameters to assist selection of prospective sites, based on pre-defined criteria which we discuss in this paper. The approach of GIS-assisted management of information for exploration purposes has been successfully applied in other fields including regional mineral exploration (Bonham-Carter et al., 1988; Bonham-Carter et al., 1994; Bonham-Carter, 1991; Agterberg, 1989; Katz, 1991; Chung et al., 1992).

In applying GIS tools, the conceptual model plays an important role in the choice of layers that will be involved in making a favourability map, as well as for scoring and weighting the selected layers. The score and weight in each layer are assigned using statistical criteria or estimated on the basis of expert opinion, referred to as "data-driven" or "knowledge-driven" models respectively. In data driven modelling, the layers are combined using approaches such as logistic regression or weight of evidence, while knowledge-driven models usually employ Boolean operators, Index Overlay (IO) and Fuzzy Logic GIS methods (Bonham-Carter et al., 1994).

GIS is often used to define the spatial associations between different thematic information in a specific area in order to define suitable geothermal areas (Prol-Ledesma, 2000; Coolbaugh et al., 2002; Coolbaugh et al., 2005; Noorollahi et al., 2007; Noorollahi et al., 2008; Yousefi et al., 2007; Tufekci et al., 2010 and references therein).

Prol-Ledesma (2000) proposed an evaluation of the results using three different GIS knowledge driven models for siting geothermal wells, for planning further detailed explorations, and for expanding the boundaries of the known field being exploited. Coolbaugh et al. (2002), Coolbaugh and Shevenell (2004) characterised the most suitable locations for geothermal exploration in the Basin and Range province (Nevada, USA), involving GIS spatial analysis for integrating input maps and using a logistic-regression method. Noorollahi et al. (2007, 2008) dealt with GIS knowledge-driven models as a decision-making tool for geothermal exploration and well siting.

Yousefi et al. (2007) produced an assessment of promising geothermal areas in Iran, using logic operator integration methods to combine the input maps. EBA Engineer Consultants Ltd. (2010) produced geothermal favourability maps in the North West Territory of Canada for areas with and without geothermal gradient data. Potential areas in Anatolia (Turkey) have been identified by Tufekci et al. (2010) with a data-driven approach, using both "Index Overlay" and "Weight of Evidence" methods, as well as training points to obtain maps. In this study, these procedures were adapted to account for the specific geological context of Sicily.

To produce favourability maps for conventional geothermal systems in Sicily, we used a GIS model to combine geological, geophysical and geochemical evidence. Although much hydrocarbon well data were taken into account, only a small amount of direct geothermal information, such as geothermal wells and exploitation data, are available in Sicily. We therefore applied a knowledge driven model using, for our knowledge-driven GIS model, the Index Overlay (IO) method, which provides a flexible way to apply a common scale of values, to non-uniform inputs, thus creating an integrated analysis. When information is organized in thematic maps (e.g., raster layers) with diverse value scales and importance, the values can be classified and scored before being overlaid. In addition, each information layer receives a defined weight.

The average score of the resulting map is therefore:

$$\bar{S} = \frac{\sum_{i=1}^{n} S_{ij}}{\sum_{i=1}^{n} W_i} \quad (1)$$

where, S is the weighted score for each pixel, W_i is the weight for the ith thematic map, and S_{ij} is the score for the jth class of the ith thematic map (Bonham-Carter, 1994).

We used the raster calculator to perform a favourability analysis and to develop an integration model making use of the spatial analysis capabilities of the open source software Quantum GIS and GRASS GIS. These tools overlay raster elements using a common spatial resolution, a common origin for the coordinates, and the same number of cells.

3. Geological setting and thermal features of Sicily

Sicily is situated in a complex geodynamic setting of economic interest due to the occurrence of hydrocarbon, sulphur and salt ore deposits. Sicily is a sector of the south verging Apennine-Maghrebian orogenic belt, stacked since Late Oligocene and located along the African-European plate boundary. The "collisional" complex of Sicily (Catalano and D'Argenio, 1982; Catalano, 2004; Roure et al., 1990; Nigro and Renda, 1999; Bello et al., 2000; Monaco and De Guidi, 2006; Accaino et al., 2011) (Fig. 1), is made up of: (i) the "Foreland", cropping out in south-eastern Sicily (Hyblean carbonate platform) and located in the Sicily Channel, (ii) a narrow northwest dipping "Foredeep" and (iii) the "Chain", a complex fold and thrust belt locally more than 20 km thick (Catalano, 2013; Catalano et al., 2013)consisting, from internal to external, of a "European" element (Peloritani Units), a "Tethyan" element (Sicilide Units) and an African element (Maghrebian–Apenninic Units). Peloritani units, part of the European crystalline basement, constitute the northeastern corner of Sicily (Roure et al., 1990).

According to Catalano et al. (2002) and Catalano (2004), the central-western areas of Sicily are made up of an imbricated wedge of Meso-Cenozoic carbonate and siliciclastic rocks resulting from the deformation of different paleo-geographic domains. The tectonic edifice is made up mainly of an 8–9 km thick wedge of Meso-Cenozoic imbricated carbonate platforms (Panormide, Trapanese and Saccense Units). The intermediate structural level consists of a 2–3 km tectonic stack of basinal carbonate thrust sheets (Imerese and Sicanian). These are overlaid by the Oligo-Miocene siliciclastic deposits of the Numidian Basin (Giunta, 1985) and by remnants of the Mesozoic-Tertiary basinal deposits of Sicilide nappe. Neogene-Quaternary syn- and post-tectonic deposits overlay the "collisional" complex.

Active tectonic processes (Monaco et al., 1996; Corti et al., 2006; Visini et al., 2010; Doglioni et al., 2012), have given rise to several geothermal anomalies in this Mediterranean area. The heat