Earth-Science Reviews 169 (2017) 180–201

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Geothermal resources within carbonate reservoirs in western Sicily (Italy): A review

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ARTICLE INFO

Keywords:
Geothermal systems
Carbonate reservoirs
Temperature modeling
Fluid geochemistry
Groundwater flow paths
Sicily
Structural geology
Italy

ABSTRACT

Low-to-medium temperature fluid reservoirs hosted in carbonate rocks are some of the most promising and unknown geothermal systems. Western Sicily is considered a key exploration area. This paper illustrate a multidisciplinary and integrated review of the existing geological, geochemical and geophysical data, mainly acquired during oil and gas explorations since the 1950s, specifically re-analyzed for geothermal purposes, has led to understanding the western Sicily geothermal system as a whole, and to reconstructing the modalities and particular features of the deep fluid circulation within the regional reservoir. The data review suggests the presence of wide groundwater flow systems in the reservoir beneath impervious cap rocks. We identified the main recharge areas, reconstructed the temperature distribution at depth, recognized zones of convective geothermal flow, and depicted the main geothermal fluid flow paths within the reservoir.

We believe that our reconstruction of geothermal fluid circulation is an example of the general behavior of low-to-medium enthalpy geothermal systems hosted in carbonate units on a regional scale. Due to the recent technological developments of binary plants, these systems have become more profitable, not only for geothermal direct uses but also for power production.

1. Introduction

With the exception of active volcanic areas where geothermal reservoirs are generally hosted in permeable volcanic horizons (e.g., Henley and Ellis, 1983; Moeck, 2014), deep carbonate aquifers host what are probably the most important geothermal resources in the world (e.g.; Gousmania et al., 2006; Homuth et al., 2015; Minissale and Duchi, 1988; Mohammadi et al., 2010; Pasquale et al., 2014; Simsek, 2003). Within karstified carbonates, widespread fracture systems generally play an important role in geothermal fluid flows, both as recharge and discharge, such as occurs in the high-enthalpy Larderello-Travale geothermal field in Italy, the most famous high-enthalpy reservoir hosted in carbonates units (e.g., Bertini et al., 2006; Minissale, 1991; Romagnoli et al., 2010; Sani et al., 2016).

The features and behavior of these high temperature systems are uncommon because of the exceptional nature of the heat source, however they are fairly well known due to the great economic interest in these resources, and their longtime exploitation. On the other hand, low-to-medium temperature reservoirs (i.e. below 150 °C) are widespread, but much less understood. These geothermal systems are not strictly related to an individual heat source and thus they can be characterized by much greater extent. Because of the high permeability and storage and drainage capacity of limestones and dolostones, these systems are very favorable targets, also on a regional scale, for exploiting geothermal energy. These geological units often host significant low-to-medium temperature resources, and can be found, for example, in central Europe (Goldscheider et al., 2010 and references therein) and China (Duan et al., 2011).

These kinds of reservoirs are already exploited both for electric power generation and district heating. Table 1 reports a list of applications in central Europe. These low-to-medium temperature applications are still not well developed worldwide because research has been mainly targeted at high temperature systems suitable for producing electricity.

In Italy, low-to-medium temperature systems are underdeveloped, despite the huge geothermal potential (Trumpy et al., 2016; Cataldi et al., 1995). There is only one good example of the use of such carbonate circulating fluids for space heating near the city of Ferrara in northern Italy (Gianbastiani et al., 2014). Mesozoic carbonate rocks constitute the backbone of the Italian peninsula, as well as western Sicily, which is a natural laboratory for the study of these low-to-medium temperature geothermal systems.

We choose western Sicily as a key area because, from a geothermal point of view, Sicily (Fig. 1) is a very stimulating area characterized by

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http://dx.doi.org/10.1016/j.earscirev.2017.04.016
Received 21 December 2016; Received in revised form 21 March 2017; Accepted 29 April 2017
Available online 03 May 2017

Table 1
Example installations in Central Europe currently producing geothermal energy from carbonates (modified after Goldscheider et al., 2010). The Ferrara data from http://geodh.eu/project/ferrara/. NA not applicable, ND no data available.

Location	Production T (°C)	Well depth (m)	Installed capacity (MW)
Altheim (Austria)	106	2300	11.5
Bad Blumau (Austria)	110	2843	7.6
Bad Waltersdorf (Austria)	63	1400	2.3
Ferrara (Italy)	105	1100	14
Geinberg (Austria)	105	2225	7.8
Simbach Braunau (Austria)	81	2200	9.3
Paris Basin (France)	50–85	1400–2000	NA
Riehen (Switzerland)	66	1547	3.6
Erding (Germany)	65	2350	8
Pullach (Germany)	107	3443	6
Riem (Germany)	93	2746	9
Unterföhring (Germany)	86	2512	ND
Unterhaching (Germany)	123	3346	40
Unterschleissheim (Germany)	81	1960	13

the presence of: i) several thermal manifestations at the surface some of which are used for balneotherapy (Alaimo et al., 1978,; Caracausi et al., 2005; Favara et al., 1998; Favara et al., 2001), ii) localized areas of moderately high heat flow (Della Vedova et al., 2001) and iii) thick carbonate units extending from the surface down to great depths (Catalano et al., 2013 and references therein; Montanari et al., 2015).

In the southernmost part of the study area, several hydrocarbon exploration wells, drilled since the 1950s, have provided new geological data to define the geometric relationships between the tectonic units above the limestones and the structural reconstruction at depth (Catalano et al., 1995; Catalano et al., 1998; Catalano et al., 2002). In addition, a great amount of seismic, well-log data (i.e., thermometric, sonic, gamma-ray) and geochemical data have been useful for assessing regional geothermal resources.

According to a geothermal perspective, we reviewed the data that were also integrated with geological surveys, and new geochemical data collected at surface on a large number of thermal springs. The multidisciplinary and integrated work presented here enabled us to decipher the functioning of the regional-scale geothermal system which, in our opinion, could be taken as an example for many other similar geothermal systems worldwide. Our objective is also to stimulate and promote research into these low-to-medium temperature systems, since they represent one of the most readily-exploitable conventional geothermal sources (e.g. Trumpy et al., 2016).

2. Geological and geothermal background

The western Sicily fold and thrust belt connects central and eastern Sicily to the Late Cenozoic Maghrebian submerged chain developing along the African-European plate boundary (Fig. 1). This chain involves a complex architecture of thrust systems resulting from a deformation history which has been active since Oligocene-early Miocene times (e.g. Barreca and Maesano, 2012; Bello et al., 2000; Catalano et al., 1996; Catalano et al., 2002; Catalano et al., 2013; Di Stefano et al., 2015; Lentini et al., 1994; Monaco et al., 1996).

Western Sicily is constituted at depth by Mesozoic carbonate platforms and their clastic covers, which are Cretaceous to Miocene in age. From a structural point of view this portion of the chain is characterized in the northern sector by a tectonic stack of units up to 12 km thick (Catalano et al., 2002) and by a less deformed southern sector, but still affected by shortening (Barreca et al., 2014). Consequently, in the northern portion of western Sicily, carbonate platform units and covers extensively crop out as they are involved in a regional structural high, whereas, to the southeast, these units are encountered only in deep wells drilled for oil exploration (Figs. 1, 2 and 3).

The tectono-stratigraphic assemblages, now exposed in the western Sicily chain, are derived mainly from carbonate platforms and intervening basins lying on a sector of the Mesozoic African margin (Catalano et al., 1996). Various stratigraphic and tectonic studies in Sicily have confirmed that these Paleozoic-Mesozoic to Miocene units represent the sedimentary cover of distinct paleogeographic domains (locally named Imerese, Sicanian and Pre-Panormide, Panormide, Trapanese, Saccense and Iblean-Pelagian). These domains belonged to the Pelagian/African continental margin and to the “Tethyan” ocean branch prior to the onset of the deformation (Catalano et al., 2000 and reference therein; Bernoulli, 2001). Clastic-terrigenous Miocene-Pleistocene rocks deposited in foreland and wedge-top basins during the deformation of the continental margin domains cover these carbonate rocks, acting as a cap rock for the geothermal system at depth. For the stratigraphic characteristics of the different units exposed in Sicily, see Fig. 2 in Montanari et al., 2015.

These units are assumed to lie on top of the possibly Pan-African crystalline basement (Vai, 2001; Finetti et al., 2005; Accaino et al., 2011).

Western Sicily is bordered to the south by the Sicily Channel (Fig. 1) connecting the western and eastern parts of the Mediterranean Sea (Corti et al., 2006; Belguith et al., 2013 and references therein). This is a tectonically complex area where different unrelated geodynamic processes such as rifting and mountain building interact at the same time. In the Sicily Channel (Fig. 1) magmatism has been active since the Miocene age (Civetta et al., 1998) but is mainly associated with Pliocene-Pleistocene rifting (Corti et al., 2006). The magmatism is concentrated mainly on the Pantelleria and Linosa volcanic islands (e.g. Avanzinelli et al., 2013). In addition, in 1831 on the Graham Bank the submarine volcano Empedocles gave rise to the ephemeral isle of Ferdinandea located between the isle of Pantelleria and Sciacca on the southern coast of western Sicily (Fig. 1). Many volcanic centers are also present in the Sicily Channel such as the Pliocene-Pleistocene Anfitrite and Tetide (Fig. 1), located in the Adventure plateau (Civile et al., 2016). The Sicily Channel is accordingly characterized by heat flow anomalies with maximum values on Pantelleria (Della Vedova et al., 2001). We have very little information on the Mediterranean sector between Pantelleria and Sciacca, however it is likely that the whole area is affected by a thermal anomaly and may contain unexplored geothermal systems connected with those in Sicily (e.g. Capaccioni et al., 2011).

Regarding the thermal springs emerging in western Sicily (Fig. 2), some are described in classical antiquity (e.g. the ancient Imera near the present Termini Imerese) and, around “Terme Segestane” a magnificent Greek temple highlighting the important role of thermal springs during the Greek domination of Sicily. Most thermal springs discharge along the seashore above or below sea level (Catalano et al., 1988), or at low elevations near the coast. Others emerge inland at relatively higher elevations, but always at the edges of the Mesozoic carbonate outcrops (Alaimo et al., 1978), near their contacts with terrigenous cover units. In addition to the evidence provided by the thermal springs, many measurements within oil and gas wells showed a positive heat flux (Fig. 1c) and temperature anomalies at depth along the coastal area, especially between Marsala and Agrigento (Cataldi et al., 1995; Fancelli et al., 1991).

A further element contributing to the geothermal favourability and potential (Trumpy et al., 2015; Trumpy et al., 2016) of the region, is the fact that the tectonic deformation in western Sicily is still quite active (e.g. Angelica et al., 2013; Barreca et al., 2014; Farolfi and Del Ventisette, 2015), as evidenced by historical and instrumental seismicity (Lavecchia et al., 2007). Southwestern Sicily is characterized by active shortening as dramatically testified by the 5.9 magnitude destructive earthquake occurring in the Belice valley in 1968 (Monaco et al., 1996). Archaeoseismological studies also indicate that the ancient Greek colony of Selinunte located in between Mazara del