Play Fairway Analysis for Geothermal Exploration in Northwest Argentina: Initial Data Compilation and Review

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ABSTRACT

In 2017, the Great Basin Center for Geothermal Energy (GBCGE) received funding from the United States Department of State's Bureau of Energy Resources to take the geothermal play fairway approach global under the Geothermal Development (GEODE) initiative. This initiative aims to increase the capacity of foreign governments to develop their geothermal resources via collaborative knowledge transfer and training, and deployment of innovative methods such as geothermal play fairway analysis to evaluate regional geothermal potential and reduce exploration risk. The first country selected for collaborative work under GEODE was Argentina.

The collaboration in Argentina is with Servicio Geológico Minero Argentino (SEGEMAR), Argentina's national geological survey, who are tasked with producing and housing geological, mining, and environmental information for the sustained development of Argentina's natural resources and mitigation of geological hazards. Working with the GBCGE team, SEGEMAR geoscientists identified a target area for the project to apply and develop geothermal play fairway analysis workflows that are appropriate for the local geological setting and regional data availability. The study area is in the Salta and Jujuy Provinces of northwestern Argentina in the central Andes (Puna plateau) and is approximately 45,000 km² in area. It encompasses multiple thermal areas including the Cerro Tuzgle and Coranzulí volcanic centers as well as many geothermal areas associated with the Calama-Olacapato-Toro transverse lineament. The primary datasets identified for use in the project include: 1) spring locations and associated data such as temperature and geochemistry; 2) fault locations with additional attributes such as slip rate and fault recency; 3) earthquake data including depth and magnitude; 4) relative age of volcanism; and 5) hydrothermal alteration type and age.

The team from SEGEMAR and GBCGE completed compilation of available, prioritized datasets as identified during initial meetings. The resulting maps offer insight to the geothermal potential and provide direction for future refinement, weighting, and completion of the play fairway analysis.

1. INTRODUCTION

Geothermal resource evaluation has been occurring in Argentina for decades. It has been suggested that with proper development, 20% of Argentina's electricity needs could be powered by geothermal energy (Gawell et al., 1999), and with today's technology produce as much as 2010 MWe (Battocletti et al., 1999). In the 1950s, the Argentine government commissioned the evaluation of potential prospects, resulting in the identification of several high-interest locations spanning multiple provinces. Among these were the Tuzgle-Tocomar area, Domuyo, and Copahue. Despite the identification of potential resources, significant activity did not begin again until the 1970s when the national government, supported by the United Nations Development Program (UNDP), carried out another investigation into potential resources. Several resources were again identified and subsequently the National Commission of Geothermal Studies was created in 1974 to continue research and exploration. In 1979, the Government prepared a plan, along with the support of international cooperation programs, for the development of geothermal energy, the Geothermal Realization 1979. Pre-feasibility was assessed in several provinces but focused on three primary sites - Tuzgle-Tocomar, Copahue, and Domuyo (Bona and Coviello, 2016). In 1982, a geothermal survey project was developed by Universidad Nacional de Salta specialists covering part of the southern Puna (UNdS, 1982).

In 1985, the Regional Center for Geothermal Energy of Neuquén (CREGEN) was created, and a small pilot plant of 0.67 MWe was commissioned in 1988 at Copahue. Concurrently, the feasibility study with the support of the Agency of International Cooperation of Japan (JICA) was completed. CREGEN also developed hydrogeological and geochemical studies in Tuzgle-Tocomar in Salta and Jujuy, Famatina in La Rioja, and Termas de Rio Hondo (Tucumán and Santiago del Estero) (Bona and Coviello, 2016). In 1992, the feasibility study ended at Copahue and production ceased (Mas, 2005).

In December 2006, Law 26.190 established national policy to promote the use of renewable sources. The law mandated a contribution of 8% to the national electricity consumption for 2017 and an increase to 20% by 2025, and in recent years there has been an emergence of provincial initiatives to revive the geothermal electric sector (Neuquén, San Juan, Mendoza, Jujuy, and Salta) (Bona and Coviello, 2016). The current energy demand, renewable mandates, and abundance of geothermal resources in Argentina led to the current collaborative project, funded by the United States Department of State, between the Great Basin Center for Geothermal Energy, and SEGEMAR, the Servicio Geológico Minero Argentino, Argentina's national geologic survey.

The current project is styled after recent United States Department of Energy-funded Geothermal Play Fairway Analysis (PFA) projects. The term "play fairway" originates in the oil and gas industry. The objective of a PFA is to compile data that are related to resource potential, and then weight and compile those layers to identify areas that are prospective and of lower risk for future exploration.

The United States Department of Energy funded the PFA initiative in 2014, and since then, multiple multi-phase geothermal play fairway projects were carried out in the U.S.A (Weathers et al., 2015). Phase three (the final phase) projects culminated in 2019 with geothermal gradient drilling to validate the various PFA workflows that were developed in earlier project phases. While some projects are still in the final phases of completion as of July 2019, initial results indicate the success of at least two projects. In 2018 and 2019, the Nevada Bureau of Mines and Geology completed drilling of temperature gradient wells of two blind geothermal systems in Nevada that were identified as prospective using the PFA workflow (Faulds et al., 2015; 2016). At one location (Gabbs Valley), temperatures of 120 °C were reached at a depth of approximately 150 m (Craig, 2018) and are interpreted to reflect intersection with a shallow geothermal outflow plume.

Eager to apply this predictive approach in Argentina, teams of scientists at SEGEMAR encompassing several disciplines, as well as scientists from the Great Basin Center for Geothermal Energy, have worked to compile and organize available data and create preliminary data maps that will ultimately be weighted and layered to create a play fairway analysis of an area in northwestern Argentina. Here, we present the work conducted to date to locate, compile, visually represent, and interpret the available data, which are the necessary precursors to conducting a PFA.

2. REGIONAL SETTING

2.1 Geological Background

The Argentine Puna within the central Andes is bounded to the west by the Cordillera Occidental in Chile, which includes the Miocene-Holocene magmatic arc, and to the east by the Cordillera Oriental and Sierras Pampeanas geological provinces. The plateau has an average elevation of 3,700 m above sea level, north-south length of 1,800 km, and width of approximately 350-400 km. It includes part of the Andean orogeny, where the Nazca plate subducted, with an inclination of approximately 30°E, for more than 200 million years under the South American plate (Allmendinger et al., 1983; Isacks, 1988; Allmendinger et al., 1997). The high elevation of the Puna is attributed to the thick crust generated by tectonic shortening and to the magmatic inflation associated with Miocene volcanism (Allmendinger et al., 1997; Isacks, 1988). Regional kinematic and chronological studies suggest that uplift of the Puna took place between the Eocene and the middle to late Miocene (Allmendinger et al., 1983; Jordan and Alonso, 1987; Quade et al., 2015; Perkins, 2016).

The structural and volcanic framework of the region is complex. Andean tectonics produced systems of thrust and reverse faults, some of which reactivated normal faults corresponding to a Cretaceous intracontinental rift (e.g. Grier et al., 1991; Mon and Salfity, 1995) or older Paleozoic tectonism (Salfity et al., 1976; Hongn et al., 2010; Seggiaro et al., 2017b).The current relief of the region is characterized by north-trending mountain ranges separated by valleys that in many cases contain salt salars, the product of evaporitic basins with internal drainage. The ranges are generally bound by thrust or reverse faults. Also within the study area are the Coyahuaima and Calama-Olacapato-Toro (COT) lineaments, on which the Coranzulí (Seggiaro, 1994) and Aguas Calientes (Petrinovic, 1994) calderas lie, respectively. Many hot springs in the area are associated with the transverse lineaments, indicating that these areas host high secondary permeability that reaches relatively deep levels within the crust. Records of transcurrent displacements in Quaternary volcanic and sedimentary deposits (Lanza et al., 2013; Giordano et al., 2013 Seggiaro et al., 2016)) suggest neotectonic activity as a likely trigger for some eruptions of the Tocomar (0.5 Ma) (Petrinovic et al., 1999), San Jerónimo (0.78 Ma), Negro de Chorrillos (0,2 Ma) (Aquater, 1980) and Tuzgle (0.5 Ma) (Aquater, 1980) volcanic centers.

2.2 Known Geothermal Potential of the Puna

Cerro Tuzgle is an active volcanic center along the Jujuy/Salta provincial border, about 10 km west of San Antonio de los Cobres. Early geophysical studies in the Tuzgle-Tocomar area, including magnotelluric and gravimetric surveys, indicated the presence of a young, active magma chamber (<0.5 Ma) with an upper depth of approximately 8 km beneath Tuzgle (Aquater, 1980; Coira, 1995). This magma chamber is the presumed source of geothermal activity in the area (Giordano et al., 2013). Studies by Aquater (1980) also indicated a possible 100-600 m thick shallow geothermal reservoir (varying from 50 m to 200 m deep) hosted by Trinchera ignimbrite (10 Ma) and capped by the Miocene-Pliocene Pastos Chicos sedimentary formation. This was later confirmed by Coira (1995), and a second, deeper reservoir was indicated with a depth range of approximately 2 to 3.6 km and hosted in fractured Ordovician rocked capped by the Cretaceous Pirgua Subgroup sediments (Giordano et al., 2013).

South of Tuzgle along the COT lineament is the Tocomar geothermal field. Linear hydrothermal features dot the area, with surface fluids depositing both sinter and travertine (Pesce, 1999). The Tocomar and Tuzgle fields are often categorized together. However, hydro-chemical differences in the surface fluids surrounding Tuzgle and those in the Tocomar field support the existence of a physical separation between the fields associated with the COT (Tocomar and others) and Tuzgle (Giordano, 2013).

Currently, both fields are under exploration by the private sector companies Andean Geothermal Power Inc. (Canada) and British Columbia (Pesce, 2015; Lahsen et al., 2015). In 2015, Andean Geothermal Power Inc. completed prefeasibility studies at Tuzgle. The company reported geothermometry values of 180 °C to 200 °C (type of geothermometer not reported) and suggested a minimum capacity of 16 MWe to 34 MWe with 50% probability via Monte Carlo simulation modeling, and higher values ranging from 35 MWe (90% probability) to 70 MWe (50% probability) based on geophysical studies. According to the company's website, the Tocomar fault geothermal project is ongoing (http://geotermiandina.com.ar/e/saltajujuy1/).

Another area with known geothermal potential is Coranzulí in the northern part of the project area. The main geologic structure in the Coranzulí area is a collapsed caldera at the intersection of the NW-trending Coyaguayma and the NE-trending Rachaite lineaments (Seggiaro and Hongn, 1994; Peralta et al., 2017). The area has active surface thermal manifestations but is less well explored than the Tuzgle-Tocomar geothermal area. Hydrochemical evaluation of the fluids in the Coranzulí area do suggest the occurrence of a deep hydrothermal reservoir of mature alkali-chloride fluids (Peralta et al., 2017). Coranzulí is also home to lithium mining operations that could benefit from geothermal energy production in the area.

Apart from these larger volcanic systems, many smaller systems are known in the Argentine Puna. In the northern Puna (in the Jujuy province), these include Agua Caliente de Orosmayo, Agua Caliente de Rachaite, Agua Caliente del Oratorio, Agua Caliente Mina Pirquitas, Agua Caliente Rosario de Coyaguayma, Mina Betty, Mina Libertad, Pozo Verde, and Susques. In the southern Puna (in

the Salta province), there are Antuco, Baños de Pompeya, Incachule, Aguas Calientes, El Macón La Salinita, Quebrada del Porongo, Quebrada Paya, Santa Elena, and Salar de Rincón.

3. METHODS

3.1 Area selection

In fall of 2018 during meetings in Buenos Aires, team members from SEGEMAR and the GBCGE began defining the project scope. The initial objective was to define an area with geothermal potential and available data to serve as the play fairway study area. The area selected encompasses Cerro Tuzgle, an active volcanic center, and Tocomar, a hydrothermal zone with surface manifestations associated with the COT. Both are areas of active geothermal research in Argentina, making data availability more favorable. To the north of Tuzgle and Tocomar is Coranzulí, a volcanic center with active surface manifestations. In addition to these areas with obvious surface indications of geothermal potential, it is likely that blind geothermal systems also exist that are currently undiscovered and could be identified through conducting a PFA. Thus, an area encapsulating all three areas was chosen as Area 1 for a PFA in Argentina (Figure 1). It encompasses approximately 44,000 km^2.
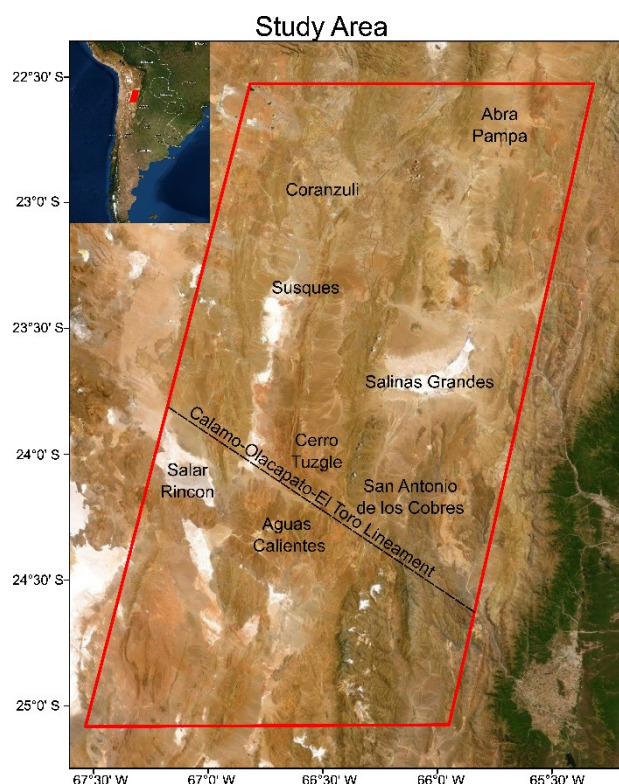

Figure 1: Study area (red outline) in north-western Argentina, with country inset.

3.2 Data Availability and Compilation

As the PFA requires a compilation of datasets, the team identified the minimum requisite datasets for the project. Geothermal systems require three characteristics to be productive – heat, fluid, and permeability, so in identifying the datasets, the team worked to ensure that each characteristic could be represented in the datasets that were compiled. The primary datasets identified as being integral to the success of the project were hot spring information (to include location, geochemistry, temperatures, and geothermometry), structural data (to include Quaternary faults and attributes such as recency, dip, and slip sense), earthquakes (date, depth, and magnitude), and volcanism (relative or absolute age). Other datasets that were investigated included hydrothermal alteration, gravity, well log information, salars, surface springs, and detailed structural setting.

Currently, geologic data are dispersed among various universities, SEGEMAR branches, other government agencies, and private organizations in Argentina. Dedicated teams within SEGEMAR were established for each dataset to compile, QA/QC, and report the available data so that it can be used for the PFA and also centrally housed for future research projects in SEGEMAR. The final datasets acquired were earthquake data including data, depth, and magnitude; hydrothermal alteration; volcanic ages, hot spring data including location as well as some geochemistry and physical characteristics; structural data including fault traces with some attributes, caldera locations, and favorable structural setting; horizontal gravity gradient; magnetic anomalies and lineaments, geothermometry; and ASTER thermal data. While we were able to compile more data than originally anticipated, data scarcity and disparity are challenges for this project and will likely require some innovative adaptations of the PFA workflow.

3.2 Geostatistics and Analysis

We processed each separate dataset as a layer in ArcGIS to develop individual map products. Some data remained as point data such as hot spring location and geothermometry while others were treated with statistical methods to account for data density and spatial distribution. As many data sets such as gravity and include some degree of spatial correlation, those layers were treated with geostatistics and interpolation methods to create contours. Some data were plotted as lines with a buffer zone of a given distance (e.g. such as the Quaternary faults). Density plots were created for layers such as earthquakes. Each layer was treated individually to best represent the associated geothermal characteristic – heat, fluid, or permeability.

4. RESULTS
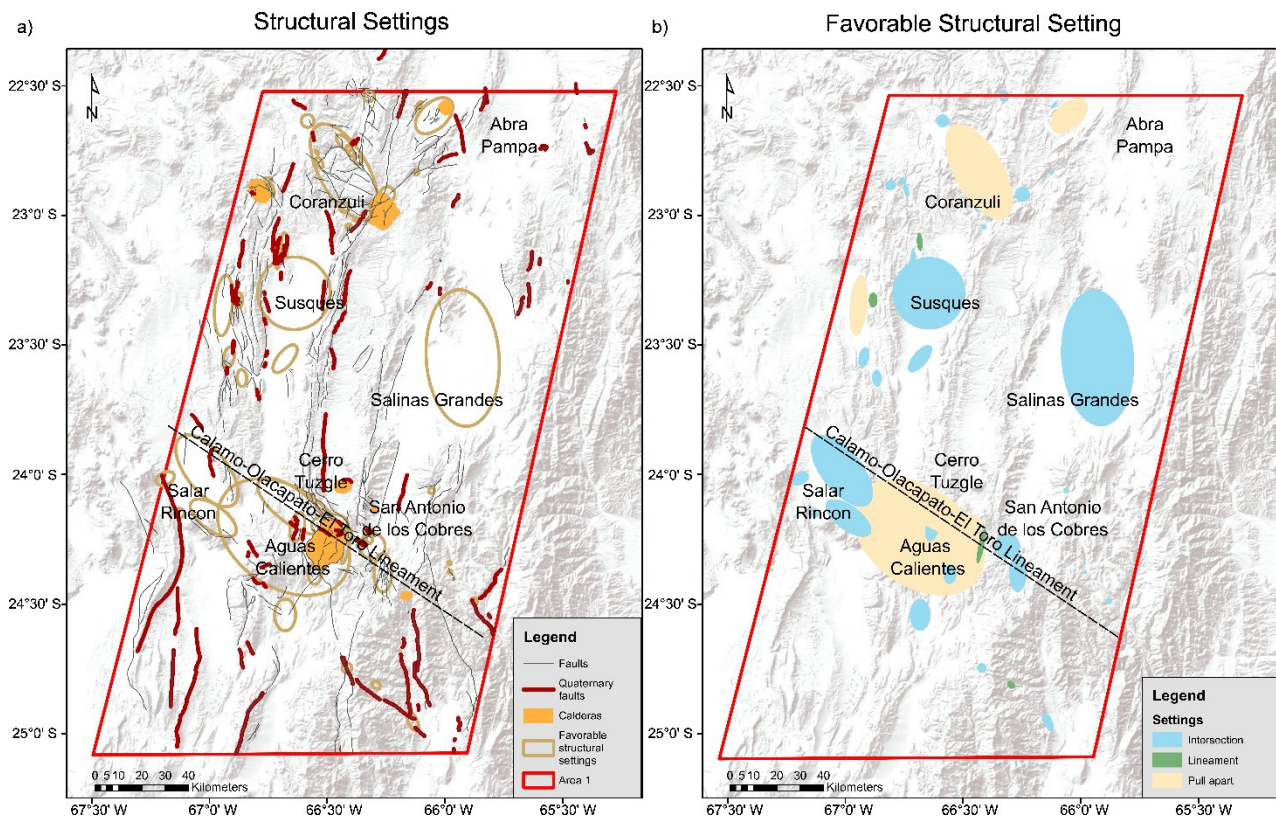
4.1 Structural Settings

4.1.1 Calderas

Calderas are commonly associated with geothermal activity (Cole et al., 2005; Saemundsson, 2013). Calderas can provide not only a heat source but enhanced permeability as well. Inflation, eruption, and deflation of calderas create signature ring fractures around caldera margins increasing permeability in these zones and parent magmas associated with caldera-forming events commonly persist after caldera eruption and cool slowly. Caldera systems with current geothermal operations include the Long Valley Caldera in California (Suemnitch and Sorey, 2005; Hurwitz et al, 2010), parts of the Taupo Volcanic Zone in New Zealand (Spinks et al., 2005), and Krafla in Iceland (Nielsen et al., 2000) among others.

For this study, caldera structures were identified from SEGEMAR geologic maps (Blasco et al., 1996 and Seggiaro et al., 2015) and plotted in Google Earth (Google Earth Pro, v. 7.3.2.5776). The resulting kmz files were imported to ArcGIS and the caldera structures presented as polygons (Figure 2). Three main caldera structures were identified: Coranzulí, Aquas Calientes, and Negra Muerta. Other structures in Area 1 have been identified as possible calderas – Pairique, Pan de Azucar, Tuzgle, and Ramada. These four have not been confirmed in current literature but are included, although for the final play fairway model the uncertainty will be taken into consideration.

The Coranzulí caldera is a part of the Coranzulí Complex volcanic area in the northern part of Area 1. Its location is associated with the intersection of the NW-striking Coyaguayma fault and the NE-striking Rachaite fault (Seggiaro and Hongn, 1994). Four pyroclastic events formed the caldera, three large and one small, beginning approximately 6.6 Ma. The pyroclastic sequences are moderately to intensely welded, crystal-rich dacite containing vesicular pumice fragments. The deposits cover 1900 km^2 with a volume of 400 km^3 (Seggiaro et al., 2014). The caldera has a diameter of 5 km (Kay et al., 2008).

Aquas Calientes, south of Tuzgle, is a major caldera located on the Calama-Olacapato-El Toro lineament. The caldera had two major eruptive events: 1) the 350 km^3, 10.3 Ma Tajamar Ignimbrite; and 2) the 17.5 Ma Verde Ignimbrite with a volume of 140-300 km^3 (Petrinovic et al., 2010). As is the case with Coranzulí, Aquas Calientes caldera is thought to be structurally controlled.

The Negra Muerta caldera, in the southeast corner of Area 1, is also along the Calama-Olacapato-El Toro fault zone. The caldera straddles the eastern margin of the Puna plateau. The caldera formation consisted of two eruptive episodes, the first of which deposited K-rich, calc-alkaline volcanic rocks. The second episode had two pulses that produced rhyolitic then andesitic volcanic rocks. An unwelded matrix with lithic fragments of metapelite and subvolcanic rhyolite and quartz and biotite-rich pumice characterizes the rhyolitic episode. The second pulse created a 300 m thick sequence of andesitic flows that are hydrothermally altered at the caldera margin (Riller et al., 2001).
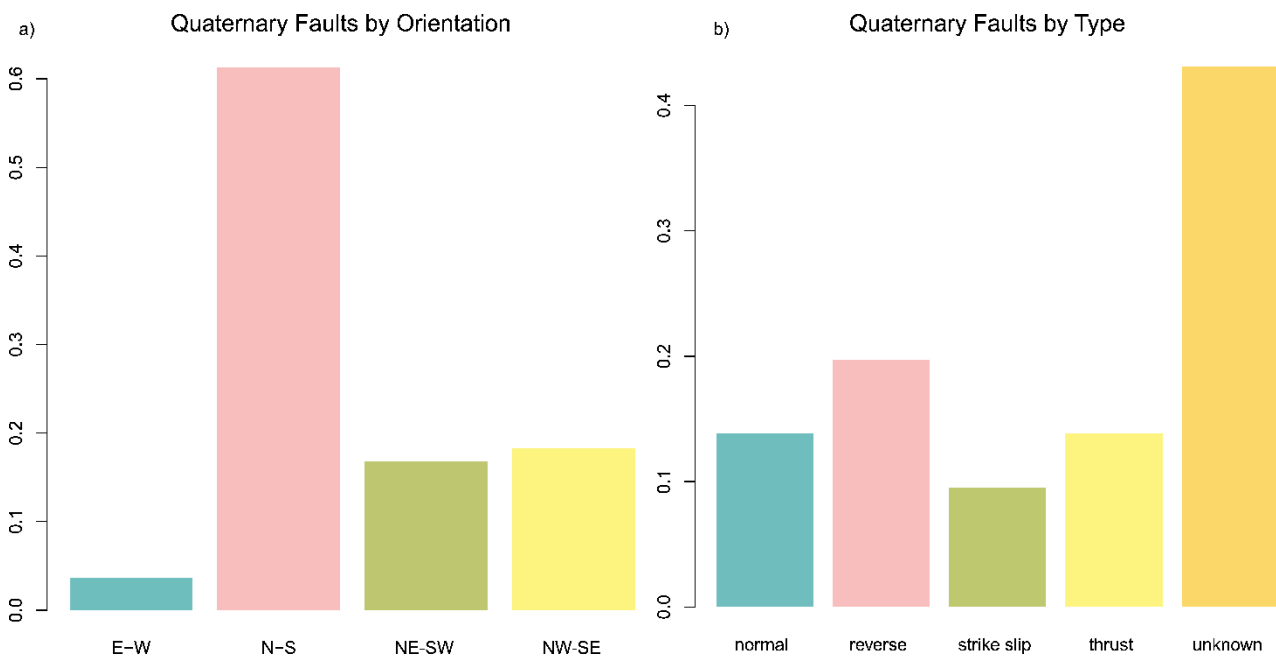

Figure 2: Favorable structural settings including (a) faults, Quaternary faults with buffer zones, calderas, and identified favorable structural areas; and (b) favorable settings by type.

4.1.2 Faults

Faults are key components of many geothermal systems. In a survey of global hot springs, Curewitz and Karson (1997) found that 78% of hot springs were associated with faults. Further work by Faulds et al. (2011) characterized fault types that are most likely to host geothermal systems in the Great Basin region of the western USA, with similar findings in other extensional settings such as western Turkey (Faulds et al., 2010). For this study, our primary focus is on Quaternary faults, which are likely to have open fractures and damage zones that have not been sealed by mineralization (Coolbaugh et al., 2002).

Fault traces were obtained from the 1:250,000 SEGEMAR geologic maps (Blasco et al., 1996; Seggiaro et al., 2015), additional literature (Casa and Cegarra, 2016), and observations and field interpretation. New data were digitized using Google Earth and imported into ArcGIS. Each Quaternary fault was treated with a 1 km buffer in ArcGIS using the geoprocessing tool (Figure 2a). Where possible, additional attribute data were added to the fault database, such as sense of motion, fault type, and recency.

Of the Quaternary faults identified, the majority are N-S striking normal or thrust faults (Figure 3b). Approximately 40% of the Quaternary faults mapped in the area have no sense of motion information and three have no information on attitude (Figure 3a and 3b).

Figure 3: Quaternary faults by (a) strike and (b) type.

4.1.3 Favorable Structural Settings

Favorable structural settings have previously been identified for geothermal systems in the Great Basin region of the western USA (Faulds et al., 2006, 2011) and western Turkey (Faulds et al., 2010), and similar procedures were used to define favorable settings in Area 1. Once all Quaternary faults and calderas were compiled in the area, polygons were drawn encapsulating areas of favorable structure settings in Area 1 in NW Argentina (Figure 2). The applicable favorable settings found in Area 1 included lineaments, fault intersections, and pull-aparts.

Additional attributes for favorable structural settings include certainty and quality. Certainty values range from 0 to 1 and refer to our confidence in the data for delineating a favorable structural setting. Quality refers to the favorability itself and also ranges from 0 to 1. A high quality ranking of 1 would be assigned to an area with a greater occurrence of favorable structural settings such as complex fault interactions zones. These additional attributes will be incorporated as the final PFA model begins to be constructed.

4.2 ASTER Hydrothermal Alteration

Geothermal fluid circulation typically results in hydrothermal alteration of rocks. The type and degree of alteration preserves evidence of characteristics of the system, in particular the temperatures and chemistry of the fluid responsible for the alteration, although these are not the only factors in hydrothermal alteration. Rock type, pressure, and other parameters also affect alteration and these should be considered when using alteration as a tool for exploration.

Argillic alteration is caused by the hydrothermal alteration of feldspars to minerals such as illite and smectite, and can indicate the presence of geothermal activity. Advanced argillic alteration occurs where acid-bearing steam released by boiling fluids rises towards the surface and condenses or mixes with shallow groundwater to produce acidic waters that alter host rocks to minerals such as kaolinite and alunite. Phyllic alteration is represented by alteration of feldspar, biotite and silicate minerals to quartz, sericite and pyrite, and typically occurs at higher temperatures than argillic alteration.

ASTER data for Area 1 were used to identify zones of hydrothermal alteration. The ASTER L1T images (14 bands per scene) were orthorectified and corrected for any crosstalk effect present in the SWIR bands of ASTER. The images were then converted from radiance to reflectance by applying an atmospheric correction using the FLAASH module of the ENVI program. Identification of the hydrothermal alteration zones was made through the application of algebra and logical relations between bands with the establishment of thresholds using the Band Math tool in ENVI (Exelis Visual Information Solutions, Boulder, Colorado) following the methodology of Mars (Mars and Rowan, 2006; Mars, 2013). Hydrothermal alteration types identified were argillic, phyllic, propylitic, and silicic. Subsequently, a mosaic was generated for each type of alteration. The results were then exported to a shapefile format after elimination of false positives.

Of the four types of alteration inferred from the ASTER data, two are used for this study – phyllic and argillic. Silica alteration can be valuable when it is associated with young silicification; however, the silica mapped is most likely associated with silica-rich rocks such as quartzite and sandstone and thus is not very useful. Propylitic alteration is used to characterize the heart of many high-temperature geothermal systems, but to see this type of alteration at the surface often signifies extinct, eroded, and exposed cores of geothermal systems. It is unexpected to see this type of alteration at the surface of an active system and when it is found it is more indicative of a breached system that may no longer be producible.

Argillic alteration appears to be the most common of the alteration types identified in Area 1. Mapped areas of phyllic alteration appear around all identified geothermal areas and surface manifestations. There is also a large area of phyllic alteration in one of the salars to the east of Cerro Tuzgle that we interpret as salt deposits. Argillic with some silicic alteration is predominant in Aguas Caliente and other smaller thermal areas that fall along the COT moving off to the southeast (Figure 4a).

Upon comparison of the alteration layer and the volcanic ages layer, it was determined that further refinement of the alteration ages could be achieved by cross-referencing the alteration ages with the ages of the volcanic units the alteration coincides with. This work was completed in ArcGIS. Alteration was plotted as type of alteration (Figure 4a) as well as approximate age of alteration (Figure 4b), which was determined from regional geology.

In this PFA, age of alteration may be an indication of remnant heat being present, especially with Quaternary age alteration. Alteration of this age is found near Quaternary age calderas such as Aguas Calientes and Coranzulí as well as near Cerro Tuzgle. Further refinements of age of alteration will be accomplished using information from more recent geologic mapping efforts. This work is expected to continue.
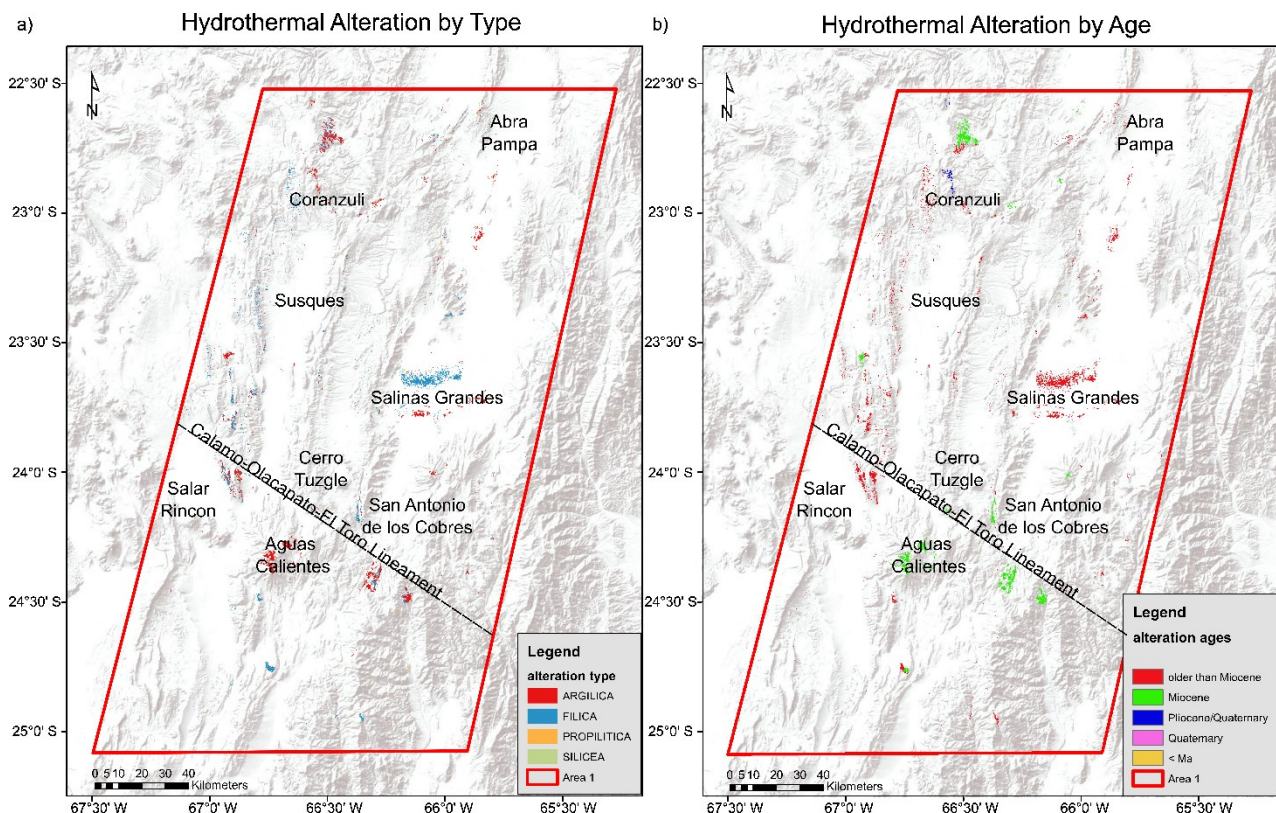

Figure 4: Surface hydrothermal alteration map by (a) type derived from ASTER images and (b) approximate age.

4.4 Volcanic Ages

Heat flow data are scarce in Area 1; therefore, other datasets that give some indication of heat were necessary. Here, we used the age of volcanism as an indicator of current and/or past presence of heat. Area 1 has multiple areas of volcanics less than 5 Ma. The Cerro Tuzgle-Tocomar area as well as Aguas Caliente in the south are primarily in this age range. Coranzulí has relatively young, late Miocene volcanics with younger (< 5 Ma) volcanic units to the west along the Ramallo and Coyaguayma fault zones.

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Type of rock was also collected for the project (5b). Volcanic units were subdivided into felsic, intermediate, and mafic. We inferred that felsic volcanic rocks are more likely to be a heat source for geothermal systems in the Puna, due to larger volumes and greater crustal interaction (vs the simple, mono-genetic basaltic cinder cones in the area).

Igneous geology was gathered from SEGEMAR 1:250,000 GIS products (Blasco et al., 1996; Seggiaro et al., 2015). Absolute ages for the volcanic units were gathered from the Andean Igneous and Non-Igneous Datasets (Pilger, 2018) (Figure 5a). Rock types for all volcanic units less than 5 Ma are also plotted (Figure 5b).
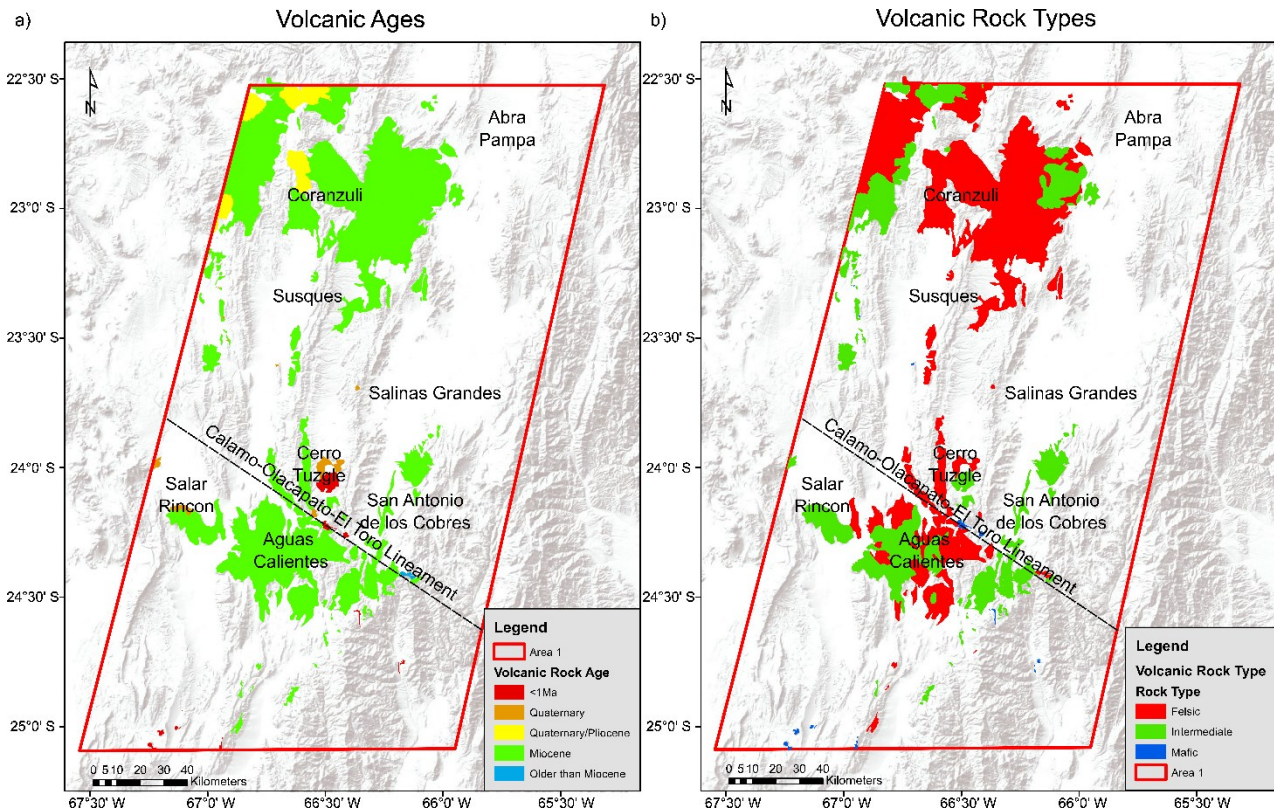
Figure 5: Volcanic units by (a) absolute age and (b) rock type.

4.5 Hot Springs

Hot springs and other surface manifestations are often the first indication of the presence of a geothermal system. The presence of springs can provide information regarding all three components of a geothermal system – heat, fluid, and permeability. For these reasons, spring data were identified as compulsory for the study.

Hot spring data were compiled from a catalog of manifestations published by SEGEMAR (Pesce and Miranda, 2003). The catalog contained duplicate values for some locations, disparate quality of location values, and was missing some newly identified springs. The catalog was supplemented with spring data from various researchers (Aquater, 1981; Sierra and Pedro, 1988; Dames and Moore, 1999; Salusso and Moraña, 2015; Carrizo, 2015; Carrizo, 2015b; Carrizo, 2016a; Carrizo, 2016b; and Peralta et al., 2016) Springs were plotted as points, and for the purposes of the future PFA, were mapped with a 2.5 kilometer buffer zone as the heat, fluid, and/or permeability likely extends some distance from the point location of the spring itself (Figure 6a).

As expected, many of the springs fall around identified geothermal areas. A southern cluster is associated with Cerro Tuzgle, Tocomar, and Aguas Caliente. Northward toward Coranzulí, the springs follow a N-S trend and move off to the west following the faults that bound the Coranzulí caldera. It should be noted that this is not an exhaustive list of thermal springs in Area 1 but represents those documented to date.

Over 50% of the springs fell into two categories, 15-30 °C or 40-55 °C, and six springs in the area had recorded field temperatures of over 65 °C. All springs with measured temperatures over 65 °C were south of Tuzgle in the Tocomar geothermal area. Most of the measured temperatures around Coranzulí were low temperature (< 30 °C), but there were higher temperature springs west of Coranzulí associated with the two major lineaments in the area (the Coyaguayma and Rachaite lineaments).
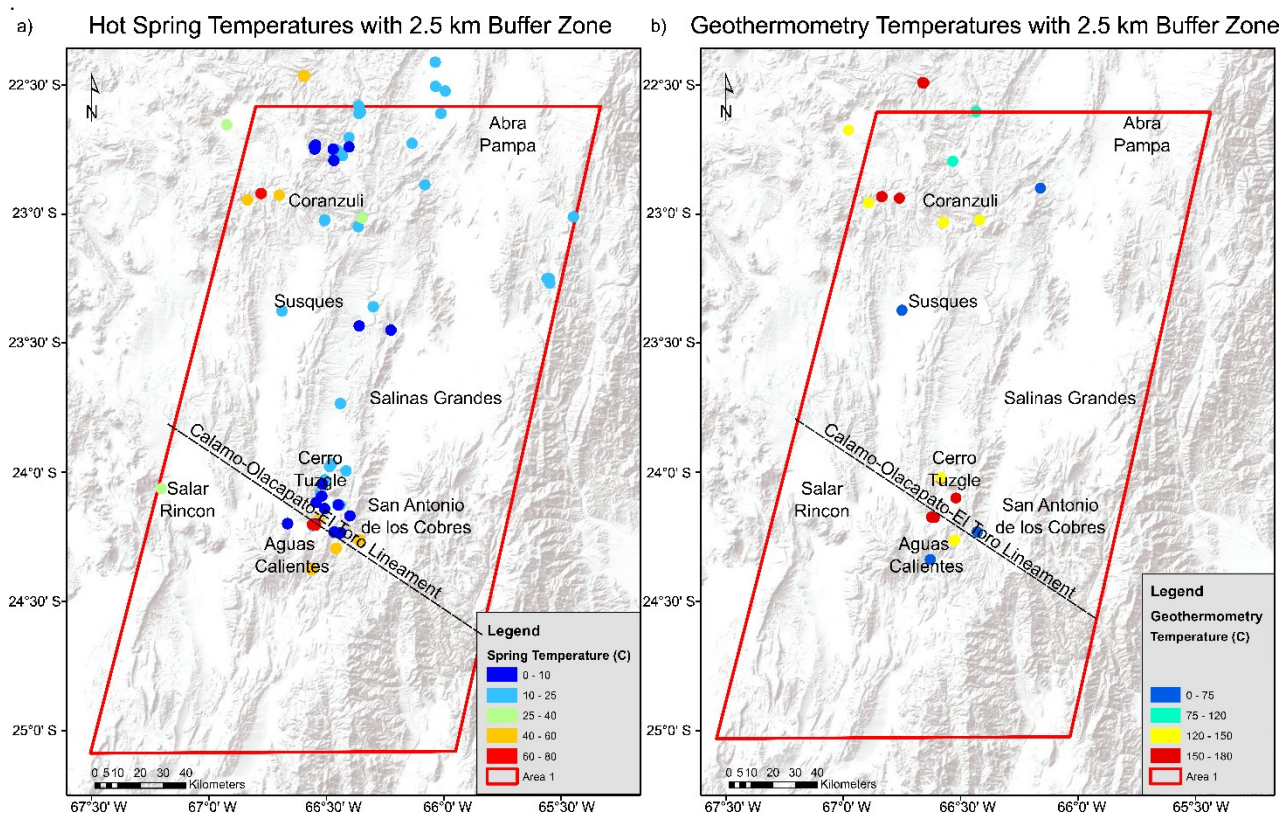
Figure 6: Springs temperatures (a) and geothermometry with a 2.5 km buffer zone

## 4.6 Geochemistry

4.6.1 Geochemistry

Geochemical data for Area 1 were compiled from various published and unpublished sources. Key sources include Panarello et al. (1992), Pesce and Miranda, (2003), Carrizo (2015a), and Peralta et al. (2016). In total, 132 geochemical analyses of spring or stream waters were available; however, of these, only 113 had an ionic charge balance within 10% and were used for subsequent interpretation and evaluation. Samples were obtained from the following geothermal areas: Aguas Calientes, Antuco, Aritzar, Baños de Pompeya, Baños de Incachule, Cerro Tuzgle, Cono Panizo, Coranzulí, Mina Pirquitas, Olaroz, Orosmayo, Pairique, Queñual, Rachaite, Salar de Rincón, Tocomar and Vilama. Review of the data indicates that most fluids are alkali-chloride or bicarbonate waters – only a couple of samples are sulfate-dominated (Figure 7). Total dissolved solids range from less than 1000 mg/l, to over 300,000 mg/l. Most samples contain less than 10,000 mg/l.

4.6.2 Geothermometry

For the purposes of the PFA of Area 1, the geochemistry data were reviewed to evaluate which geothermometers were appropriate to apply to the samples to estimate reservoir equilibration temperatures. Many of the samples are not classified as mature alkali-chloride fluids (Figure 7), thus it is not appropriate to apply traditional cation geothermometers to these samples, and our initial evaluations thus used the SiO_2 geothermometer of Fournier (1977) to estimate sub-surface temperatures. Additionally, for some locations there were several spring and stream samples collected for an area. The samples chosen for SiO_2 geothermometry were those collected from the hottest springs in an area, as we infer that these are the most representative of the deep geothermal system and should thus be more reliable. We applied the conductive quartz geothermometer to these representative measurements initially: if the quartz (conductive) geothermometer estimated temperatures less than 120 °C, the chalcedony (conductive) geothermometer was used instead. The results indicate that the highest estimated equilibration temperature was 172 °C at the Tocomar geothermal system. Similar temperatures were estimated at Cerro Tuzgle, and Queñual. Geothermometry values are plotted with the same 2.5 kilometer buffer as used with the hot springs (Figure 6b).

Future efforts will perform multiple-component equilibrium geothermometry calculations to evaluate reservoir equilibration temperatures and see how these compare to the silica geothermometry.
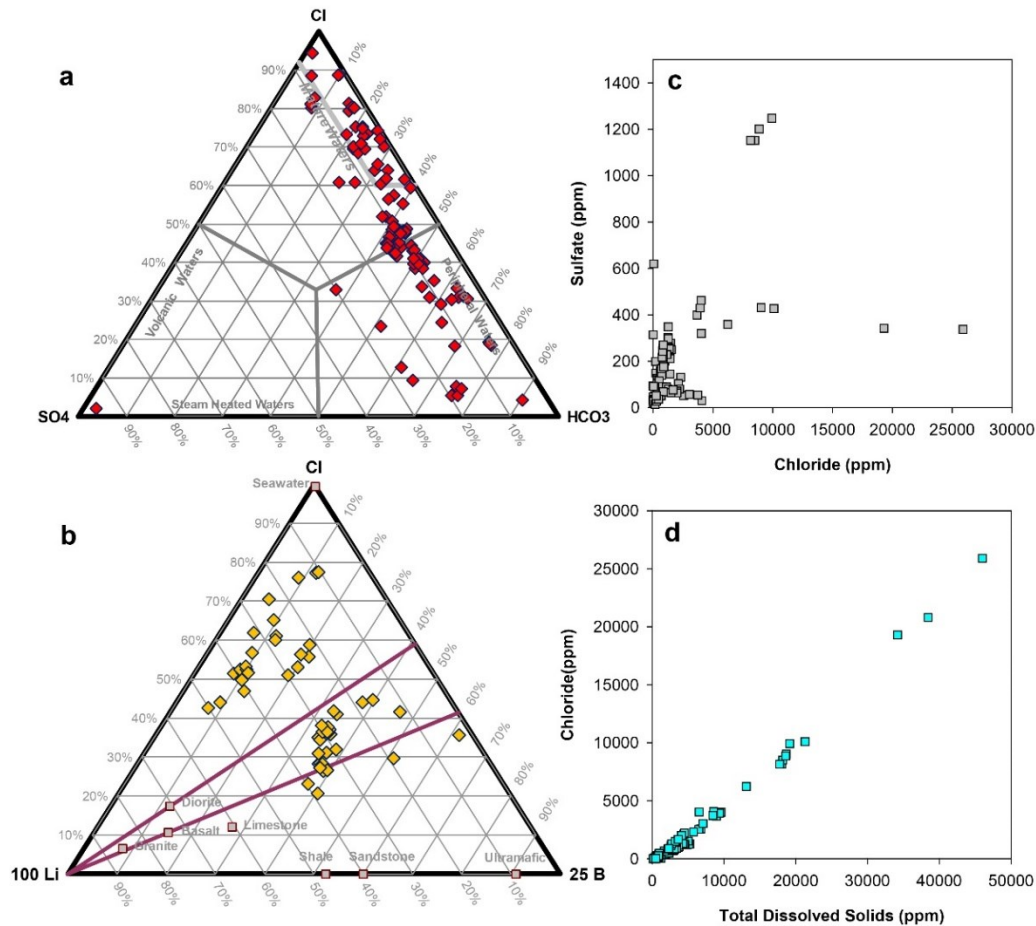
Figure 7: Ternary plots of the fluid chemistry samples compiled for the target PFA area in the Puna, NW Argentina. (a) Cl-SO₄-HCO₃, (b) Cl-F-B, (c) Cl vs SO₄ cross plot (d) Total Dissolved Solids vs Cl.

4.7 Geophysics

4.7.1 Magnetic Data

The magnetometry information compiled for this project corresponds to the combination of the Puna Norte and Salta-Catamarca geophysical datasets, belonging to SEGEMAR. These data were processed with two filters: first vertical derivative of the magnetic field reduced to the pole, and analytic signal. The first technique highlights the magnetic effects caused by relatively shallow and local bedrock characteristics, such as magnetized intra-sedimentary faults. The analytical signal filter is used to detect geological discontinuities associated with magnetization (contrasts of magnetic susceptibility), such as faults or dykes and contacts of intrusive bodies, which are represented as maximums in the grid. However, when comparing the results of this filter with the hydrothermal alteration areas (identified by the band ratio of RGB 4/5, 4/6 and 4/8 of the ASTER image), the grid had local minimum values in the alteration zones. This is possibly associated with the destruction of the magnetite by alteration fluids. The map of magnetic anomalies can be seen in Figure 9a.

Upon review, the location of magnetic lows does not appear to be associated with alteration as anticipated. This layer will not be used in the final PFA product for this reason. The lows seem well dispersed across Area 1 with the exception of the calderas and volcanic centers.

4.7.2 Horizontal Gravity Gradient

Gravity data were provided to SEGEMAR by IGN (Argentina's National Geographic Institute). The gravity stations are somewhat limited for the area, thus our map may not capture the true spatial variability in gravity. There are 231 measurements for Area 1, most along roadways and a cluster around Cerro Tuzgle. A density for topography of 2670 kg/m³ was applied. We interpolated the gravimetric data, calculated the first order horizontal derivatives of the field, and applied a horizontal gradient filter. The objective of this technique was to identify the rapid lateral changes of density, as can happen across vertical formation contacts or at the edges of a sub-surface body.

For geothermal exploration, gravity gradients can be used to identify possible structural discontinuities that may be associated with faulting (and thus potential permeability). Density contrasts between formations that are displaced across a fault will produce changes in horizontal gravity gradient. This is especially true at the margins of ranges where normal faults are down-dropping rocks allowing colluvium to accumulate in basins. In Area 1, we generally observe north-south trending zones of high and low horizontal gravity anomalies, which likely reflect the structural fabric of the area and variable lithologies of the thrust sheets. However, the low data

density for Area 1 does not provide sufficient spatial resolution to resolve such density contrasts, and consequently the team decided not to use this layer in the play fairway model of the area.
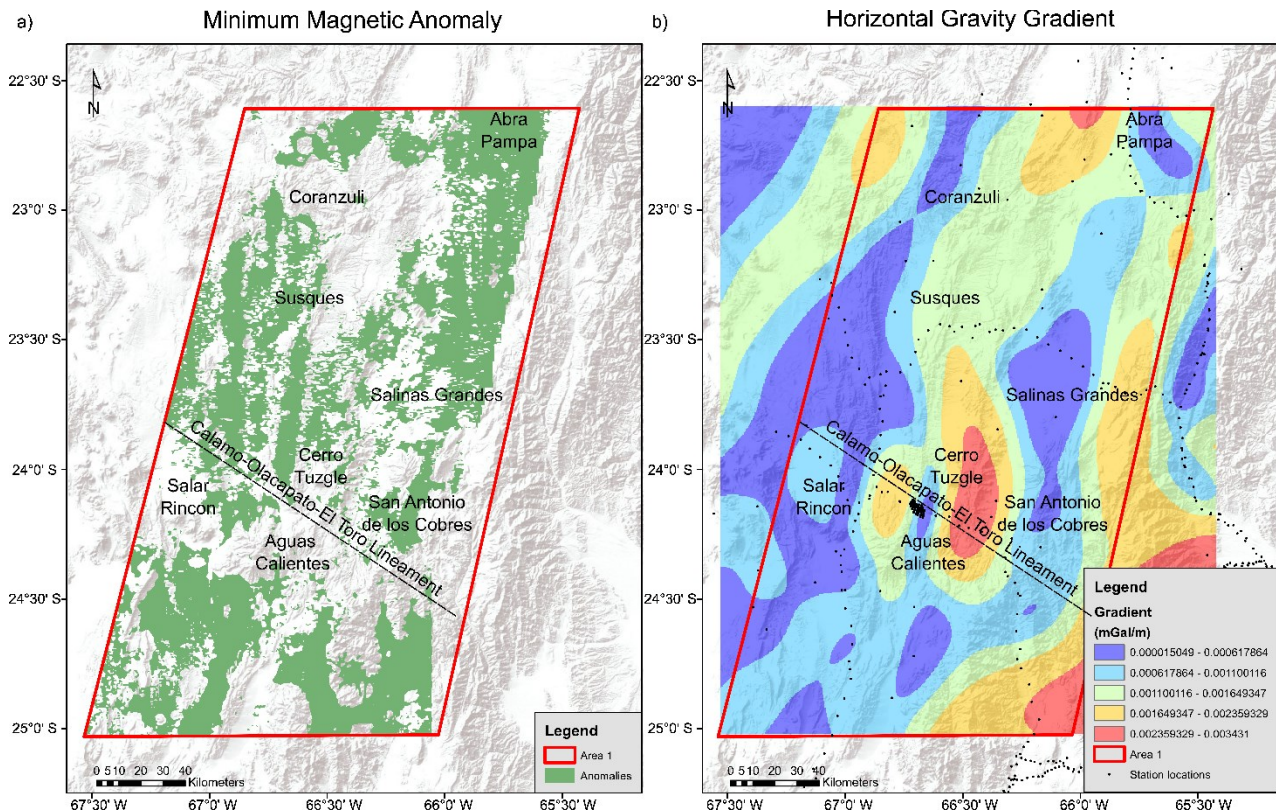
Figure 9: Geophysical data for Area 1 includes aeromagnetometry, plotted here as magnetic low anomalies of the analytic signal (a); and horizontal gravity gradient (b) with stations plotted.

4.7.3 Earthquake data

Areas of active tectonic activity and earthquake occurrence commonly coincide with areas that have geothermal resource potential (Coolbaugh et al., 2002). A relatively high stress field is required to fracture rock and dynamically maintain open fractures in the rock (Curewitz and Karson, 1997) (which is important for maintaining permeability in some geothermal systems), and the presence of earthquakes in an area can be an indicator of such high levels of stress.

Earthquake data for the study were acquired from the National Institute of Seismic Prevention (INPRES). The original data span a date range from December 30, 1999 to January 23, 2019 and include > 6,000 points. As the data covered two separate provinces, some work was needed to standardize the data. The date format was different for the two provinces, and these were converted to the scientific format (yyyy-mm-dd). The second "cleaning" of the data involved removing earthquakes with focal depths of greater than 20 km, as these would not likely be related to crustal geothermal systems (Figure 10).

5. DISCUSSION

5.1 Controls on geothermal systems in the Puna

Geothermal centers in Area 1 and of the Puna tend to be associated with young volcanic systems, such as Tuzgle and Coranzulí. These volcanic centers and calderas appear to be structurally controlled. We speculate that faults and fractures associated with multiple caldera forming eruptions provide pathways for recharge and geothermal fluid migration to the surface at Coranzulí. The Tuzgle geothermal system may be recharged from high altitude ridges above 4,500 m (Giordano et al., 2013). At lower elevations, upwelling geothermal fluids exhibit plume-like movement in areas such as Tocomar, where the valley cover seals the fractured Ordovician basement that is thought to host geothermal reservoirs in the area (Coira, 1995).

Tocomar produces higher temperature surface fluids, and this has been attributed to the intersection of the COT and secondary extensional structures in the area (Giordano et al., 2013), creating a complex and thus more favorable structural setting (Faulds et al., 2011), and therefore greater potential for permeability. Thermal areas to the southeast of Tocomar are likely similarly controlled, as are thermal areas to the northwest of Coranzulí.

Geothermal centers of Puna play fairway Area 1 tend to be associated with deep reactivated fractures zones as Coyaguayma and COT lineaments where volcanic centers and calderas appear to be structurally controlled. We infer that faults and fractures associated with multiple caldera forming eruptions such as Aguas Calientes and Coranzulí also provide pathways for recharge and fluid migration to the surface from deep geothermal reservoirs.
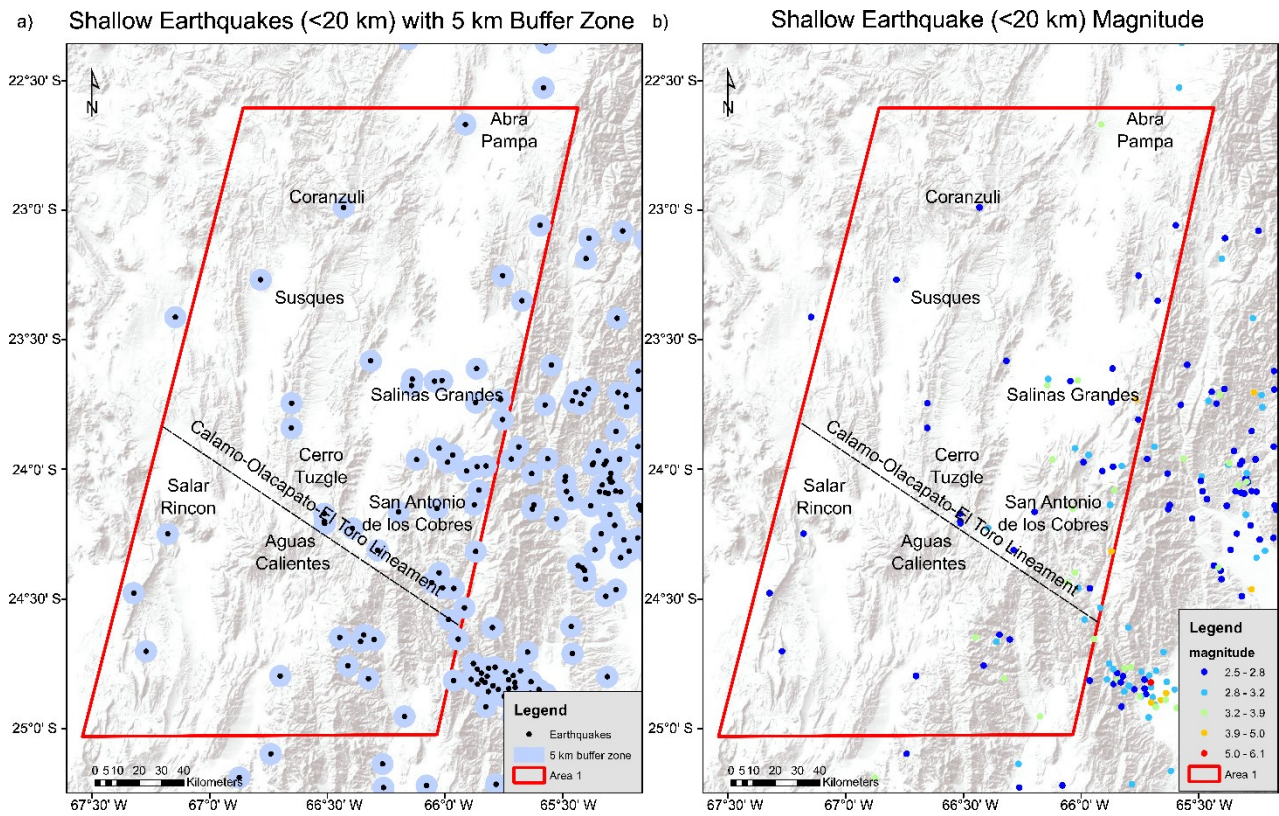
Figure 10: Earthquake (a) locations (for depths of less than 20 km) and density and (b) magnitude.

The highest temperature surface fluids in Area 1 are at Tocomar geothermal system where we see favorable structural settings conducive to high potential permeability (Faulds, 2011): these are attributed to the intersection of the COT and secondary extensional structures (Giordano et al., 2013), a magmatic heat source evidenced by Quaternary volcanic activity such as San Geronimo and Negro de Chorrillos monogenic cones and Tocomar ignimbrite and the fractured Ordovician basement that is thought to host geothermal reservoirs in the area (Coira, 1995). Even when there is no evidence of Quaternary volcanism along the Coyaguayma lineament, we suggest that thermal areas to the northwest of Coranzulí are structurally controlled in a similar fashion as the Tocomar geothermal system. The Tuzgle geothermal field is a system associated with Quaternary volcanic activity with no evident structural control. Other similar systems exists in the Puna such as Cono Panizo, Olaroz, Orosmayo, Pairique, and Vilama although they are not in the current study area. It is possible a better understanding of the geothermal system associated with Tuzgle with give insight into the others as well.

5.2 Determining value of each dataset for PFA

Many datasets were gathered and layers created that can give some insight to geothermal resource potential. As the next stage of the project moves forward and weightings are assigned so that layers can be combined to produce the play fairway, it is important to determine the role of each dataset. For traditional geothermal systems, three properties are required: heat, permeability, and fluid. Each of the layers generated represents the potential for one, two, or all these three properties. For this project, we allocated the various datasets to one (or more) of these three categories (Table 1).

Table 1: Datasets by geothermal property represented

Heat	Permeability	Fluid
Age of hydrothermal alteration	Age of hydrothermal alteration	Age of hydrothermal alteration
Presence of hot springs	Presence of hot springs	Presence of hot springs
Geothermometry	Calderas	Cold springs
Volcanic ages	Quaternary faults	Salars
	Favorable structural setting	
	Earthquakes	

6. CONCLUSIONS

For Argentina, we anticipate that the results of this PFA will provide insight into future exploration priorities for Area 1. As mentioned previously, missing data and data disparity provided a challenge for the team, but as the PFA is an iterative process that can be updated as new data become available, this initial PFA can be improved in the future. We anticipate that areas with previously unrecognized geothermal potential in Area 1 as identified by the PFA may provide targets for future exploration to fill in missing data gaps, as well as to confirm previously collected data to increase confidence in selected layers. As confidence increases and gaps are filled, the model can be adjusted, and it is possible that exploration targets can be refined even further. Additionally, the completed PFA can be combined with direct evidence and conceptual models to increase our understanding of the geothermal systems in Area

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1, and it is possible that data compiled during this project can be used to fine-tune previous conceptual models of the area such as those proposed by Giordano et al. (2013).

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