Reservoir characterization for the completion of the geothermal district heating system in Grado (NE Italy)

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ABSTRACT

As part of the *Grado geothermal Project - Phase 2*, an integrated gravity and seismic prospecting was recently conducted in downtown Grado Island (North Eastern Italy) and in the surrounding lagoon. The aim of this study was to characterize the carbonatic geothermal reservoir and to locate the second well of the geothermal doublet, planned to feed the district-heating system for public buildings on the island. The joint interpretation of the new seismic and gravity data, integrated with the previous Grado-1 site-survey and well data, allowed us to define the major structural features characterizing the carbonatic geothermal reservoir. This preliminary characterization was integrated into a 3-D thermo-fluid dynamic numerical modelling to evaluate the coupling of the production/re-injection wells with the geothermal reservoir and to assess the geothermal potential and the sustainability of the production.

1. INTRODUCTION

The structural highs of the Mesozoic carbonate platform, buried beneath the lower Veneto and Friuli plains (NE Italy) and the north-Adriatic coastal areas, were characterized a few decades ago on the base of the available seismic, gravity and magnetic data calibrated using borehole data of hydro-carbon exploration wells drilled on some structural culminations (e.g., AGIP, 1977, 1986, 1994; Cassano et al., 1986; Cati et al., 1987; Casero et al., 1990; Fantoni et al., 2002; Venturini, 2002; Fantoni et al., 2003; Nicolich et al., 2004). The Cesarolo-1 AGIP well in the Lignano-Cesarolo structural culmination, together with a large number of geothermal water wells of 500-600 m drilled in the upper sedimentary cover of the north-Adriatic coastal area (Barnaba, 2001; Grassi, 1994) and the new Grado-1 exploration borehole, reaching 1110 m of total depth (Della Vedova et al., 2008a,b; Cimolino et al., 2010), allowed us to substantiate the conceptual model of heat transfer at depth by Bellani et al. (1994) and by Calore et al. (1995) supporting the geothermal anomaly in the area. Heat transfer by advection mainly occurs in the permeable and fractured carbonates of the buried outer Dinaric front thrust interested by anti-Dinaric strike-slip fault systems (Cimolino et al., 2010). Heat transfer by conduction prevails trough the low-permeability Cenozoic clastic deposits of the cover (Plio-Quaternary sequences, Lower Miocene terrigenous deposits, Oligo-Miocene Alpine Molasse, and Eocene Dinaric flysch).

The first phase of the *Grado Geothermal Project*, conducted by the Regione Autonoma Friuli Venezia-Giulia, Servizio Geologico, and supported by European Commission structural funding 2000-2006, had the purpose: (i) to verify the heat-transfer conceptual model in the area, (ii) to assess the geothermal potential of carbonatic aquifer and, finally, (iii) to evaluate the feasibility of a district heating system, sustained by a production well and a re-injection well (Della Vedova et al., 2008a,b). The Grado-1 well was drilled in 2008 on the sand beach at the westernmost end of Grado Is., at about 100 m from the shoreline. The drilling phase included well logging and pumping tests (Della Vedova et al., 2008a,b; Cimolino et al., 2010). The stratigraphic record shows 290 m of Plio-Pleistocene sediments, followed by 250 m of Neogene terrigenous successions and 50-60 m of Paleogene turbidites (Eocene flysch). The top of the Paleogene Nummulitic limestone shelf was encountered at 616.5 m depth. The K-T boundary, found at 1007 m depth, is marked by a sudden transition to Mesozoic (Upper Cretaceous) limestones, including a sedimentation *hiatus* and clear evidence of sub-aerial exposure and karstic phenomena (Cimolino et al., 2010). The well logs and the core data show that the Paleogene and the upper Cretaceous limestones are interested by open fractures and vugs containing salty warm waters with a temperature of 42-45 °C and an artesian flow rate of 0.025 m^3/s with a pressure of 280 kPa at well-head.

Given the positive results and the favourable conditions for the utilisation of the low-temperature geothermal resources, the European Commission endorsed the second phase of the Grado Geothermal Project funding the Grado Municipality (POR-FESR 2007-2013 funding Program) to extend eastwards the geophysical survey, drill the second borehole and complete the surface distribution network. The main objective of the new geophysical survey was to investigate in detail the geometry, structures and physical properties of the carbonatic geothermal reservoir and cap-rock units in the surrounding area of the Grado-1 well. The study is aimed at reconstructing the main features of the Paleogene-Upper Cretaceous limestones reservoir and identifying the fault zones and thrust units that represent favourable hydraulic conditions for the hydrothermal circulation. The optimal performance of the geothermal doublet would require the average hydraulic transmissivity between the two well bottoms to be not too high, to avoid a hydraulic and thermal shortcut, and not too low, with the effect to preclude the closure of the hydrogeologic circulation system. The thrust and fault systems (still active) favour the fluids circulation and therefore their knowledge is crucial to characterize the geothermal reservoir and to locate the second borehole. For this purpose, we acquired an integrated surface and bore-hole seismic and gravimetric survey. In this paper we present the results of multichannel seismic reflection profiling combined with an accurate gravity investigation over a broader area. The borehole multi-offset vertical seismic profile (VSP), planned to provide a strong link between the Grado-1 well logs and the surface reflection seismic acquisitions, including a detailed seismic information in the well area and eastwards, are presented more in detail in a companion paper in this volume (Poletto et al., 2013).

2. GEOPHYSICAL SURVEY

2.1 Surface reflection seismic

An accurate scouting was performed to plan the surface reflection seismic acquisition, to get the best signal to noise ratio and to minimize the off-line deviations. Walk-away tests were useful to evaluate seismic source penetration/resolution power and to select the optimal parameters and geometries for the seismic acquisition with a target reflector assumed at depths ranging between 600 – 1200 m (Petronio et al., 2012). The seismic reflection survey is composed by three new lines: G11, G12 and G13, that are 2.4, 2.6 and 2.4 km long, respectively. Figure 1 shows the location map. We adopted a fixed-spread configuration with a trace interval of 10 m and six geophones (10 Hz natural frequency) per station, placed in a 10 m linear array, and 20 m shot interval. The source for the G13 line was a seismic vibrator (IVI Minivib T-2500) operated with 11.12 kN peak force (2500 lbs), 18 s linear upsweep (in the frequency range 8-200 Hz).

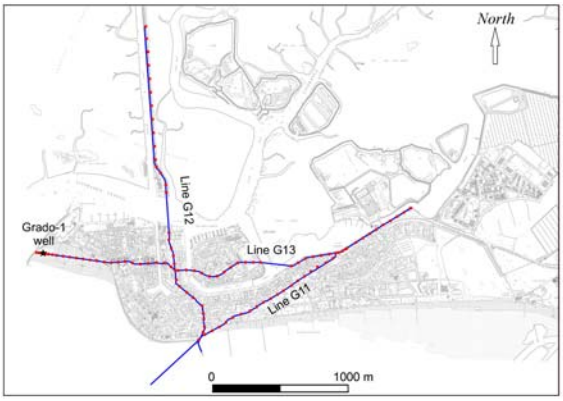


Figure 1: Location map of the surface seismic reflection (blue lines) and of the gravity stations (red points) along the seismic lines. The Grado-1 well (black star) is also indicated.

The recording parameters included 1 ms sampling rate and 22 s of recording time. Line G11 and line G12 were shot with an accelerated dropping weight (Hydrapulse source), recording from 1 to 4 energizations per point, with 4 s listening time. Multichannel hydrophone bay-cable and offshore shots by airgun - 0,0013 m^3 (80 cubic inches), 12 MPa - were utilized to extend the onshore lines, and to increase the subsurface coverage and illumination at the end of the offshore line G11. Onshore shooting was performed during the night to limit the impact of the cultural noise on the data. In the most sensitive areas a vibration monitoring was accomplished. Seismic data were recorded by a Summit DMT telemetric system. A shot-by-shot quality control was performed during the whole seismic survey. The signal-to-noise ratio in the raw field data files is good and allows a confident identification of reflections in most of the raw-field data files. Common shot gathers show a strong reflector at about 320-340 ms two way time (twt), corresponding to the top of the pre-Plio-Quaternary terrigenous sediments. The top of the Paleogene limestone (upper part of the geothermal reservoir) is clearly observable for most part of the data at about 560-580 ms twt. Data were processed with a standard sequence, including post-stack migration and time to depth conversion. The velocities obtained by the Grado-1 well near-offset VSP data (Poletto et al., 2013) were used to calibrate the time to depth conversion of surface seismic reflection data.

2.2 Borehole seismic survey

Four vertical seismic profiles (VSP) were acquired with different offsets in the Grado-1 well with the goals to provide time-to-depth conversion, log calibration, reflection characterization, high-resolution seismic information in depth and to measure the lateral variations of the physical rock properties in the geothermal reservoir. This provides an integrated interpretation with surface seismic and well data. A detailed description of the results of the seismic borehole survey is presented in a paper contained in this volume (Poletto et al., 2013).

2.3 Gravity data

A focused gravity investigation was conducted by the Trieste University starting from 1987 (Della Vedova et al., 1988) with a collection of a consistent dataset, tied to the gravity stations belonging to the Friuli microgravity network linked to the absolute gravity station in Trieste (Marson et al., 1978). The same instrument *LaCoste&Romberg mod. D,* equipped with a feedback system to improve measurement quality, was used in the new survey. A total of 121 new gravity stations were acquired in the broad Grado area surrounding the reservoir structures, to increase the spatial coverage of the dataset collected in the eighties. Figure 2 shows the map with all the available gravity stations on Grado Is. and adjacent lagoon.

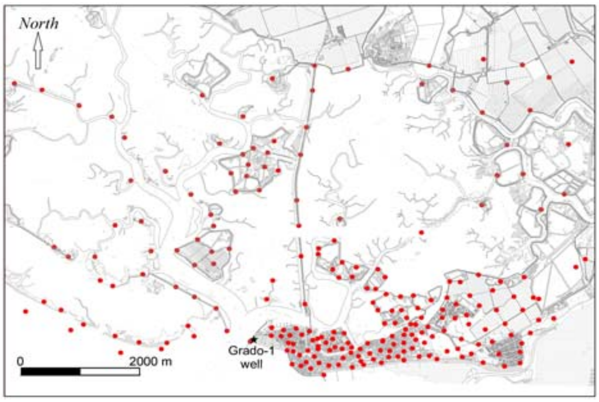


Figure 2: Gravity survey position map: all measurement stations acquired starting from 1987 are indicated by red points.

Additional 108 gravity measurements were collected along the three seismic lines (Fig. 1) with an average space interval of 60 m. In the field data acquisition, the loop method was adopted to check both the drift term and the closure errors. These values were always maintained less than ±0.005 mGal/h and ±0.005 mGal, respectively. The topographic locations were established with GPS Real Time Kinematics method and processed using the *Verto3k* software. The old and new gravity data were processed according to the standard procedures (Hinze et al., 2005): the theoretical g values were computed using the GRS80 formula, the Free Air correction using the formula that takes into account also the station latitude, the Bouguer correction with the Bullard B term, and the terrain correction, up to a radius of 10 km, with the right prism formula (Banerjee et al., 1977). The corrections were computed using a mass density of 2400 kg/m^3. Additional corrections were applied to compensate building effects for the measurements located downtown Grado city.

3. GEOPHYSICAL DATA RESULTS

Surface reflection and borehole seismic data were jointly interpreted starting from Grado-1 borehole stratigraphy. The interface between the terrigenous cap-rock sediments (Paleogene flysch) and the Paleogene carbonatic geothermal reservoir is clearly detectable on the seismic sections. Figure 3a shows the line G13; the interpretation of the principal horizons and discontinuities is indicated in Figure 3b.

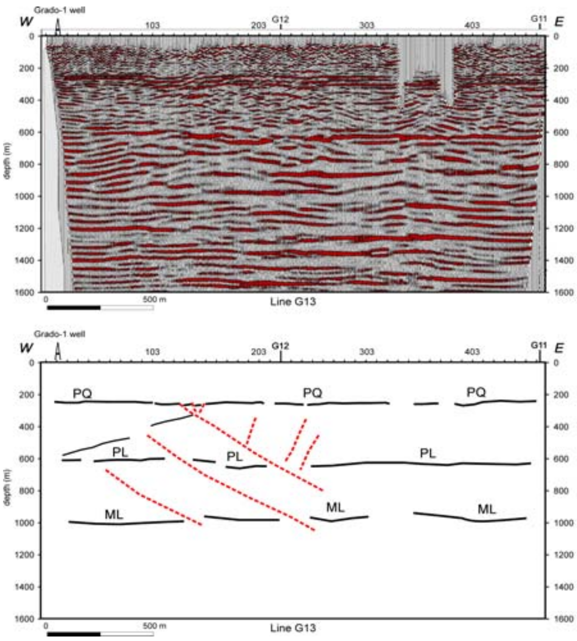


Figure 3: Multichannel seismic Line G13, depth section (a) and interpreted section (b). PQ (Plio-Quaternary), PL (top of Paleogene limestone), ML (top of Mesozoic limestone).

The top of geothermal reservoir is gently deepening (3-4°) to the North, as evidenced by line G12 (Figs. 4a and 4b) and confirmed by the Bouguer anomaly gradient of 1.1 mGal/km.

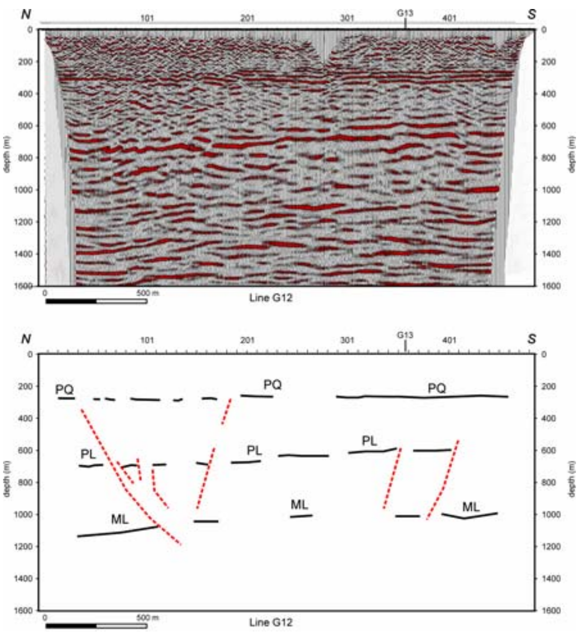


Figure 4: Multichannel seismic Line G12 - depth section (a) and interpreted section (b). PQ (Plio-Quaternary), PL (top of Paleogene limestone), ML (top of Mesozoic limestone).

The surface seismic images were integrated by VSP near offset and multi-offset results (Fig. 5), which provide robust data to analyse formation properties (Poletto et al., 2013). In the studied area the Paleogene platform depth ranges from 600 to 750 m with a good lateral continuity.

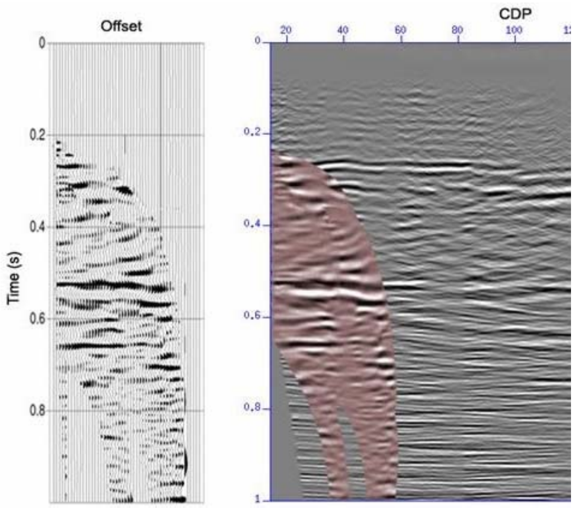


Figure 5: Multi-offset VSP data (left side) and superposition with surface seismic data (right side), easternmost part of G13 line.

Locally some abrupt discontinuities of the seismic signal were interpreted as faults with relatively modest vertical displacement.

The horizontal gradient of the Bouguer gravity anomaly (Cordell, 1979) was used to map structural lineations and to perform a 3D characterization, starting from 2D information given by the seismic lines. The axis of the major gravity anomalies (Fig. 6) likely correspond to the segments of the frontal Dinaric thrust system, NW-SE oriented, which are bounded by orthogonal strike-slip transfer faults.

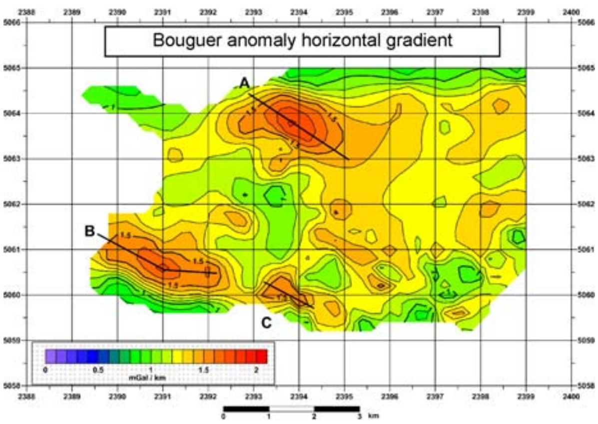


Figure 6: Bouguer anomaly horizontal gradient map. The axis of major gravity anomalies are indicated by black line and labelled (A, B and C).

The joint data interpretation allows to recognize the fractured area that represents favourable geologic conditions for drilling and provides the most informative image of the lateral heterogeneity in the mass distribution at the depth of the reservoir and cap rock units, beneath the Grado Island. These structural features (Fig. 6) are interpreted as a faulted segments of the distal Dinaric thrust front (Cimolino et al., 2010). The Grado-1 well is located to the SW of C gravity anomaly, whereas Grado-2 borehole will be drill to the NE of the same anomaly.

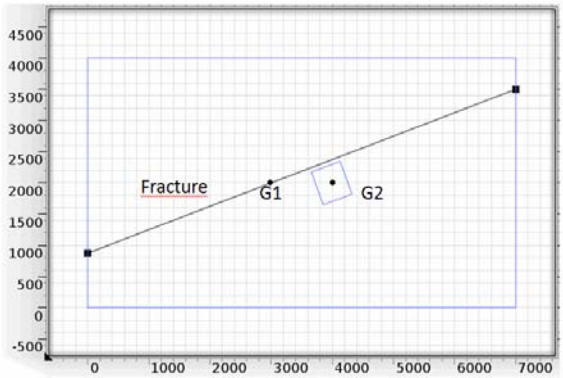
4 THERMO FLUID-DYNAMIC MODELLING

We performed numerical thermo-fluid dynamic simulations (COMSOL 4.3a), as a support tool for the drilling of the second well and for the final design of the district heating system (Marcon, 2012). We evaluated and compared the performance of the geothermal doublet, also by inverting the flow between the production and re-injection wells. In this perspective the available geological and geophysical data were integrated into a simple conceptual model: (i) to assess the influence of the heterogeneities in the physical properties and the impact of the different boundary conditions on the model of the pressure and temperature fields, (ii) to preliminarily assess the reservoir energy production potential, and (iii) to evaluate the response to production and re-injection of fluids over different time periods.

To make a realistic estimate of the reservoir energy production potential and to monitor reliable scenarios of the production capacity over time, these simulations will be adequately calibrated using the results of the logging, pumping and interference tests planned for late 2013, after the completion of the second borehole (Den Boer, 2008; Wong et al., 2012). The simulation domain of the confined fractured aquifer starts from the top of the carbonatic aquifer at about 600 m depth (Fig. 7). The horizontal model dimensions are 7 x 4 km and the two vertical wells are located 1 km apart; the vertical model dimension is 2.9 km. The capping formations were assumed impermeable and not included in the model; the production and the re-injection wells enter into the geothermal reservoir 500 and 600 m, respectively.

The heat flow entering at the base of the model was calibrated using the Grado-1 well temperature data (Fig. 8), assuming a constant heat flow (45 mW/m^2) through time. The equilibrium geotherm is monitored by two temperature sensors (Pt 100) cemented at 450 and 695 m depth, respectively, on the outer steel casing.

The open and diffuse network of fractures, represented by the active Dinaric and Anti-Dinaric thrust and fault systems interesting the carbonatic reservoir, is the most crucial feature responsible for the onset and duration of the fluid circulation in the hydrothermal system. The fault system was conceptually simulated by an equivalent single vertical fault passing through the westernmost well (as encountered during drilling and confirmed by the seismic and gravity results) and assumed to be at an arbitrary distance of about 350 m from the second borehole (G-2). The unknown hydraulic resistance of the formation interposed between the reinjection borehole and the major fault directly controls the hydraulic shortcut between the two wells and substantially determines the heat exchange rate between rocks and moving fluids in the aquifer. The permeability parameter of this prism centered on the reinjection well requires to be calibrated with pumping and hydraulic interference test measurements. The values used for the physical properties of rocks, fluids and fracture and for the hydraulic and thermal boundary conditions are summarized in Table 1. In these initial tests, the equilibrium steady state temperatures at 1.5 and 3.5 km depth were estimated to be 50-55 °C and 74-78 °C, respectively, on the base of the experimental temperature measurements in Grado-1 well (Fig. 8) and of the preliminary geochemical analyses of the geothermal fluids (Petrini, pers. communication).



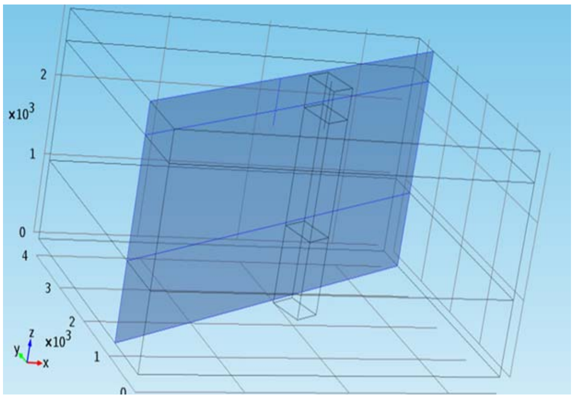


Figure 7: Plane (top) and 3-D view (bottom) of the simulation volume. The two wells G-1 and G-2 are in the central part of the domain; the diagonal plane indicates the fracture location. The prism centered on the re-injection borehole (G-2) represents the aquifer portion of unknown permeability between the well and the fracture.

Transient simulations were obtained by assuming a geothermal water production of about 0.030 m^3/s and a difference of temperature between production and re-injection fluids of 20 °C.

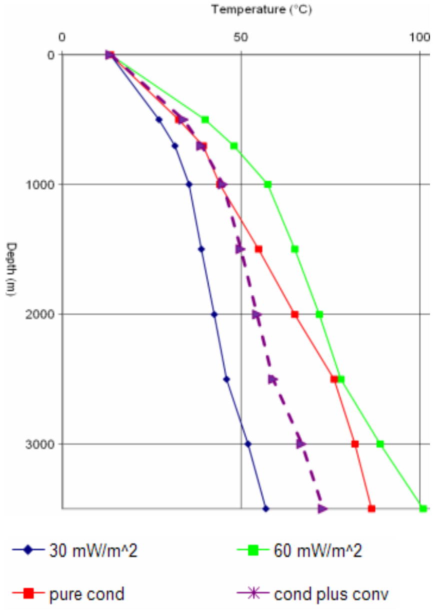


Figure 8: Sensitivity analysis and calibration of the vertical temperature distribution, with different basal heat flow inputs (30 and 60 mW/m^2), assuming pure conduction (red line), or conduction plus convection (shown with purple dashed line), as supported by the experimental measurements down to 1100 m.

Physical Property	**Assumed value**
Water dynamic viscosity	0,001 Pa·s
Water heat capacity	3925 J/kg/°C
Water density	1025 kg/m^3
Matrix porosity	0,05
Fracture porosity	0,3
Reservoir heat capacity	950 J/kg/°C
Reservoir rock density	2700 kg/m^3
Reservoir rock permeability	1 mD (10^{-15} m^2)
Vertical prism permeability	100 mD
Fracture permeability	500-1000 mD
Fracture thickness	0,05 m
Boundary Condition	
Upper boundary T condition	39 °C
Re-injected fluid temperature	25 °C
Basal heat flux	45 mW/m^2
Undisturbed water pressure	300 kPa
Pumping/injection rate	0,030 m^3/s
Simulation time period	1,5·10^9 s (50 a)

Table 1: Values for the physical properties of various materials and for the hydraulic and thermal boundary conditions used in the thermo-fluid dynamic modelling.

These values correspond to 2.4 MWt nominal power production potential, which would imply about 4.000 MWh of thermal energy over a period of six months at maximum load. These simulations allowed us to evaluate the strong influence of the fracture network permeability (Wong et al., 2012), for which we used values between 500 and 1000 mD, and to preliminarily assess the hydraulic and thermal sustainability of the district heating system over 50 years. Figures 9 and 10 show the steady-state pressure field around the pumping and re-injection wells. The white lines represent the flow lines, the black arrows are the flow vectors within the fracture.

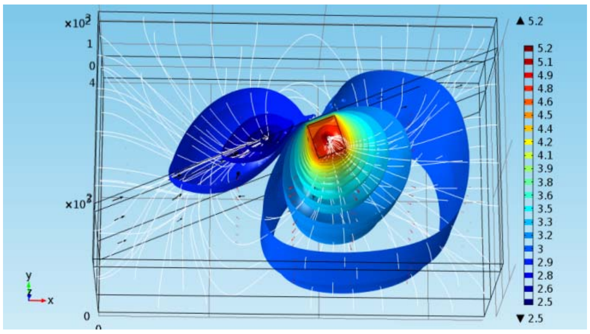


Figure 9: Axonometric vertical view of the steady-state pressure field around the production and re-injection wells.

The red arrows in Fig. 9 indicate the flow vectors in the compact calcareous formation. The colored envelops around the production and re-injection wells represent the iso-pressure surfaces, plotted with values in bars, according to the palette to the right. This simulation shows as the fracture acts as a preferential channel draining water also from the highly resistive carbonatic formation (Wong et al., 2012).

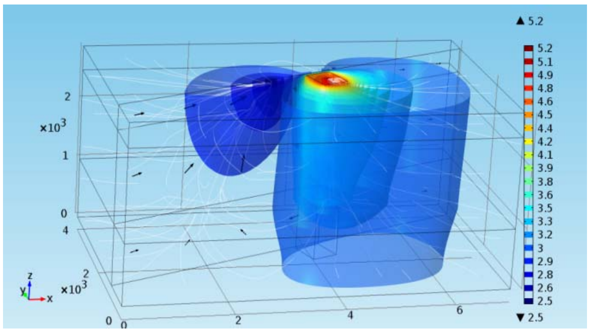


Figure 10. Axonometric lateral view of the steady-state pressure field around the production and re-injection wells.

The planned down-hole investigations and cross-well interference tests shall allow to properly realize the distribution network and to choose the most adequate management parameters in order to guarantee an economic and sustainable use of the Grado geothermal resource.

5. CONCLUSION

The seismic and gravity surveys carried out in the Grado Is. and surrounding lagoon constitute a fundamental tool for the potential assessment of the Grado geothermal resource, and for the completion of the district-heating system planned for the public buildings of the city. The integration of the new geophysical data with the previous Grado-1 site-survey and well data allowed us to define the major structural features characterizing the confined carbonatic reservoir and to locate the second well of the geothermal doublet at the crossing between G12 and G13 seismic lines.

The results highlight the main features of the geothermal reservoir and of the cap rock formations belonging to the outer Dinaric thrust front (Cimolino et al., 2010). The open and diffused network of fractures and strike-slip transfer faults with anti-Dinaric direction (NE-SW) is the most crucial feature responsible for the onset and duration of the fluid circulation in the hydrothermal system.

This information was used to constrain the conceptual model, physical properties and boundary conditions of a preliminary 3-D thermo-fluid dynamic numerical modelling, including the presence of a fracture system. The simulations allowed us to evaluate the coupling of the production/re-injection wells and the strong influence of the permeability of the fracture network, that acts as a preferential drain, and to preliminarily assess the geothermal potential and the long-term sustainability of the district heating system.

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