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Preliminary Assessment of the Geothermal Resources in the Santa Lucía Basin, Uruguay

Morales, E. [1]; Vieira, F. [2]; Veroslavsky, G. [1]; Plenc, F. [1]; de Santa Ana, H. [3]

[1] *Universidad de la República, Facultad de Ciencias, Montevideo, Uruguay*

[2] *Observatorio Nacional, Rio de Janeiro, Brasil*

[3] *Administración Nacional de Combustibles, Alcohol y Portland (ANCAP), Montevideo, Uruguay*

Abstract

Geothermal energy is the energy stored in the form of heat in rocks, sediments, soils, and groundwater, regardless of temperature, depth, and origin. This study presents a primary assessment of the geothermal resources in the Santa Lucía Basin. This basin contains Mesozoic volcanic and sedimentary rocks and a thin cover of Cenozoic sediments and sedimentary rocks. It is compartmentalized into two sub-basins, Norte and Sur, by the Santa Rosa High. Using stratigraphic and bottom hole temperature data from 10 exploratory wells, the crustal temperature and the geothermal resource up to 3 km depth are calculated. The highest temperature values are recorded in the eastern sector of the Sur sub-basin near the Cochengo and San Jacinto wells, both of which are located very close to the Santa Rosa High. The regional distribution of the geothermal resources mirrors the distribution of crustal temperatures. These results align with the conceptual geological-geothermal model for the basin, which suggests that the heat source follows a normal geothermal gradient, with recharge waters circulating through deep faults that define the main structural features of the basin. The Santa Lucía Basin is a region of significant social, productive, industrial, and economic importance in Uruguay, where the use of geothermal energy could contribute to its sustainable development.

Keywords: energy transition, direct use of geothermal energy, renewable energies

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Claudio Gaucher
Universidad de la República, Centro Universitario Regional del Este, Treinta y Tres, Uruguay

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Correspondence

Ethel Morales
ethel@fcien.edu.uy

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Evaluación preliminar de los recursos geotermales en la Cuenca Santa Lucía, Uruguay

Resumen

La energía geotérmica es aquella almacenada en forma de calor en las rocas, los sedimentos, los suelos y las aguas subterráneas, cualquiera sea su temperatura, profundidad y procedencia. En este trabajo se presenta una evaluación preliminar de los recursos geotermales de la Cuenca Santa Lucía. Esta cuenca presenta un relleno de rocas volcánicas y sedimentarias mesozoicas y una delgada cobertura de sedimentos y rocas sedimentarias cenozoicas, y se presenta compartimentada, por el Alto de Santa Rosa, en dos subcuencas, Norte y Sur. Utilizando datos e información estratigráfica y de temperatura de fondo de pozo (BHT) de diez perforaciones exploratorias se calculó la temperatura del subsuelo y el recurso geotermal base hasta 3 km de profundidad. Los valores más elevados de temperatura se ubican en el sector este de la subcuenca Sur, en las proximidades de los pozos Cochengo y San Jacinto, en ambos casos ubicados muy próximos al Alto de Santa Rosa. La distribución regional del recurso geotermal base sigue el mismo diseño que el de las temperaturas del subsuelo. Estos resultados son coherentes con el modelo geológico-geotérmico conceptual disponible para la cuenca, donde la fuente de calor es un gradiente geotérmico normal y en el que las aguas de recarga circulan a través de fracturas profundas que configuran sus principales rasgos estructurales. La Cuenca Santa Lucía constituye una región de significativa importancia social, productiva, industrial y económica de Uruguay en la que el uso de la energía geotérmica podría contribuir a su desarrollo sustentable.

Palabras clave: energías renovables, uso directo de la geotermia, transición energética

Avaliação preliminar dos recursos geotérmicos na Bacia Santa Lucía, Uruguai

Resumo

A energia geotérmica é a energia armazenada sob a forma de calor nas rochas, sedimentos, solos e águas subterrâneas, independentemente da sua temperatura, profundidade e origem. Este trabalho apresenta uma avaliação dos recursos geotérmicos da Bacia Santa Lucía. Esta Bacia é caracterizada pelo preenchimento predominantemente de rochas vulcânicas e sedimentares mesozoicas, com uma fina cobertura de sedimentos e rochas sedimentares cenozóicas, sendo compartimentada pelo Alto de Santa Rosa, em duas sub-bacias, Norte e Sul. Utilizando dados estratigráficos, medições de temperatura de fundo de poço (BHT) e informações provenientes de dez poços exploratórios foram calculadas a temperatura do subsolo e a estimativa de recurso geotérmico para profundidades até 3 km. Os maiores valores de temperatura são encontrados no setor leste da sub-bacia Sul, nas proximidades dos poços Cochengo e San Jacinto, ambos situados próximos ao Alto de Santa Rosa. A distribuição regional do recurso geotérmico reflete o padrão observado nas temperaturas do subsolo. Estes resultados são consistentes com o modelo geológico-geotérmico conceitual existente para a bacia, onde a fonte de calor é um gradiente geotérmico normal. O modelo indica que as águas de recarga circulam através de fraturas profundas que definem as principais características estruturais da bacia. A Bacia Santa Lucía constitui uma região de significativa importância social, produtiva, industrial e econômica no Uruguai, na qual o uso da energia geotérmica poderia contribuir para o seu desenvolvimento sustentável.

Palavras-chave: energias renováveis, aproveitamento direto da energia geotérmica, transição energética

1. Introduction

The social and economic development of modern societies increasingly relies, both directly and indirectly, on the availability of energy resources. Global energy demand has steadily increased since the Industrial Revolution, having tripled in the past 50 years, and is expected to increase by at least the same amount over the next 30 years. Although hydrocarbons remain the primary source of energy, there is a clear global trend toward strengthening energy transition, with a growing emphasis on the use and diversification of renewable and clean energies (International Energy Agency, 2025; International Renewable Energy Agency, 2021).

Uruguay has made notable progress in diversifying and decarbonizing its energy matrix, a process referred to as its first energy transition, which has garnered international recognition. Since 2016, renewable sources, primarily hydropower, wind, and biomass, have accounted for nearly 60% of the country's overall energy matrix and 98% of its electricity generation, positioning Uruguay as a regional leader in Latin America. The country is now advancing its decarbonization strategy through what is known as the second energy transition, which aims to reduce fossil fuel consumption and achieve carbon neutrality by 2050 (Ministerio de Industria, Energía y Minería, 2025). Despite this progress, geothermal energy is yet to be incorporated into the energy portfolio of Uruguay, and thus, has not received the research and investment needed for its development.

The aim of this study is to present a first and primary assessment of the geothermal resource base, i.e., all the thermal energy contained beneath an area, in a specific volume, and to a given depth for the Santa Lucía Basin.

There have been very few studies on geothermal energy and its potential in the Santa Lucía Basin. Two of them are geophysical studies focusing on the southeastern sector of the basin, particularly in the Rincón de la Bolsa region (Canelones, Uruguay). These studies identified low-resistivity intervals at depth, which may correspond to sandy units or fractured basement rocks capable of hosting groundwater. Therefore, assuming a geothermal gradient of 30 °C/km, they estimated that at depths of around 800-900 m, groundwater temperatures would range from approximately 36 °C to 40 °C (Corbo et al., 2021; De los Santos et al., 2018). Besides, a conceptual geological-geothermal model was proposed through the integration of geological and geophysical data, corresponding to a classic low-temperature geothermal system, where waters circulate at deep levels through fractures that constitute the structural edges of the basin. Thus, assuming a normal geothermal gradient in the basin, it would be reasonable to expect temperatures between 65 °C and 75 °C at depths of ~2000 m and between 90 °C and 105 °C at depths of ~3000 m (Morales et al., 2021).

1.1 Geological Framework

The Santa Lucía Basin is described as an intracratonic pull-apart basin (Rossello et al., 2001), which propagates through the main planes of crustal weakness in the ENE direction of the Piedra Alta terrane (Oyhantçabal et al., 2011). Its geometry in plan is rhomboidal, compartmentalized into two sub-basins, namely, Norte and Sur by the E-W Santa Rosa High (Veroslavsky et al., 2004) (Figure 1). The Sur sub-basin has a thicker volcano-sedimentary filling than the Norte sub-basin, with a maximum estimated thickness from geophysical methods of 2,712 m (3 km west to the Sauce 1 well) (Rodríguez et al., 2020).

The filling of the Santa Lucía Basin comprises mostly Mesozoic continental sedimentary rocks with a thin cover of Cenozoic sedimentary rocks and sediments (Figure 1C). The Cretaceous Migues Formation (Bossi, 1966) makes up most of the fill of the Santa Lucía Basin (>2000 m) (Veroslavsky et al., 2004). The Migues Formation includes continental silico-clastic lithologies, essentially fluvial, eolian, and lake deposits. Exploratory hydrocarbon wells, particularly in the Sur sub-basin, show the development of important sandy bodies with thicknesses of >100 m, average porosities of 22%, and permeability values between 150 and 460 mD intercalated with claystones at various depths (H. de Santa Ana & N. Ucha, personal communication, 1994; Tomasini et al., 2019; Veroslavsky et al., 2004).

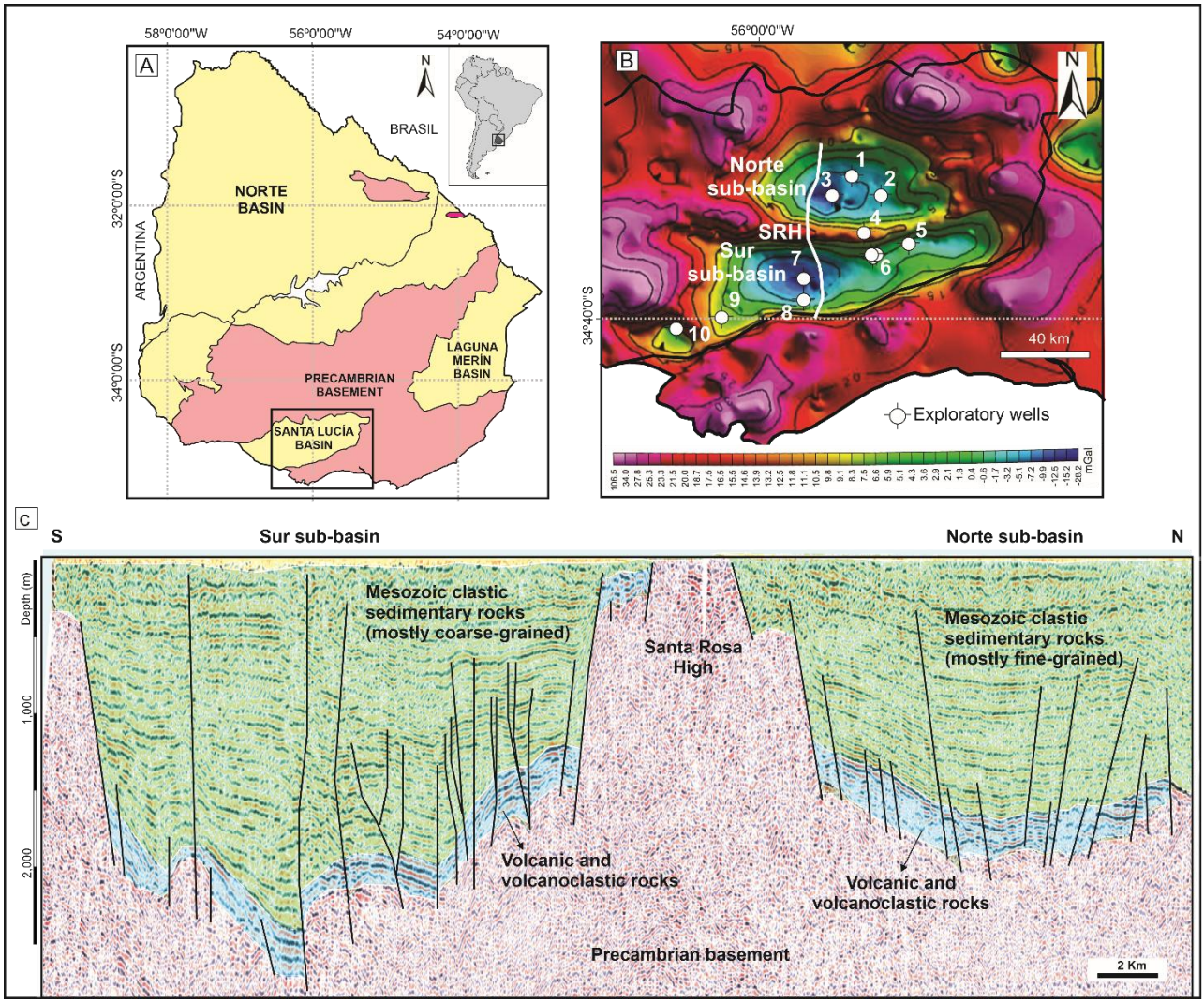

Figure 1. Santa Lucía Basin. A) Simplified geological map of Uruguay; the box indicates the location of the map shown in B. B) Bouguer anomaly map. The locations of the seismic section (see below) and the exploratory wells are indicated. Wells: (1) Castellanos, (2) Tala, (3) San Bautista, (4) Cochengo, (5) Piedra Sola, (6) San Jacinto 2, 3, and 4, (7) Sauce 1, (8) Sauce 2, (9) Progreso, and (10) Las Brujas; SRH: Santa Rosa High. C) S-N interpreted seismic section of the Santa Lucía Basin showing its structural configuration

Note. Modified from Morales et al. (2021) and Rodríguez et al. (2020).

2. Materials and Methods

This study follows a sequential workflow to estimate subsurface temperatures and geothermal resources in the Santa Lucía Basin. First, bottom-hole temperature (BHT) data from hydrocarbon exploration wells were compiled and corrected to approximate equilibrium formation temperatures using an empirical approach. Subsequently, the geothermal gradient and heat flow were calculated for each well, and the vertical distribution of subsurface temperature was modelled using a one-dimensional conductive heat transfer model. Finally, the base geothermal resource was estimated using a volumetric method based on the calculated temperature field.

Herein, the BHTs from 10 hydrocarbon exploration wells (Figure 1B, Table 1), drilled by the state-owned oil company ANCAP in the second half of the 20th century, were used. These BHT data were compiled from log header for each well.

Table 1. Wells used in this work with their coordinates, total depths, and bottom hole temperatures (BHTs)

Name	Latitude (°)	Longitude (°)	Total depth (m)	BHT (°C)
San Jacinto 2	−34.545849	−55.875060	1119	54.4
San Jacinto 3	−34546025	−55.866753	1211	54.4
San Jacinto 4	−34.544231	−55.871659	1231	48.9
Sauce 1	−34.597369	−56.050458	2460	63.3
Sauce 2	−34.646865	−56.053746	1692	41.1
Las Brujas	−34.686111	−56.381350	724	23.9
Castellanos	−34.387471	−55.921867	2026	52.2
Cochengo	−34.498411	−55.895172	318	28.9
San Bautista	−34.414410	−55.959704	1952	62.2
Tala	−34.419061	−55.851575	1747	53.3

Subsurface temperature (Tsub) was estimated from BHT data corrected using the empirical polynomial correlation of the American Association of Petroleum Geologists, originally developed by Kehle et al. (1970), according to the following equation:

$$\Delta T = az + bz^2 + cz^3 + dz^4 \qquad \text{(equation A)}$$

where ΔT is the correction temperature (°C); z is the BHT depth (m), corresponding in this case to the total well depth; and a, b, c, and d are the coefficients with values of 1.878×10^{-3}, 8.476×10^{-7}, 5.091×10^{-11}, and 1.681×10^{-14} °C/m, respectively.

The AAPG method was adopted as a methodological approach for estimating the geothermal gradient in this study because only a single BHT measurement is available for each well, and there is a lack of sufficient parameters to allow the application of more refined correction methods (e.g. Horner plots or analytical thermal models). The AAPG empirical correction is used in regional geothermal assessments where data are limited, providing a practical approximation of equilibrium temperatures (e.g. Mejía-Fragoso et al. (2024) and Cardoso and Hamza (2014)). Although more recent approaches (e.g. Agemar (2022)) provide improved corrections, they also rely on large, calibrated datasets or regional constraints that are not currently available for the Santa Lucía Basin.

Surface temperature (To) corresponds to the average annual air temperature (García Gil et al., 2020). Herein, the air temperature data were obtained from the Uruguayan Institute of Meteorology.

The vertical distribution of temperature in the subsurface was estimated using a one-dimensional conductive heat transfer model (Beardsmore & Cull, 2001). Excess temperature (T) relative to surface temperature is calculated using the following equation:

$$T = ((q_0/\lambda) * z) - ((A_0 D^2/2\lambda)(1 - e^{-z/D})) \qquad \text{(equation B)}$$

where q_0 is the surface heat flow, λ is thermal conductivity, A_0 is radiogenic heat production at the surface, D is the characteristic depth of heat production decay, and z is depth. Thermal conductivity values were assigned based on lithological information from wells, using representative theoretical values from Beardsmore and Cull (2001) for the identified rock types. Radiogenic heat production (A_0) and its characteristic decay depth (D) were assigned based on typical values for continental crust, using A_0 = 1.0 μW/m³ and D = 12 km, consistent with global compilations (Beardsmore & Cull, 2001).

The regional distribution of excess temperature was calculated for depths of 1, 2, and 3 km.

Based on the obtained thermal distribution, the base geothermal resource (QRB) was estimated using the volumetric method, considering discrete depth intervals (Muffler & Cataldi, 1978). The QRB is calculated as the excess thermal energy at a given depth, with the surface temperature as the reference value. The QRB of a layer of thickness d, associated with the temperature distribution given by equation (B), is calculated using the following equation:

$$QRB_i = \rho_i \, C_{pi} \, A_i \, d_i \, (T_i - T_0) \qquad \text{(equation C)}$$

where ρ_i is the average density of layer *i*, C_{pi} is the specific heat, A_i is the cell area (1 m^2), d_i is the thickness of the layer *i*, T_i is the temperature at depth *i*, and T_o is the surface temperature. For density (ρ) and specific heat capacity (Cp) were assigned constant values of 2650 kg/m³ and 836 J/kg·ºC, respectively. These values are consistent with typical ranges reported for continental crust materials (e.g. Beardsmore and Cull (2001) and Dickson and Fanelli (2003)).

In this study, constant depth intervals were adopted for the numerical discretization of the thermal profile, allowing the incremental estimation of the base geothermal resource (QRB) along the analyzed depth. This approach was used to facilitate the integration of the stored thermal energy associated with temperature variations in the subsurface. When constant depth intervals are assumed, the representative temperature of each layer (Ti) was taken at the midpoint of the discretized interval. Thus, for a layer bounded between zi and zi+1, the reference depth used in the calculation is given by:

$$z_{ref} = (z_i + z_{i+1}) / 2$$

The temperature Ti was then obtained from the analytical equation of thermal distribution evaluated at this midpoint depth.

This approach provides an adequate representation of the average temperature of each layer for the numerical integration of QRB, particularly when uniform discretization intervals are used throughout the depth range.

3. Results

Table 2 shows the distribution of subsurface temperatures and the QRB calculated at 1-, 2-, and 3-km depth in the Santa Lucía Basin.

Table 2. Subsurface temperatures and base geothermal resource calculated at 1-, 2-, and 3-km depth for each well in the Santa Lucía Basin

Name	T 1km (°C)	T 2km (°C)	T 3km (°C)	QRB 1km (GJ)	QRB 2km (GJ)	QRB 3km (GJ)
San Jacinto 2	34	68	102	38	152	341
San Jacinto 3	32	64	95	36	142	318
San Jacinto 4	27	54	81	30	120	269
Sauce 1	22	44	66	25	99	221
Sauce 2	16	33	48	18	73	162
Las Brujas	9	18	26	10	40	89
Castellanos	20	40	59	22	89	199
Cochengo	33	66	98	37	146	328
San Bautista	26	51	76	29	114	255
Tala	23	46	68	26	102	228

The highest temperatures are recorded in the eastern sector of the Sur sub-basin near the San Jacinto and Cochengo wells. In this sector at 1-, 2-, and 3-km depth, subsurface temperatures reach close to 35 °C, 70 °C, and 100 °C, respectively. In this sector, the QRB values are approximately 38, 150, and 340 GJ at 1-, 2-, and 3-km depth, respectively. Figure 2 shows the subsurface temperature at 2- and 3-km depth.

Figure 3 shows the QRB calculated in the Santa Lucía Basin at depths of 2 and 3 km. It can be observed that this distribution follows the same pattern as that of the subsurface temperature. The area with the greatest resources corresponds to the eastern sector of the Sur sub-basin near the Cochengo and San Jacinto wells.

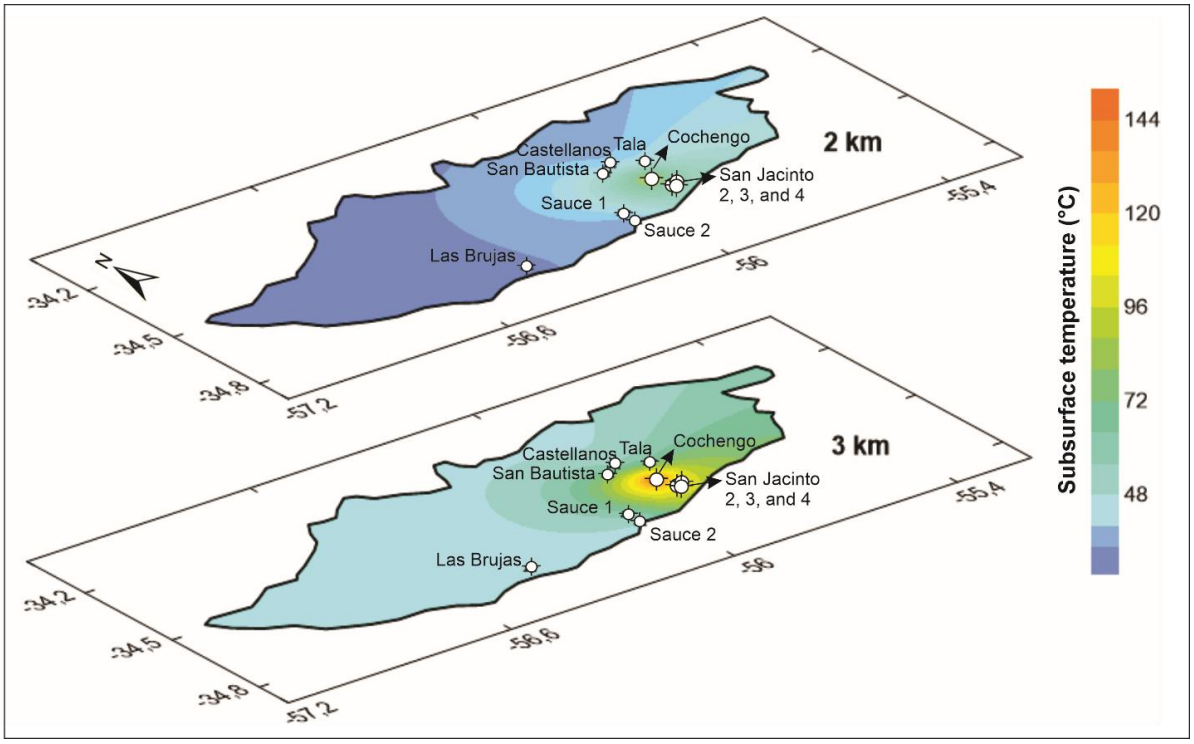

Figure 2. Subsurface temperatures in the Santa Lucía Basin at depths of 2 and 3 km

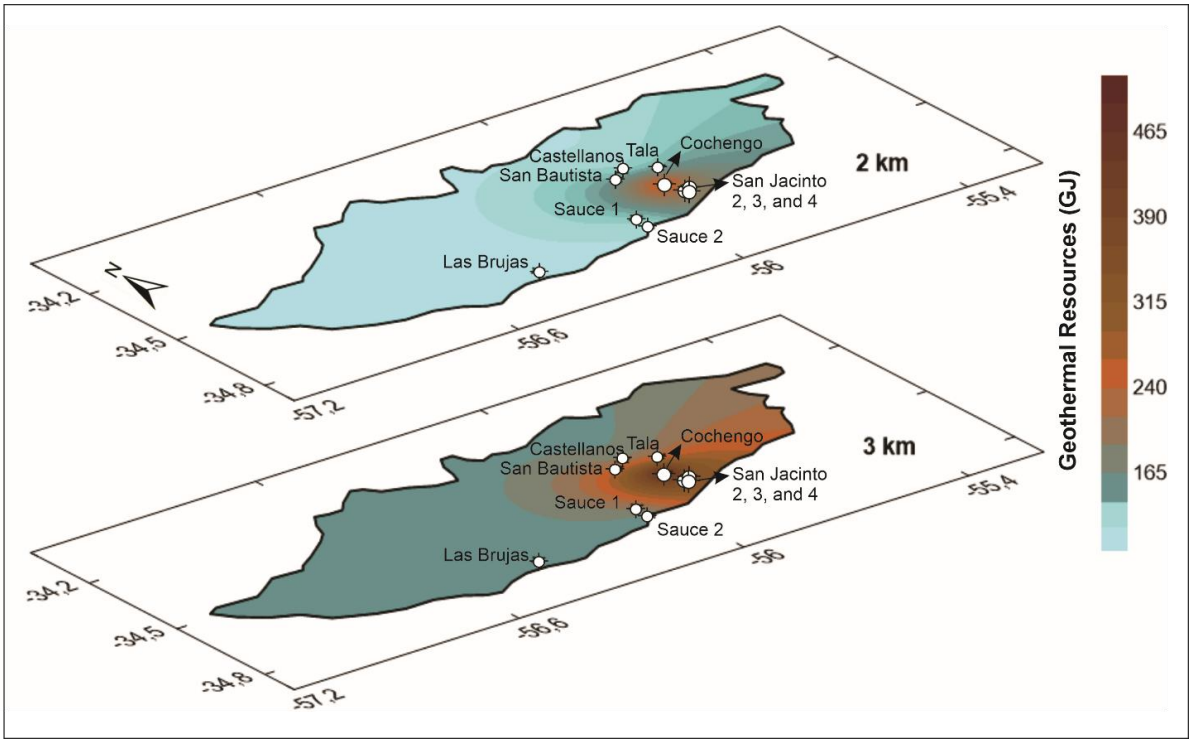

Figure 3. Base geothermal resources at depths of 2 and 3 km in the Santa Lucía Basin

4. Discussion

The results obtained in this study are consistent with the conceptual low-temperature geothermal model available for the Santa Lucía Basin, wherein the heat source is the normal geothermal gradient, the reservoir rocks are the sandstone levels of the Migues Formation, and the seals are the shale interbeds within the same unit. Recharge waters would circulate toward deeper levels of the basin through the faults bordering the basin and toward the area around the Cochengo and San Jacinto wells, favored by the dip of the basement. Figure 4 presents the conceptual model of the basin, alongside a three-dimensional view of the structural contour map of its basement. Likewise, the lithologies of the Cochengo and San Jacinto wells are presented in a simplified form, showing the intercalation of thick sandstones and shale levels, which constitute essential elements of the presented model.

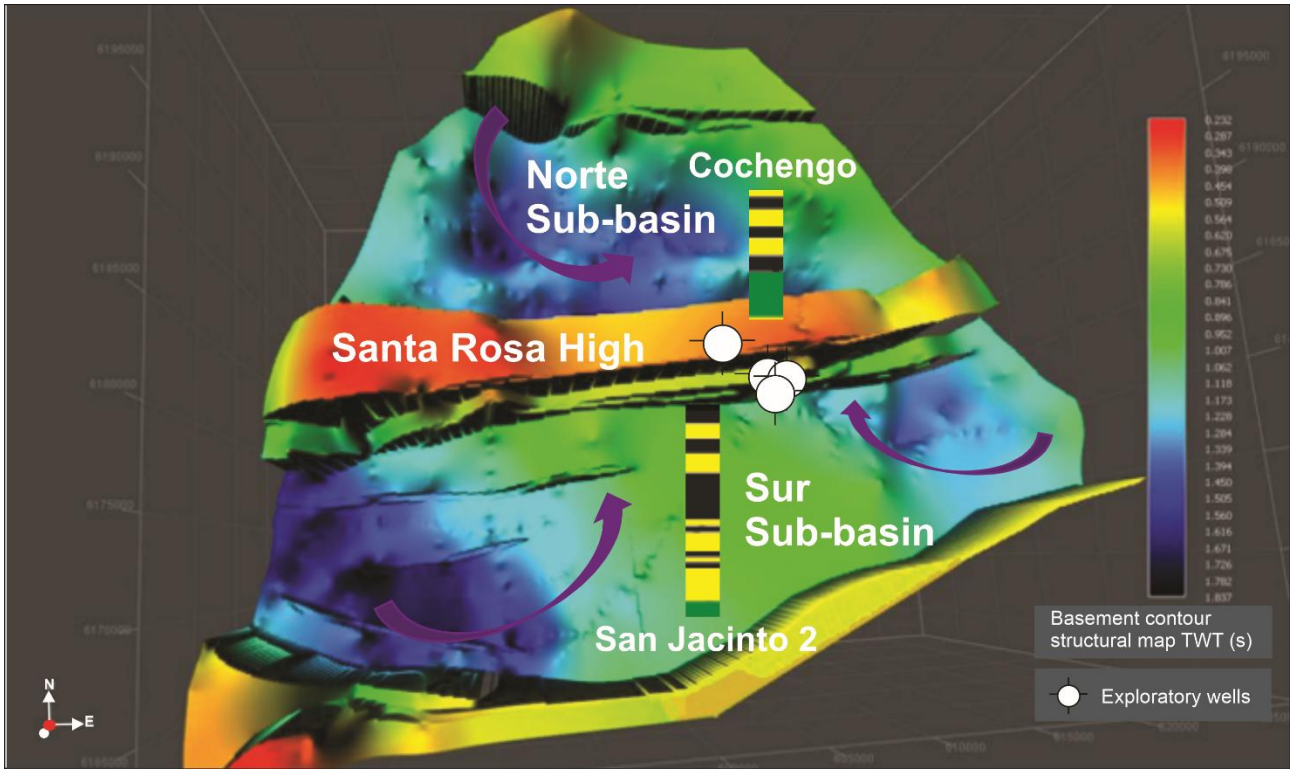

Figure 4. Three-dimensional view of the structural contour map of the basement top of the Santa Lucía Basin. Lithological profiles of the Cochengo and San Jacinto 2 wells are shown in simplified form (green: volcanic, yellow: sandstone, and black: shale). Purple arrows indicate possible fluid circulation favored by the basement topography

Note. Modified from Benvenuto et al. (2022).

The suitability of sandstone and shale layers of the Migues Formation as potential reservoirs and seals has been studied in terms of storage of gases, such as methane, hydrogen, and CO_2 (H. de Santa Ana & N. Ucha, personal communication, 1994; Tomasini et al., 2019).

At a depth of 2 km, much of the basin experiences temperatures of ~45 °C to 70 °C, representing thermal levels appropriate for direct purposes, including recreational or agro-industrial uses, such as thermal pools, drying grains, leather, milk, and air conditioning. At a depth of 3 km, subsurface temperatures near the Cochengo and San Jacinto wells are close to 100 °C, enabling their use for both direct and indirect purposes, generating electricity through binary cycles (Dickson & Fanelli, 2003).

The basement of the basin is found at depths of ~3 km in the deepest sectors; hence, beyond this depth, the possibilities of using geothermal energy are limited to enhanced geothermal systems (EGS), which can provide

the system with the permeability and fluid it lacks naturally. These systems are used for generating electricity, generally through binary cycles (Dickson & Fanelli, 2003).

The sector of the basin with the lowest temperature values is the southwest region, but it should be noted that it is represented by a single well (Las Brujas); hence, it may not be representative of that region.

5. Conclusions

The eastern sector of the Sur sub-basin near the Santa Rosa High presents the greatest excess temperature and QRB in the Santa Lucía Basin. These results are consistent with the available conceptual geological-geothermal model, where recharge waters circulate through the deep fractures that constitute the structural elements of the basin, favored by the general dip of the basement.

The main potential uses are direct, primarily for space air conditioning and in agricultural and industrial processes (dairy, textiles, paper, etc.). At depths close to the occurrence of the basement of the basin, thermal levels suitable for generating electricity through binary cycles are identified. At the basement level, the possibilities correspond to enhanced geothermal systems for electricity production.

However, the implementation of these technologies requires detailed studies of the geothermal gradient, including its estimation from direct measurements of well temperature profiles, terrestrial heat flow, quality of potential reservoirs and seals, and possible fluid migration pathways.

The area in which the basin is located is of significant social, productive, and economic importance to our country. Owing to its proximity to the most populated cities, geothermal energy could therefore provide a valuable energy source for regional development. Future work could focus on a more rigorous and better-constrained characterization of the parameters used in this study, with the objective of delineating more precisely the priority areas for the exploration and utilization of geothermal resources in the Santa Lucía Basin.

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Transparency of Data

Available data: The entire data set that supports the results of this study was published in the article itself.

Author Contribution Statement

	E Morales	F Vieira	G Veroslavsky	F Plenc	H de Santa Ana
Conceptualization	■				
Investigation	■		■		■
Methodology		■		■	
Writing – original draft	■	■			
Writing – review and editing			■	■	

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