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Geothermal Potential to Meet Heat Demand in Magallanes, Chilean Patagonia

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ABSTRACT

Based on previously gathered data during oil and gas exploration by the hydrocarbon industry as well as the heat demand, the aim of this work is to assess the potential of developing deep geothermal energy in the Magallanes basin for district heating purposes. Two main options are evaluated for deep geothermal energy recovery: (1) Geothermal Doublet; and (2) Deep Borehole Heat Exchanger (DBHE). In both cases a district network is considered due to its wide range of long-lasting advantages. The good permeability (~250 mD) of a 15 m thick sandstone sequence in the Springhill Formation of the Magallanes basin shows promising economic feasibility for a geothermal doublet development from a hydrothermal system. The formation temperature ranges from 105 to 147 ˚C at depths of 2,420 to 2,900 m. The latter in conjunction with a favourable vertical thermal property distribution of rocks seem also economically reasonable for the development of DBHE. As the Chilean National Oil Company (ENAP) has been exploring and exploiting oil and gas for more than six decades, 40% of the wells are no longer hydrocarbon producers. Therefore, rehabilitation of no longer producing oil and gas wells as deep geothermal injection and/or production wells should reduce significatively the initial investment of the systems. Based on heat demand, for medium size urbanised areas geothermal doublets are preferred. However, for small villages and boundary crossing points the DBHE are preferred.

1. INTRODUCTION

The cities and towns of the Magallanes region have the highest thermal energy consumption of Chile (Ortega, 2017). For more than six decades heating has been provided by oil and gas reserves available in the region. Nevertheless, the decrease in oil and gas reserves and the global context of energy transition to clean and renewable resources create the need of looking for clean, renewable, sustainable and resilient energy sources for heating (SUBDERE, 2012). The large geological and geophysical database that resulted from the oil and gas exploration/exploitation by The National Oil Company (ENAP) along with the global successful and promising heat transition to geothermal (e.g. Van Wees et al., 2017) encourage to carry out a deep geothermal assessment for heating purposes in the study region.

To assess the potential of supplying heating with geothermal, two concepts of deep geothermal utilization are used: Doublets and Deep Borehole Heat Exchangers (DBHE) (LIAG, 2017 and references therein). Deep geothermal concepts consider coupling a geothermal heat source with a district network, due to its excellent compatibility and wide range of positive impacts (IRENA, 2017). Therefore, the solution must supply the energy consumption and fit a district heating network. The concepts of geothermal use depend on the available resource and the energy demand of the analysed locations. If there is not enough and/or good quality geological data, the cities or towns situated in the Magallanes region are not analysed in this approach. For this reason, large cities such as Punta Arenas (capital city) are not analysed.

The methodological approach includes an assessment of implementing a deep utilization concept in the areas of interest, according to geothermal resource and heat demand in the area under investigation. To constrain the geothermal resource, an exhaustive analysis of the geological dataset provided by ENAP is considered. The latter includes: (1) Litho-stratigraphy analysis to establish geometry and depth of the aquifer, (2) Hydro-stratigraphy analysis to establish permeability and porosity structure of the aquifer, (3) Thermo-stratigraphy analysis to establish formation temperature, geothermal gradient and thermal properties. The litho-stratigraphy analysis is complemented with self-potential well logs analyses. To establish the scope of deep geothermal utilization concepts, successful case studies are used (e.g, Agemar et al., 2014). In addition, the management experience of the Waren Müritz Stadtwerke (geothermal doublet) and the Prenzlau Stadtwerke (DBHE) in the North German Basin (NGB) is taking into account to improve the assessment.

Due to the strikingly similar geological setting of the different sites of interest (Biddle et al., 1986; González et al. 1998; Schwarz et al., 2011) and the ample dataset in the Punta Delgada village case study, the latter is chosen to show the methodology. The results obtained and the favourable conditions for deep geothermal energy development encourage to carry out more detailed analytical or numerical analyses to quantify the geothermal resource assessment in the most promising locations.

2. REGIONAL GEOLOGICAL SETTING

In this section the stratigraphic sequence is presented in the context of geological evolution and depositional environment of the Magallanes basin (Figure 1). The basin is in the southernmost part of South America, between 47˚-55 ˚S latitude. The basin covers about 200,000 km^2 and has an NNW-SSE elongated geometry, with a maximum width of 370 km and length of 700 km (Biddle et al., 1986).

2.1 Geological evolution and stratigraphic sequences

The Magallanes basin stratigraphic sequence is divided in two provinces regarding stratigraphy and deformation pattern: (1) the deformed province in the west, and (2) the platform province in the east (Natland et al., 1974). In this work, we focus on stratigraphy of the platform province, where most of the oil and gas wells were drilled (Figure 1). The nomenclature of geological units in the platform province is informal for most of the cases. The metamorphic basement of the stratigraphic sequence was generated in the Upper Carboniferous to Lower Triassic period as an accretionary prism along the Pacific margin of Gondwana (Hervé et al., 1981; Forsythe and Mpodozis, 1983; Cunningham, 1995; Kohn, et al., 1995). At the base of the Magallanes basin in the platform province, the metamorphic basement is composed mainly of granodioritic Gneiss (Natland, 1974).

From Upper Triassic until Holocene, the evolution of the Magallanes basin is divided into three stages, which control geological environment and consequently lithology of the stratigraphic sequences (Biddle et al., 1986). These stages and its related stratigraphic sequences are presented below:

2.1.1 Upper Triassic – Upper Jurassic: Tectonic extension and rifting

During the upper Triassic to lower Jurassic period, a tectonic extension started south of Gondwana, which triggered NNW – SSE graben and hemi-graben series. Afterwards, during the Middle Jurassic to Upper Jurassic period a rift was developed, which ended with the Gondwana breakup (Gust et al., 1985). In this context, the Tuff Series was deposited, which is composed of pyroclastic sequences, volcanic acid rocks, and sedimentary rocks interbedded (Thomas, 1949). This acid volcanism was triggered by the cortical crust fusion, due to its thinning in the rift stage (Prieto, 1993). The end of the rifting stage coincides with the Green Rocks Marginal Basin developing, which is characterized by passive boundaries and thermal subsidence (Katz, 1972; Dalziel, 1981).

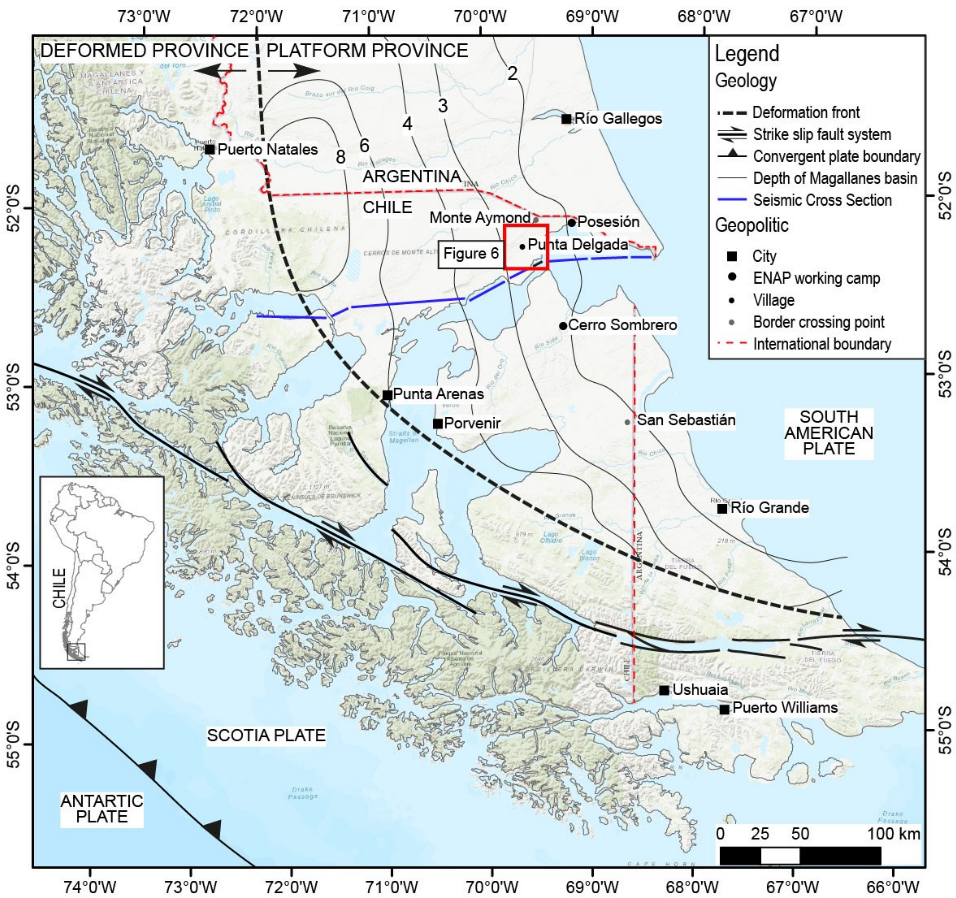

Figure 1: Regional structural setting of the Magallanes basin. Regional scale structures and Depth of the Magallanes basin from (Ghiglione et al., 2010).

2.1.2 Lower Cretaceous: Thermal subsidence

The thermal subsidence, which started in the Lower Cretaceous period, produced a large marine transgression that deposited hundreds of meters of clastic marine sedimentary rocks overlying the Tuff Series (Biddle et al., 1986). The Springhill Formation is at the base of the marine sedimentary sequence and overlies the Tuff Series or metamorphic basement in unconformity contact (Thomas, 1949). The Springhill Formation represents a transgressive succession composed of fluvial, coastal plain, estuarine and open marine siliciclastic deposits (Biddle et al., 1986).

Five stratigraphic sequences overlie the Springhill Formation from bottom to top: Strata with Favrella steinmanni Formation, Shale with Ftanitas strata set, Margas Formation, Greenish grey Shale strata set and Sandy shale strata set (Natland, 1974). These sequences were deposited in shallow to deep marine platform environments and are composed of shale, mudstone, siltstone, marges and limestone (Mordojovic, 1951; Cecioni, 1955).

2.1.3 Upper Cretaceous - Holocene: Foreland

During Upper Cretaceous, a compressive tectonic setting was developed west of the Magallanes basin. This compressive setting stopped the thermal subsidence, triggered the Magallanes fold and thrust belt developed in the west, and the Magallanes foreland basin in the east (Biddle et al., 1986). The main source of sediments came from the uplifted terrains of the Magallanes fold and thrust belt (Natland et al., 1974).

The marine stratigraphic sequence, deposited in the foreland basin tectonic setting from Upper Cretaceous to Miocene, is composed of four sequences from bottom to top: Glauconitic Zone strata set, Bahía Inútil group, Clayly Sandstone strata set and Brush Lake Formation (Natland et al., 1974). These sequences were deposited in shallow to intermediate depth marine platform environments and are mainly composed of sandstone, shale and mudstone (Mordojovic, 1951; Brawick, 1955; Cañón, 1968).

On top of the sequence of sedimentary rock, the Miocene Fílaret Formation marks a transition from marine to continental environment. The Fílaret Formation is composed of sandstone, shale, and carbon layers (Cortés, 1963). On top of the sedimentary stratigraphic sequence is the volcanic Upper Miocene – Lower Pliocene Palomares Fomation (Natland et al., 1974). Finally, Pleistocene glacial sediments cover most of the Magallanes basin (Natland et al., 1974).

2.2 Structural setting

The basement of the Magallanes basin in the platform province has a flat shape tilted to the southwest (Figure 2). The basin is limited to the southwest by basement rocks, which are raised and deformed by the compression in the Magallanes fold and thrust belt, which are part of the Patagonian Andes (Ramos, 1988).

In the platform province, it is possible to divide the structural setting into two main episodes, with implications in the generation or reactivation of fault systems (Biddle et al., 1986). The first one is the rifting setting from Triassic to Upper Jurassic, which led to normal faulting and basin formation. This tectonic setting is related to extensional regime in the south of Gondwana (Gust, 1985). A second stage of reactivation at the Cretaceous Paleogene limit resulted in normal faulting, which affected Cretaceous strata and often followed Jurassic faults (González et al., 1998).

Later on, the region was affected by middle Eocene - Oligocene strike-slip and compressional deformation in the southwest, triggered by the fast left-lateral motion between South America and Antarctica since 50 Ma (Livermore et al., 2005), and the rapid convergence subduction of the Farallon plate beneath South America (Ramos, 2005). This tectonic setting drove the onset deformation along the Magallanes–Fagnano strike-slip fault zone (Klepeis, 1994; Torres Carbonell et al., 2008).

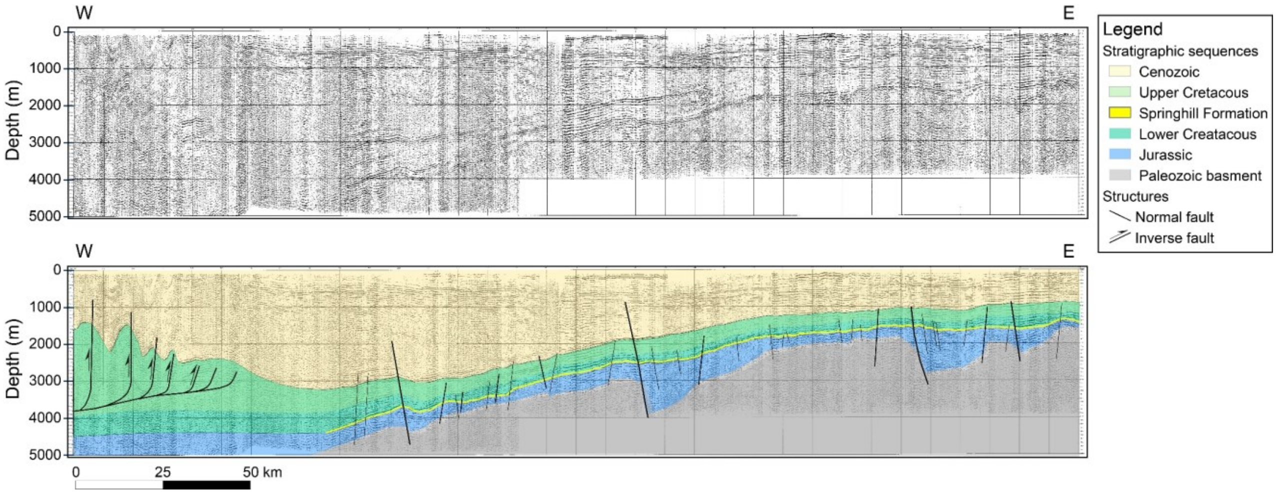

Figure 2: 2D Seismic cross section of the Magallanes basin. For location, see Figure 1. Interpretation of the seismic data in Mella (2001).

3. DIRECT UTILIZATION CONCEPTS OF DEEP GEOTHERMAL ENERGY FOR MAGALLANES

In the following sections the direct utilization concepts of deep geothermal energy for Magallanes are shown in terms of heat recovery. Those utilization concepts consider the coupling of geothermal energy with district heating based on several aspects: (1) emissions reduction, (2) systemic benefits (positive impacts on the electric grid, district heating infrastructure, and local economy), (3) positive synergies in the urban context, (4) increased energy security, (5) reduction in fossil fuel utilization and (6) diversification of energy mix (IRENA, 2017).

3.1 Open loop systems with low enthalpy aquifers: Geothermal Doublets

In the case of hydrothermal utilization, fluid is produced from deep aquifers and the heat is recovered by the use of a heat exchanger in the surface (Figure 3). The cooled water is usually reinjected into the same aquifer at a certain distance from the production well to stabilize the pressure in the aquifer and/or to accomplish an environmentally safe disposal. The system consists of at least one production and one injection well (doublet). A submersible pump raises the geothermal water to the surface. Another pump situated at the surface pressed the fluid back into the reservoir. Geothermal doublets coupled with district heating networks have proven to be an efficient way to provide district heating (e.g. Agemar et al., 2014) and are highly recommended for its environmental and technical benefits (IRENA, 2017).

Despite the global experience in the use of these systems, each site requires an specific design that depends on the site-specific geothermal resource available and the heat demand. Hydrothermal well doublets are suitable for aquifers with high hydraulic conductivity. The aquifer hydraulic properties are critical parameters along with temperature and rock thermal properties to fit the heat demand (LIAG, 2017 and references therein).

Several concerns must be addressed to planning a doublet construction and operation to minimize risk, such as scaling and/or corrosion issues related to geothermal fluid chemical composition, premature thermal breakthrough due to thermal short-circuit between injection and production wells and faster than predicted decline in pressure or production rate due to reservoir compartmentalization (LIAG, 2017 and references therein).

As described in the section 5.1, hydraulic reservoir conditions of the Springhill Formaton are similar to the targeted Keüper sandstone aquifer in the North German Basin at the Waren Müritz geothermal site. The Keüper aquifer in the NGB in the city of Waren (Müritz) is composed of an Upper Triassic sedimentary sequence deposited in a transgression/regression sedimentary environment (Aigner and Bachmann, 1992). The Keüper aquifer usually is composed by sandstones of more than 10 m thickness. Porosity of the sequences are 25-30%. The permeability of the sequences ranges from 500 to1.000 mD (LIAG, 2017 and references therein). Despite the significant differences in reservoir temperature in Waren (Müritz) and in the Springhill Formation, the experience in the operation of the system in Waren Müritz indicates that doublets in sandstones aquifers can provide heating to hundreds of houses connected to a district network (source: Municipal energy supplier of Waren Müritz - Stadtwerke Waren Müritz).

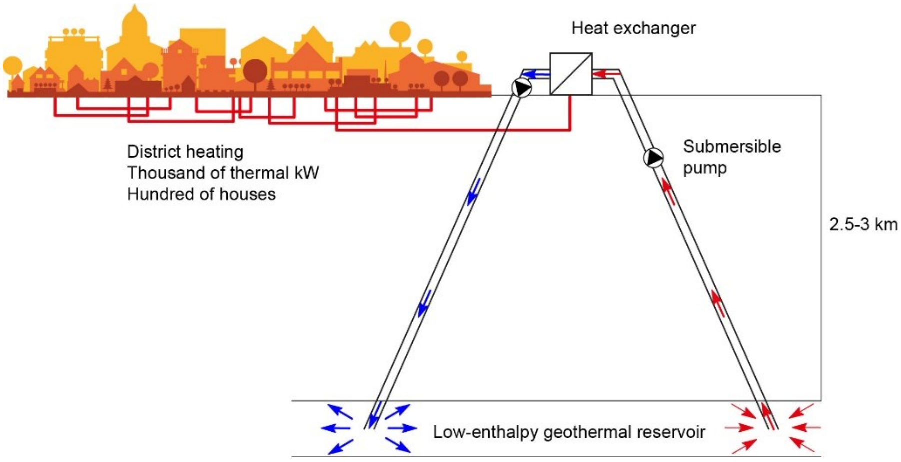

Figure 3: Scheme of an open loop system with low-enthalpy geothermal reservoirs: Geothermal Doublet.

3.2 Close loop ground source heat exchanger: Deep Borehole Heat Exchanger

The heat transfer in the Deep Borehole Heat Exchanger (DBHE) is similar to the shallow borehole heat exchanger (Florides and Kalogirou, 2007). There is a working fluid circulating within a closed system down to 800 to 3,000 m depth. The surrounding rock transfers the heat to the circulating fluid inside the DBHE by conduction through the heat exchanger casing. In case of DBHE, concentric or coaxial configuration is preferred, which traduces to one straight pipe inside the deep well. The working fluid goes down and heat up by the annular space of the DBHE and rises up through the insulated inner pipe Figure 4.

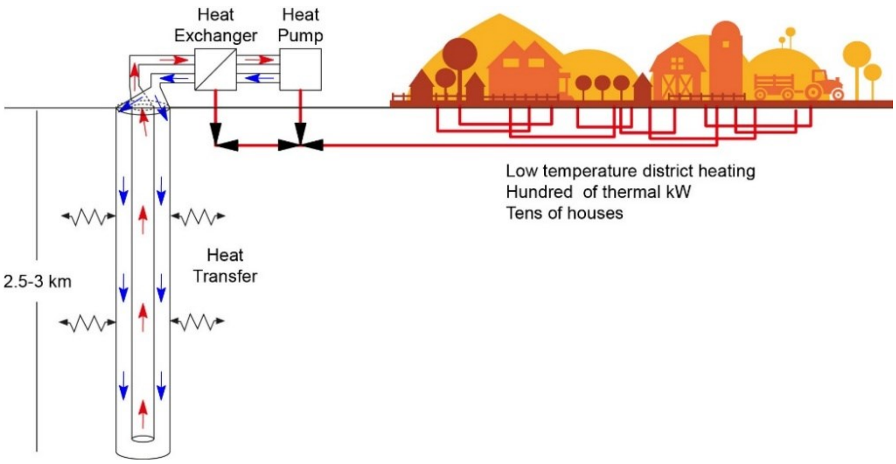

Figure 4: Close loop ground source heat Exchanger: Deep Borehole Heat Exchanger (DBHE).

The working fluid is pumped slowly downward through an annular space (5 – 65 m/min) to be heated during its way down to the bottom of the DBHE. Temperature difference between the inlet and outlet of the DBHE is approximately 15 °C (e.g. Agemar et al., 2014). In addition, if district heating network inlet temperature is required to be higher than the outlet temperature of the DBHE, an extra heat source is necessary to rise temperature levels (e.g. heat pump).

The DBHEs normally have capacities of few hundreds of kWth, which are much lower than open loop systems. This is due to the small extension of the heat transfer surface in contact to the surrounding rock, which corresponds to the heat exchanger outer casing surface. In contrast to open systems, there is no exploration risk in the case of DBHE. Due to the high investment, this geothermal utilization concept is particularly suitable in locations where abandoned oil or gas deep wells can be rehabilitated as DBHE.

A prominent example of a successful implementation of a DBHE constitutes the 2,786 m depth DBHE, which supplies the heat to a district heating network in Prenzlau, northern Germany (NGB). The system is managed and operated by the municipal energy supplier of the city of Prenzlau (Stadtwerke Prenzlau) and provides the heating to 1,400 m^2 of apartments for a retiree building complex. There is no extra heat source for the heating system because the apartments are heated by radiant floor. Nevertheless, there is a heat pump to increase temperature levels for domestic hot water (source: municipal energy supplier of the city of Prenzlau - Stadtwerke Prenzlau).

4. DATA AVAILABILITY

All data used for the geothermal assessment is provided by the Chilean National Oil Company (Empresa Nacional del Petróleo, ENAP). The geological dataset comprises 2D and 3D seismic reflection surveys, well construction features, well description, core measurements, well logs, and former hydraulic tests (drill stem test). Dataset quality is described in more detail as follows:

4.1 Seismic reflection survey

Throughout the exploration of hydrocarbons history in the Magallanes basin, the ENAP Company has carried out many 2D lines and some 3D seismic reflection survey with the aim to establish the geometry of the oil and gas reservoir and stratigraphic correlation at regional scale.

4.2 Well construction features

There is an accurate record of drilling procedures for most of the wells, considering the drilling tools and facilities, drilling time, mud loses, drilling diameter and the casing diameter. In addition, the reports include the inner pipe diameter.

4.3 Stratigraphic description and porosity/permeability measurements in well core

As the goal is to target the oil and gas reservoir for production and aquifer characterization, most of the wells are drilled with hammer technology up to the Springhill Formation (main reservoir). As soon as the reservoir is reached, a drilling rig replaces the hammer. Therefore, the stratigraphic sequence that overlies the Springhill Formation is described based on cuttings and the Springhill Formation is well described based on core samples. In addition, porosity, permeability and water/oil ratio are measured in well cores. The permeability in cores is measured with an air permeameter (i.e. Klinkenberg correction permeability).

4.4 Well logs

The ENAP Company has conducted different types of well logs throughout more than 60 years of exploration and exploitation of hydrocarbons in the Magallanes basin. For the great majority of wells there is a record of bottom hole temperature, besides caliper, self-potential, resistivity, and dipmeter logs. In addition, in most of recent wells there is record of gamma ray, sonic, density and neutron logs.

4.5 Former hydraulic test

In few cases there is a record of the oil and gas production rates and short-term former hydraulic test. Unfortunately, these short-term former hydraulic tests are not appropriate to calculate hydraulic parameters for long-term production strategies.

5. METHODOLOGY

The aim of this work is to assess the most suitable deep geothermal utilization concept for ENAP camps, villages and border crossing points in the Magallanes basin. This goal can only be achieved by conducting a thorough data-based geothermal resource assessment, evaluation of the availability of abandoned oil and gas wells, and the calculation of heat demand. Figure 5 indicates the workflow to carry out the assessment.

Based on regional studies, the Springhill Formation has proven to be persistent and to have a continuous all over the Magallanes basin (González et al., 1998; Schwarz et al. 2011). Despite the continuity of the Springhill Formation, there are variations in thickness (González, 1965) and facies (Schwarz et al. 2011). The facies variation implies difference in permeability that must be assessed. Therefore, the Punta Delgada village (Figure 1) is chosen as a case study for aquifer characterization and also to establish a range for bottom hole temperature.

The deep geothermal utilization concept for villages and ENAP camps in the Magallanes basin is chosen depending on the respective heat demand, which is in turn determined roughly by the number of inhabitants and industrial activity.

5.1 Aquifer characterization

5.1.1 Lithostratigraphy: Geometry, depth and thickness of the reservoir

Stratigraphic cross sections analyses are performed to establish the thickness and lateral variation of the Springhill Formation. The cross sections analysis also gives key information about continuity of permeable layers. The underlying data to construct the lithological cross sections constitutes the litho-stratigraphic description in well reports. To identify and classify the depositional environment, the stratigraphic information is complemented with the reported fossil record. In addition, secondary mineralization (e.g. Glauconite) and carbon deposits are taken into account. Since the self-potential logging data indicates permeability variations (Rider, 1986), it is used to complement the stratigraphic description.

5.1.2 Hydrostratigraphy: Lateral reservoir compartmentalization

The aquifer characterization is carried out considering classic worldwide examples of putting oil and gas reservoir data into a geothermal context (e.g. Van Wees et al., 2017). The aquifer characterization involves the permeability and porosity structure of permeable layers of the Springhill Formation. Therefore, a relationship between the permeability structure and its position in the Springhill Formation is established. Likewise, a relation between permeability and porosity is determined.

5.1.3 Thermostratigraphy: Bottom Hole Temperature (BHT) & rock thermal properties

Formation temperature is also a key factor for the geothermal resource assessment. There are several methods to correct the Bottom Hole Temperature (BHT) during the logging run (Hermanrud et al., 1990). One of the most widely used methods is the Horner (1951) method, which uses the plot of temperature at different mud circulating time within the well to correct the BHT. Because in most of the cases there is only BHT with no time-since-circulation in the dataset, the BHT correction is carried out by the simple addition of 18 °C to maximum BHT record (Dolson, 2016). That is considered to be a pessimistic way of correcting temperature measurements influenced by drilling mud. So, the temperature estimate is considered to be conservative. With the corrected BHT it is possible to obtain the formation temperature and geothermal gradient. Rock thermal properties are very important to carried out a geothermal assessment, because these properties control the heat exchange. Unfortunately, there is no record of rock thermal properties measurements in ENAP dataset. Thermal rock properties values (e.g. thermal conductivity and volumetric heat capacity) of sandstones are taken from the published literature.

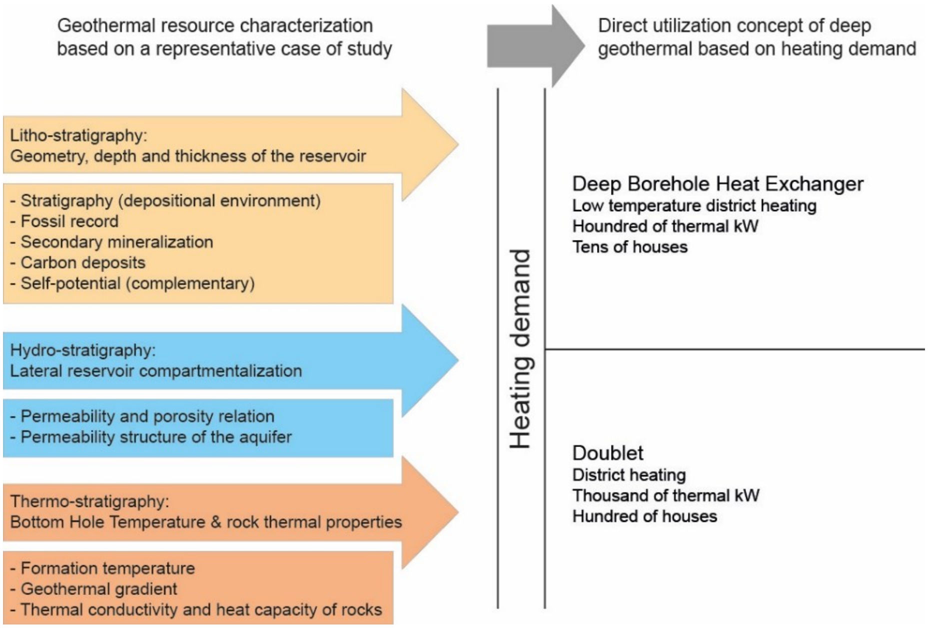

Figure 5: Work flow for assessment of geothermal potential to meet heat demand in Magallanes based on deep geothermal utilization concepts.

5.2 Deep geothermal utilization concept

As mentioned earlier (Section 3), there are potentially two direct-use geothermal concepts for deep geothermal energy in the Magallanes basin: (1) Geothermal Doublet and (2) Deep Borehole Heat Exchanger. The use of deep geothermal energy for district heating purposes is strongly recommended due to its undoubtful advantages and sustainability (IRENA, 2017). Geothermal district heating projects have worked successfully for decades in different contexts and at different scales worldwide (e.g. Agemar et al., 2014). However, it is worth mentioning that in the district heating network should be appropriate for low temperature levels (IRENA, 2017). The above is very important in case of Deep Borehole Heat Exchanger (e.g. 2,786 m depth DBHE in Prenzlau, Germany). In the case of geothermal doublets, temperature levels in district heating networks depends on geothermal gradient and aquifer depth (Van Wees et al., 2017).

As for the scale of deep geothermal projects coupled with district heating networks, a fundamental differentiation between geothermal doublets and deep borehole heat exchangers should be made:

a. Geothermal Doublet in the case of deep aquifer and heat demand of thousands of kilowatts (tens to hundreds of houses).
b. Deep Borehole Heat Exchanger in the case of more than 100˚C at the bottom of the well and heating demand of hundreds of kilowatts (tens of houses).

6. RESULTS

As mentioned earlier, the characterization of the aquifer is focused on the case study of Punta Delgada Village (Figure 6). The stratigraphic sequence (Section 2.1) exhibits a similar pattern for the whole non-deformed domain of the Magallanes basin (Figure 1) and the deep Springhill aquifer extends throughout the area of interest (Figure 2). Based on the ENAP dataset, 9 well descriptions are used for stratigraphy analyses, which represent the underlying data for stratigraphic cross sections analyses (Figure 8 and Figure 7). The porosity and permeability data compiled in 8 wells are used for porosity and permeability estimates (Figure 9) and 26 corrected BHT are used to calculate formation temperature and local geothermal gradient (Figure 10).

In the case of the DBHE, the qualitative estimate conducted in this work does not required detailed rock thermal properties values, since in terms of orders of magnitude of the thermal energy availability the estimation is not significantly affected by small variations in rock thermal properties. For instance, thermal conductivity of the sedimentary sequence at hand in average ranges from 2 to 2.5 W/m·k (Zoth and Haenel, 1988).

6.1 Aquifer characterization in the village of Punta Delgada

6.1.1 Lithostratigraphy: Geometry and depth of the aquifer in the village of Punta Delgada

Although there are other possible permeable layers in the area of interest, the work focuses on the Springhill Formation because it is the most interesting and best-characterized aquifer. As mentioned before, the lower cretaceous Springhill Fm. represents a transgressive succession in a thermal subsidence setting, which is composed of coastal plain, estuarine, and open marine siliciclastic deposits. Schwarz et al., (2011) identified four stratigraphic sequences for the Springhill Fm. Based on facies analysis and facies associations, the four stratigraphic sequences from bottom to top are the following: (1) lowstand fluvial deposits; (2) transgressive fluvial to estuarine deposits; (3) outer estuarine deposits; (4) open marine deposits.

The description of the geometry and main features of the stratigraphic sequences of the Springhill Fm. regarding geological background and cross sections are summarized in Figure 7 and Figure 8. The stratigraphic profiles are complemented with self-potential profiles, which indicate permeability variations (Rider, 1986). The stratigraphy sequences descriptions along with cross sections in Punta Delgada are displayed in Figure 6, Figure 7 and Figure 8.

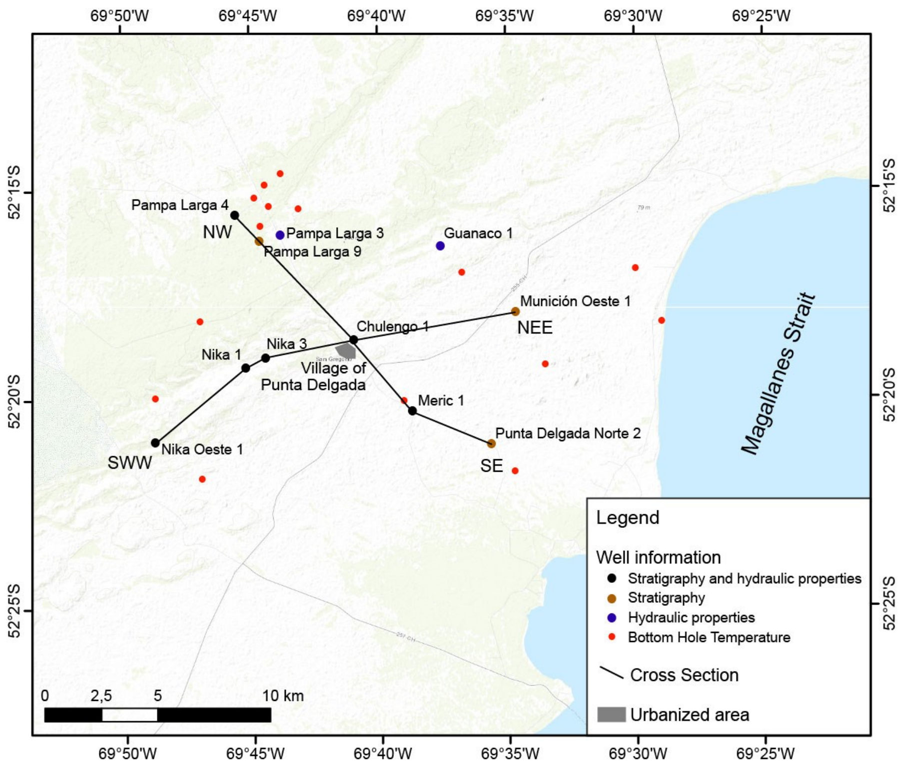

Figure 6: Location of the case of study (village of Punta Delgada) in Figure 1.

The lowstand fluvial sequence is composed of fine grain sediments, which include shale, fine grain sandstone, and massive mudstones. The Thickness of the sequence is highly variable in the NW–SE orientation (36 – 6 m). In fact, the low-stand fluvial sequence is not recorded in the northernmost profile of the NW–SE cross section (Figure 7). In contrast, in the SWW–NEE cross section the thickness of the low-stand fluvial sequence is more persistent in thickness (Figure 8). These results agree remarkably well with the sedimentary model proposed by Schwarz et al. (2011), where the Springhill Formation is deposited at the base in fluvial valleys perpendicular to the direction of preferential elongation of the Magallanes basin (NNW-SSW).

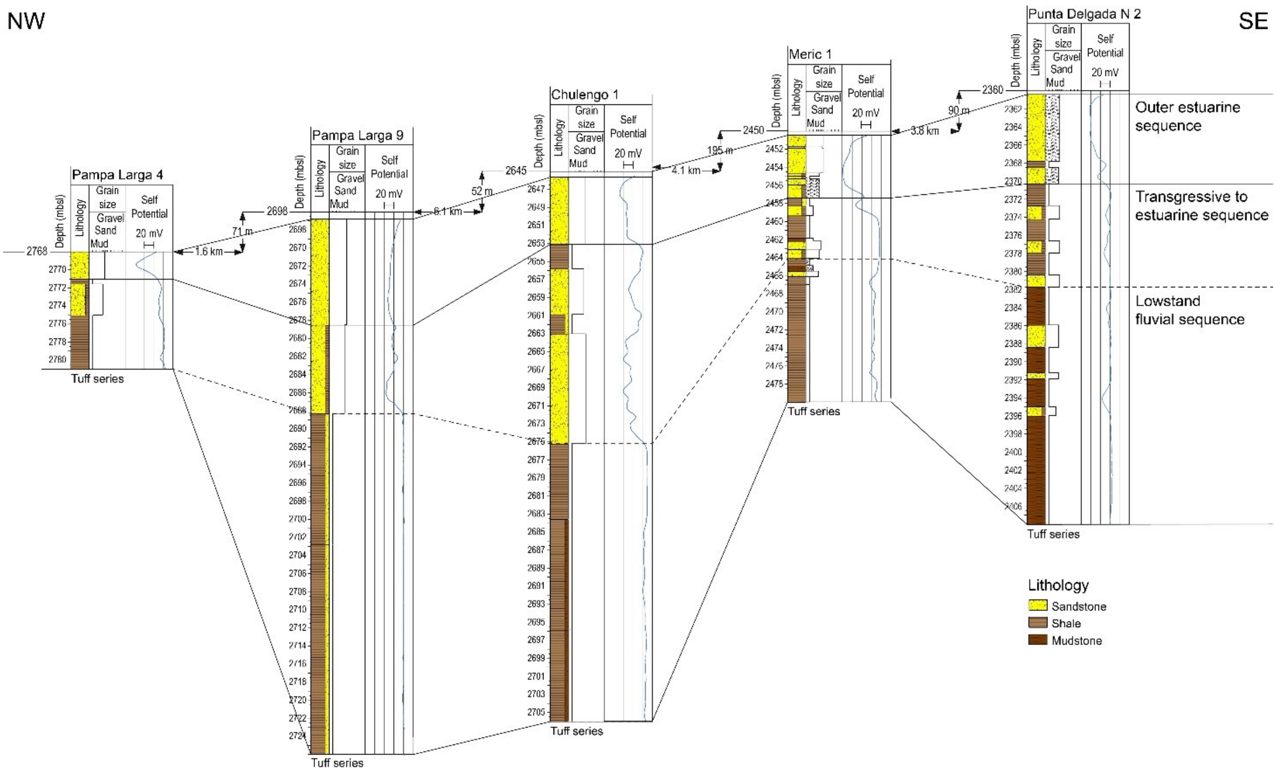

Figure 7: NW-SE cross section of the Springhill Formation in village of Punta Delgada. Location of the profile in Figure 6.

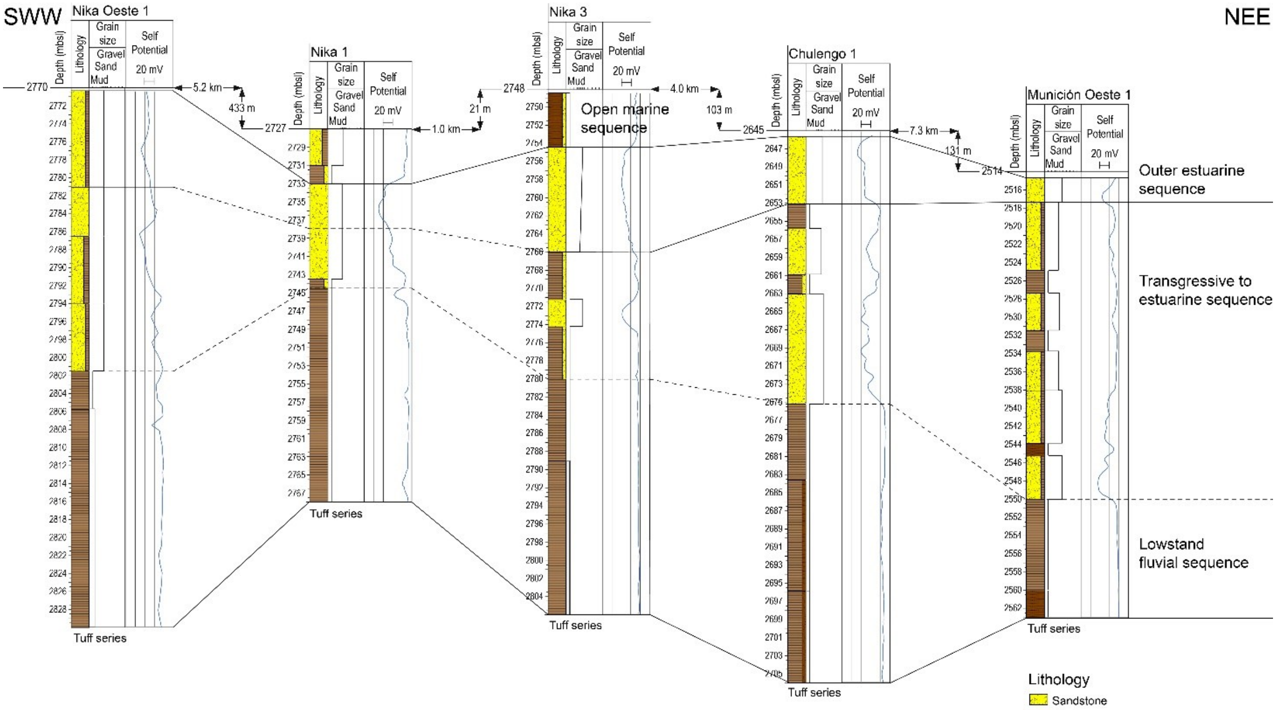

Figure 8: SWW-NEE cross section of the Springhill Formation in the village of Punta Delgada. Location of the profile in Figure 6.

The transgressive to estuarine sequence is composed of fine to coarse grain sandstone with shale interbedded. Carbon strata is distinguished in some profiles, which indicates relative weak currents in channels units. In addition, secondary pyrite is distinguished in few profiles, which indicates low energy in anoxic environments (Reading, 2009). These findings suggest a relative low energy setting. Thickness of the sequence varies in the range of 10 - 20 m, with a similar variation in both NW–SE and SWW–NEE cross sections (Figure 7 and Figure 8).

The outer estuarine sequence is composed of coarse to very coarse sandstones, which grade to fine grain sandstone at the bottom. Marine fossil record is distinguished at the base of the sequence as well as glauconite secondary mineralization, which indicates a shallow marine environment (Odin and Matter, 1981). The sedimentary paleoenvironment is interpreted as barrier complex and splits in outer segments of wave-dominated estuarine systems (Schwarz et al., 2011). Thickness of the sequence varies in the range of 3 - 10 m (Figure 7 and Figure 8).

The open marine sequence is composed of fine grain sediments, which include shale and massive mudstones with fine grain sandstone interbedded. Thickness of the sequence reaches up to 6 m thick and it is distinguished only at the top the SWW–NEE cross section (Figure 8).

6.1.2 Hydrostratigraphy: Permeability and porosity structure of the aquifer in the village of Punta Delgada

The permeable sequences in the Springhill Formation are the transgressive to estuarine and outer estuarine sequences. There is a correlation between permeability and porosity, which indicates that increasing porosity leads to increasing permeability. The estuarine and outer estuarine sequence constitutes the best aquifer, where few of permeability measurements reach up to ~2.000 mD. As mentioned in Section 4.3, permeability database is composed of individual measurements. Therefore, the scale-up to the aquifer must be carefully carried out. Besides, the transgressive to estuarine also constitutes a good aquifer, where some permeability measurements reach up to ~450 mD. In the first 7 meters (from top of the Springhill Formation), which is representative of the estuarine and outer estuarine sequence, the average permeability is 400 mD. Likewise, in the first 15 meters (from top of the Springhill Formation), which is representative of the estuarine and outer estuarine sequence and the most permeable layers of the transgressive to estuarine sequence, the average permeability is 400 mD (Figure 9).

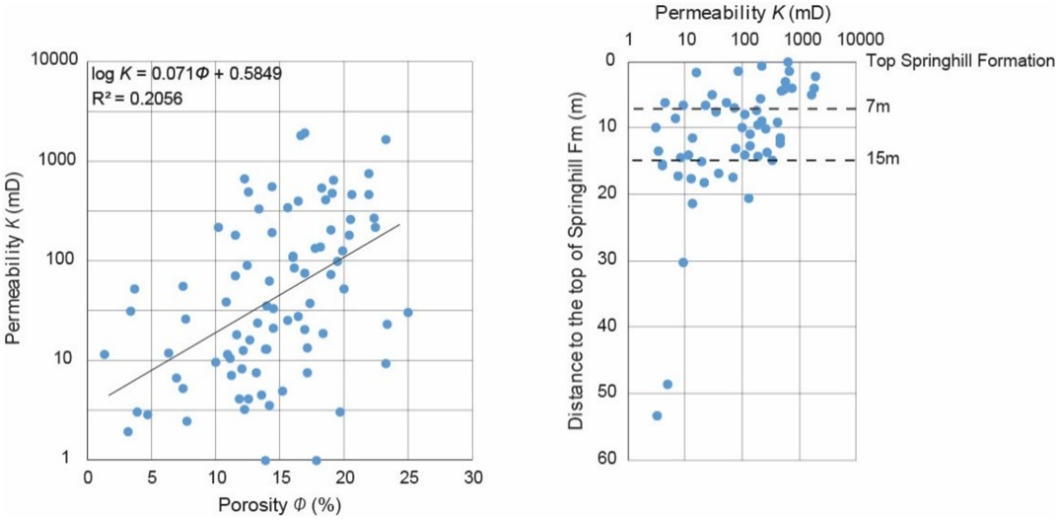

Figure 9: (Left panel) Porosity permeability relationship of the permeable layers of the Springhill Formation. (Right panel) Permeability measurements respect to the top of the Springhill Formation.

6.1.3 Thermostratigraphy: Bottom Hole Temperature (BHT) data in the village of Punta Delgada

The geothermal gradient in the Magallanes basin ranges from 40 to 52 ˚C/km (Ministerio de Energía, 2015). This geothermal gradient is almost double higher than the average gradient in stable continental areas (Mareschal and Jaupart, 2013). In the village of Punta Delgada, the geothermal gradient ranges from 38 to 51,8 ˚C/km with an average value of 43 ˚C/km.

Temperature of the Springhill Formation ranges from 105 to 147 ˚C, with an average of 120˚C. The BHTs were measured in a range of depths from 2,420 to 2,900 m. Concerning the corrected BHT and its depth of measurement, the geothermal gradient ranges from 38 to 51,8 ˚C/km with an average value of 43 ˚C/km.

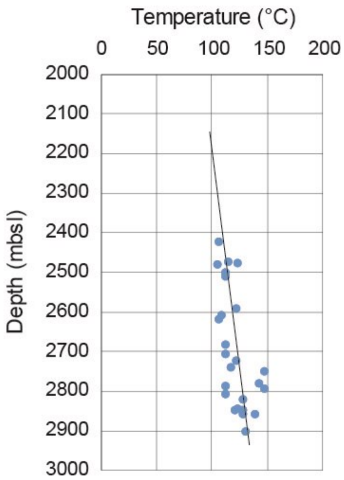

Figure 10: Corrected Bottom Hole Temperature of Punta Delgada wells. Correction of BHT is carried out with the last resort correction (Dolson, 2016).

6.2 Deep geothermal utilization concepts in the Magallanes basin

The practical experience indicates that the permeability of 250 mD in about 15 meter thick sandstone reservoirs is economically feasible for the sustainable operation of geothermal doublets in the North German Basin. Likewise, sandstones sequences of more than 10 m thick are used for geothermal heat production in the Upper Triassic sedimentary sequences of the North German Basin (LIAG, 2017 and references therein).

According to the geothermal experience in the city of Waren (Müritz), Germany and based on the deep aquifer characterization in the Magallanes basin (Springhill Formation), hydraulic properties and formation temperature in the Springhill Formation seem to reveal promising reservoir conditions for the development of an economically feasible and sustainable geothermal doublet (Section 6.1). Nevertheless, it must be considered the heating demand should be of several tens of houses to hundreds of houses to maintain sustainability in the operation of the system (geothermal doublet plus district network).

Analogue to the successful geothermal experience in Prenzlau and based on thermo-stratigraphy of the Magallanes basin (section 6.1.3), there is low exploration risk and a high probability of success in rehabilitating an abandoned oil and gas well as a Deep Borehole Heat Exchanger to provide heating to a district network. It must be taken into account, however, that the heating demand should be of tens of houses. Likewise, the district network and the heating devises in houses must be suitable for lower than conventional heating temperatures (e.g. radiant floor).

Table 1 illustrates the suggestion of direct utilization concepts of deep geothermal energy for the Magallanes based on the scale of geothermal resource and heat demand in urbanized areas of the Magallanes basin. Although in some cases both systems could be implemented, the preference is clear in each location.

Location	Geothermal Doublet	Deep Borehole Heat Exchanger
Cerro Sombrero ENAP camp	Best option	Demonstrative objective
Posesión ENAP camp	Best option	Demonstrative objective
Punta Delgada Village	Option in case all facilities and houses are heating with geothermal	Best Option for a fraction of the village
Monte Aymond border crossing point		Best option
San Sebastián border crossing point		Best option

Table 1: Suggested direct utilization concepts of deep geothermal energy for the Magallanes region based on geothermal resource availability and heating demand in urbanized areas of the Magallanes basin.

7. DISCUSSION

Although the Springhill Formation persists over an exceedingly wide region in the Magallanes basin, its hydraulic properties cannot be assumed as similar at different depths due to diagenetic processes throughout the burial history (e.g. compaction, cementation, etc.) In fact, González et al., (1998) found that at greater depths carbonate, silica and clay mineral restrict permeability.

Geochemical composition of fluid (fluid-rock interaction) is a key factor that must be managed in order to avoid scaling and corrosion issues during doublet system operation. Formation water are of chlorine-calcium type. Total dissolved solids in formation water ranges from 10 to 20 g/L. The latter is not high as in in the Upper Triassic sandstone reservoir at the geothermal site in Waren (Müritz), Germany. However, geochemical exploration is mandatory to avoid running scaling/corrosion issues.

To constrain the extractable geothermal energy of the Springhill Formation in the Magallanes Basin, detailed physically-driven numerical and analytical reservoir modelling and simulation have to be performed set up with the site-specific geometry of the geological units and their thermo-hydraulic properties (e.g. Zimmermann et al., 2019).

Finally, the binary generation of heat and electricity with geothermal doublets is also possible from geothermal reservoir conditions similar to ones encountered in the Springhill Formation in the Magallanes Basin. That is substantiated by the comparable and successful example of the geothermal heating plant in Neustadt Glewe, northern Germany, which produces electricity in addition to heat with an ORC cycle at 98 °C (Lund, 2005).

8. CONCLUSION

As for the hydraulic properties of the main oil- and gas-bearing geological formation (Springhill Formation), depth of the oil and gas producing wells and Bottom Hole Temperature (BHT) data, there is low geothermal exploration risk and a great chance of success of implementing deep geothermal heating systems. In particular, either geothermal doublets or deep borehole heat exchangers (DBHE) seem to be favourable and encouraging deep geothermal utilization concepts that integrate both (1) geothermal resource availability and (2) heat demand. Considering that ~40% of the oil and gas wells are currently not producing, there is a great opportunity and potential of rehabilitation of oil and gas wells as geothermal doublets or DBHEs.

The global experience suggests that geothermal energy must be coupled with district networks to efficiently, economically reasonably and sustainably provide heating. In the case of working camps of the Chilean National Oil Company (ENAP) the geothermal doublets are preferred. However, in the case of small villages and border crossing points DBHEs are preferred.

The energy transition global context along with the almost depleted oil and gas reserves in the Magallanes basin create a unique and excellent opportunity for the transition from gas heating facilities to deep geothermal heating systems. The latter is aimed at reducing emissions, generating positive synergies in the urban context, increasing energy safety, reducing fossil fuel utilization and hence decarbonizing the energy sector and diversifying the energy mix.

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