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CASE REPORT

Use of new technologies in water resources prospecting—A case study on Karst of the Polanco Formation, Uruguay

González Carreira Leticia Ivón[1*], Gaucher Claudio[2], Collazo Paula[2], Segovia Daniel1, Montaño Jorge[3]

[1] *Centro Universitario Regional del Este (CURE), Universidad de la República (UdelaR), Rocha, Uruguay. E-mail: letigon@fcien.edu.uy*

[2] *Facultad de Ciencias, Instituto de Ciencias Geológicas, Universidad de la República (UdelaR), Uruguay.*

[3] *GeoAmbiente, Uruguay.*

ABSTRACT

Hydrogeological background motivated the development of prospective groundwater models in carbonate rocks of the Polanco Formation (Ediacaran). Field and photographic surveys were carried out (SGM, Google Earth and Drone Phantom 2 Vision+), and 3D terrain models were generated to interpret the morpho-structural characteristics of the karst relief. Boreholes and geoelectric data were surveyed. Standard prospective techniques were complemented with remote ground access technologies to generate a specific prospective model for these lithologies. As a result, it was found the existence of folds that generate an inverted relief with "cup" and "tube" type dolines, a karst relief type lapiaz, three springs and the development of wells with an average flow of 30 m^3/h. The hydrogeochemical composition corresponds to bicarbonate-calcium waters of natural mineral water quality.

Keywords: Carbonates; Karst; Springs; Drone; Mineral Water

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1. Introduction

Karst aquifers are of considerable economic interest since infiltration in carbonate rocks is usually superior to that of detrital sediments, resulting in very good water quality and significant flow rates. Water circulation in these aquifers occurs through the development of secondary porosity, through dissolution structures of carbonate rocks (vertical tubes, hollows and caverns)[1]. The superficial karst forms are generated from the dissolution of carbonates, forming a terrain modeling called "karst landscape". Just as these structures are manifested superficially, there is also a subterranean modeling that accompanies them. Some of the most common forms are lapiaz, dolines, uvulas, poljes and ponor[2]. Karsts present intrinsic vulnerability to contamination, due to the important infiltration and the speed of water circulation in these systems, where punctual contamination events can generate plumes of rapid advance in large geographic extensions. In Uruguay, the Arroyo del Soldado Group (GAS) corresponds to a marine platform succession preserved as cover of the Nico Pérez Terrane[3,4] of Late Ediacaran[5-9] to Lower Cambrian age[10] (**Figure 1**). The GAS is integrated among others by the Polanco Formation (PF), one of the largest geographic extension units of the GAS, represented by powerful carbonate deposits up to 900 m thick, whose predominant facies are limestone-dolomite rhythmites, although limestones and pure dolomites also occur[3,4,7,11-13]. On surface, these calcareous areas are karstified and present a cover of red soils (“*terra rossa*”), sometimes several meters thick[14]. The Polanco Formation is of relevant as a source of mineral resources, both for the limestones for the production of cement and lime, as well as the increasingly valuable mineral waters, which motivates companies of national and international prestige to develop their exploitation sources in these lithologies. Similarly, Bossi and Navarro[15] characterize a series of hydrogeological provinces for Uruguay; for the eastern region they identify carbonate banks with variations in relief, fracturing, point flows and upwelling, although the chemical composition of the waters remains constant. This indicates that conditions are favorable for exploitation.

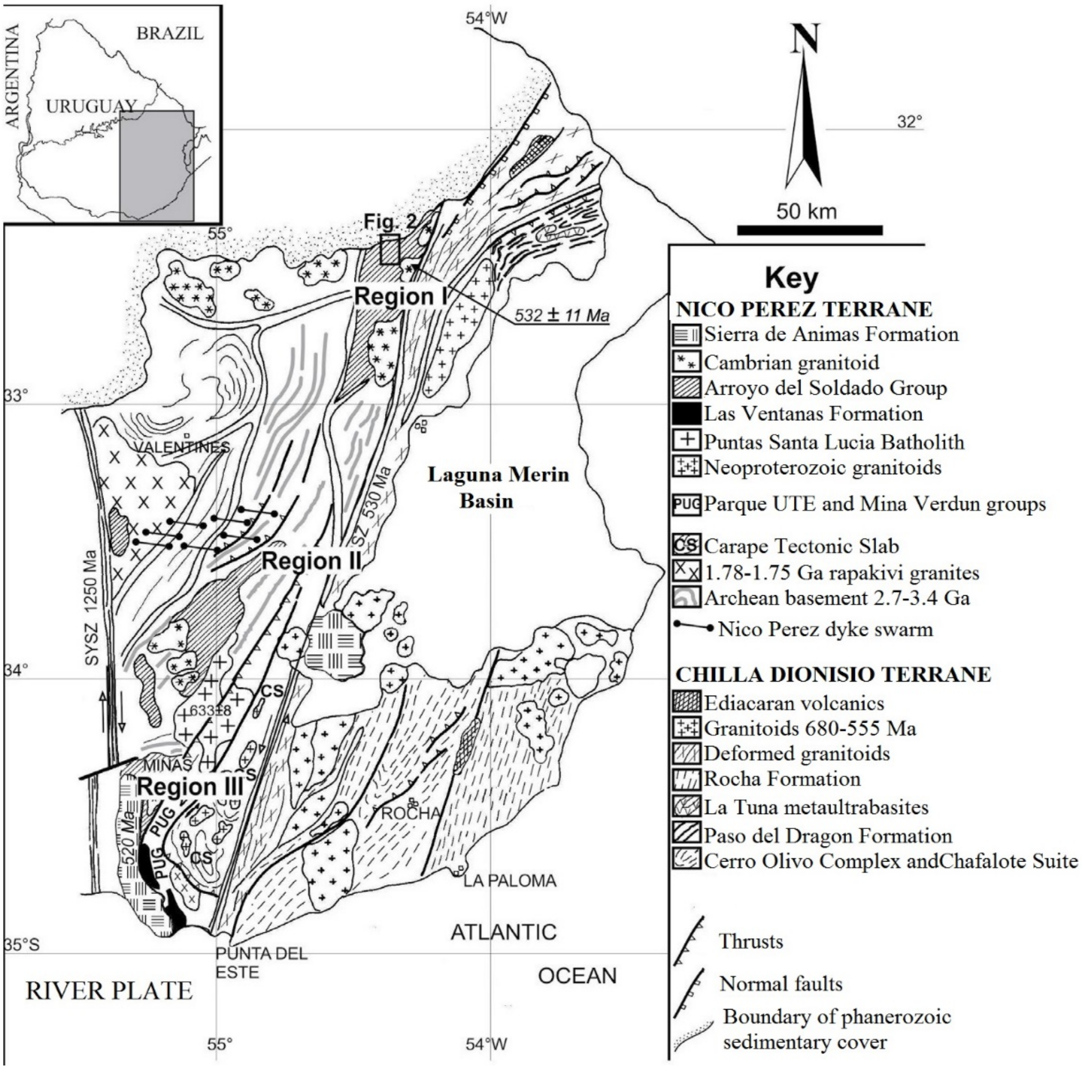

Figure 1. Geological map of the Nico Pérez Terrain with the outcrop areas of the Arroyo del Soldado Group. The regions where detailed studies were carried out are shown[9,16].

These evidences motivated the realization of a detailed study on the characteristics of the carbonate structures of the Polanco Formation, applying innovative technologies that would allow a comprehensive approach to the areas selected for this research.

The general objective of this work was to identify the geological conditions that allow the generation of a karst aquifer and mineral water sources using field survey tools.

Specific objectives include:

(1) To study the detailed geology of the Polanco Formation in the departments of Treinta y Tres and Lavalleja by means of photo interpretation, field work and drone photographic survey.

(2) Determine the hydraulic characteristics of

the aquifer and the geological conditions that allow the accumulation of the resource.

(3) Develop a prospective model for mineral waters in carbonates of the Polanco Formation.

2. Materials and methods

Three regions where the Polanco Formation outcrops were considered for this study, in the departments of Treinta y Tres and Lavalleja, which from north to south are identified as:

(1) Region I: Eastern Syncline[4,14].

(2) Region II: Tapes Grande Creek Syncline[4].

(3) Region III: Surroundings of the city of Minas.

2.1 Cabinet phase

For the geological, structural and geomorphological study, a photo-interpretation at 1/20,000 scale of the aerial photos (133–074 to 076; 177–140 to 14135–152 to 154) of the Cartographic Plan of the Military Geographic Service (SGM) of 1966–67, as well as the analysis of satellite images obtained through the Google Earth program, were carried out.

2.2 Field phase

The geological and geomorphological survey of the study areas was carried out, paying special attention to the structural geology (folds, faults, joints) and karst landforms. A drone (DJI Phantom II Vision+) was flown over the studied regions at a height of 150 m (**Figure 2**) and orthophotos with a 60% overlap were obtained. The boreholes in the area were surveyed and their depth, piezometric level, flow rate and position in the terrain were determined. S.E.V. geoelectric data (vertical electrical soundings), provided by the consulting company GeoAmbiente, were used to interpret information obtained in the field.

2.3 Data processing

For the design of geological-structural maps, the Map Info-Discover program (version 10.5) was used, together with data from aerial photos and satellite images from Google Earth Pro. StereoNet (version 1.0.1) was used for structural data processing.

Figure 2. Unmanned aerial device (DJI DRONE–Phantom II Vision+).

The morpho-structural analysis was completed by using Agisoft Photoscan software to generate 3D digital terrain models of the topography of the study area from images obtained by drones. Corel Draw X6 and Adobe-PHOTOSHOP software were used to create the diagrams and process the images of the structures and outcrops.

3. Results

The results obtained from the field survey are presented. The description of outcrops, photo-reading, analysis of 3D terrain models, geological sections, study of drainage network lineaments, fractures, thrusts and geomorphological aspects characteristic of the relief of a karst system are included.

3.1 Geology and geomorphology

3.1.1 Region I

The lithologies that make up the East Syncline correspond to the Yerbal, Polanco and Cerro Espuelitas formations, from the base to the top and constitute the transitional passage. The Polanco Formation is represented by banks of pure limestones, dolomitic limestones and intercalated with calcoarenites. It is a recumbent synclinal fold, with axial plane N 45° E, dipping between 35° and 40° to the NW. There are thrusts with vergence to the SE, which generate marked limits to the N and S of the synclinal area (**Figures 3** and **4**). From NW to SE, a geological section was made over the area of the syncline, where the arrangement of the units and the structures that operate can be appreciated

(**Figure 5**). The direction of the geological section corresponds to the sector where we have data from vertical and hydro-geological drillings. The analysis of the lineaments was complemented with heading diagrams (**Figure 6**). The predominant direction corresponds to N 35°–45° E, a value that coincides with the strike of the thrusts in the NW and SE sectors of the area and with the direction of the fold axis. To a lesser extent, lineaments with a N 60°–70° E strike are observed.

In the first instance, surface structures are considered as possible surface manifestations of the existence of a karst system. These structures are relevant in this study and correspond to temporary water bodies (water eyes), which are mostly disposed on the meta-sediments of the Yerbal Formation. In the images taken by the drone it was possible to corroborate the temporal aspect of these water bodies, since in the aerial photos of the year 1966–1967 the distribution of the “water eyes” also differs with historical satellite images registered in Google Earth. It was found that the highest concentration of this water accumulation phenomenon occurs over the pelites of the Yerbal Formation (**Figure 7**). The data provided by the SEV indicate that these “water eyes” correspond to surface manifestations, since this water accumulates in a flat area on a low permeability substrate with a thickness of 20 meters and these materials are not very favorable for the circulation of water in a vertical direction. In other words, these are accumulations of rainwater.

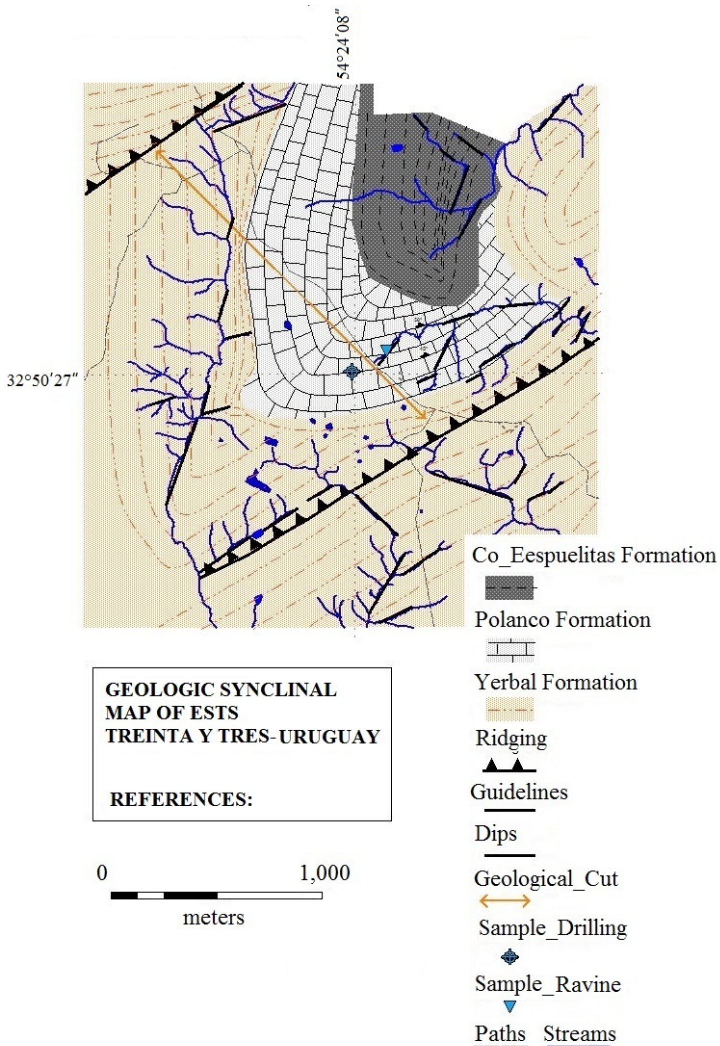

Figure 3. Geological map of Region I (East Syncline), Treinta y Tres.

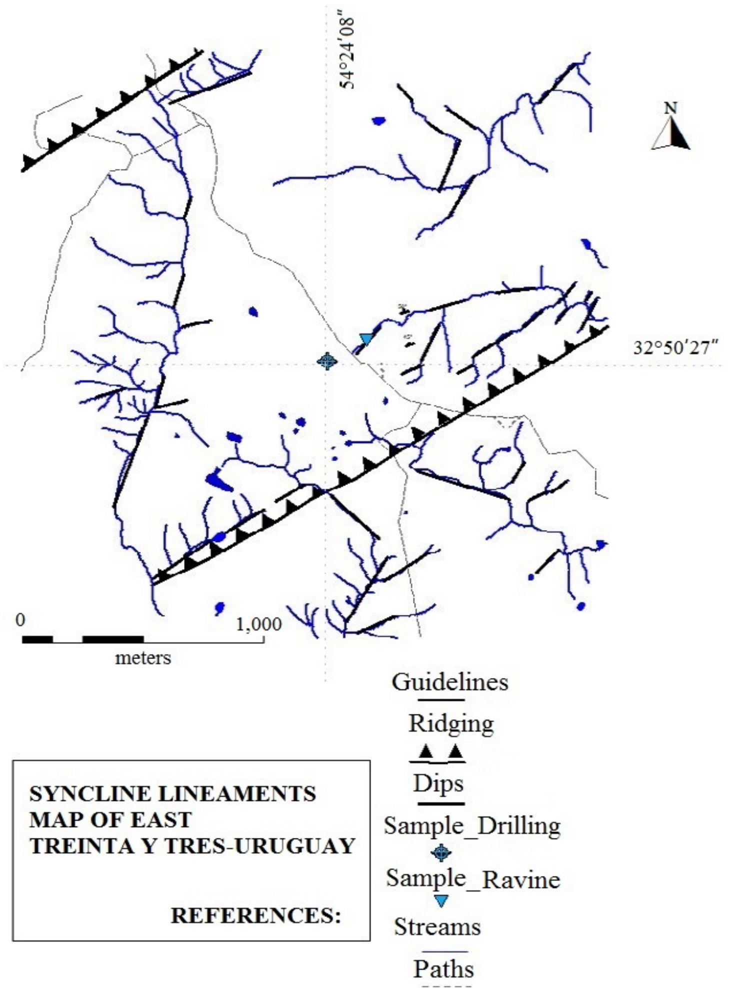

Figure 4. Lineaments map of Region I (East Syncline), Treinta y Tres.

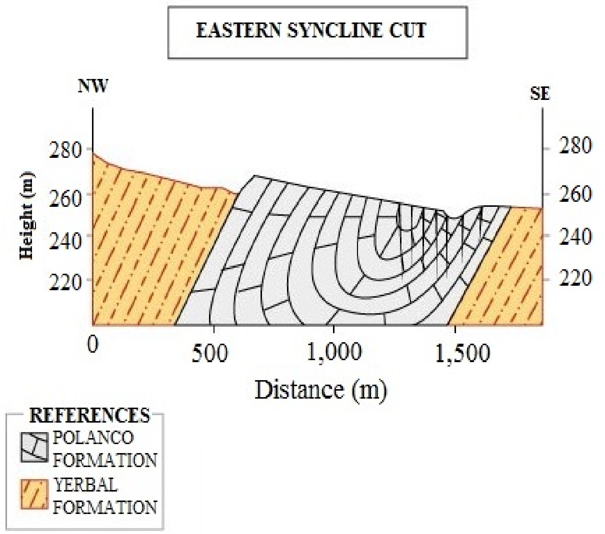

Figure 5. Geological section of Region I (East Syncline), Treinta y Tres.

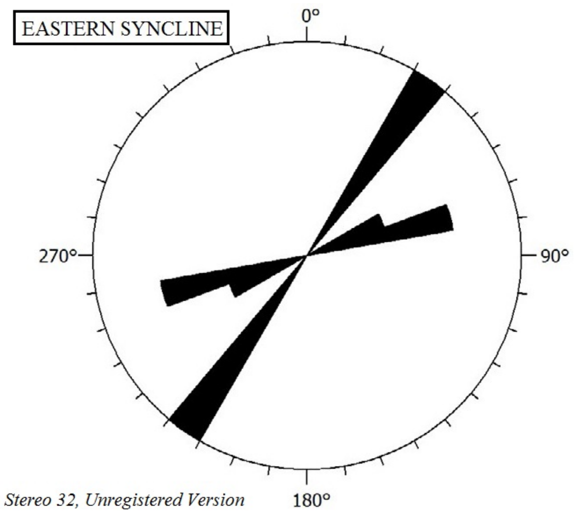

Figure 6. Lineament compass rose for Region I, East Syncline, Treinta y Tres. The N 35° to 45° E direction corresponds to the axis of the syncline, structure on which the Sinclinal del Este 1 borehole is developed, and to the thrusts indicated in the cartography. The direction N 60° to 70° E corresponds to faults of minor presence in the area.

Figure 7. Temporary water bodies developed over the Yerbal Formation, near the contact with the carbonates of the Polanco Formation in the East Syncline.
Source: Photo taken from drone (coordinates at the center of the photo: X: 32°50′36″, Y: 54°24′10″, date: 19/9/15).

In the outcrop area of the carbonates, the development of ground depressions arranged in a liner pattern is observed. These structures were corroborated and recorded with a reference scale standard. The direction of these structures corresponds to the strike N 40° E, a value that coincides with the direction prevailing in the lineament rose diagram and with the strike of the fold axis and thrusts affecting this sector. Dolines are exokarstic structures that are characterized by being depressions in the ground surface that behave as infiltration areas, since they communicate with the subway drainage and, according to their morphogenesis, can be classified into different types[2]. In Region I, a well-developed karst relief associated with the limestones of the Polanco Formation was identified, with evident dissolution structures. These structures were recorded on the surface by means of plan photos and drone images (**Figure 8**). Cup-type dolines were identified where dissolution and subsidence processes are observed with the development of "*terra rossa*" type soils. These structures are associated with a structural control linked to the direction of the East Synclinal fold axis. The concentration of "cup-type" dolines is associated with the N 40° to 45° E direction, which corresponds to the fold axis direction. The digital terrain models generated from the images captured by the drone provide a panoramic view of these karst structures. Morpho-structurally, this fold constitutes a depressed relief, which hosts the karst depressions in the direction N 40° to 45° E. The data recorded with the SEV indicate that near this sector the subsurface conditions are favorable for finding groundwater, since the resistivity values decrease indicating a high permeability, around the -60 m level (Montano, J., pers. comm., July 2015).

Secondly, dissolution structures were identified in limestones of the East Syncline, with apparent vertical development greater than the opening diameter at the surface, where the vertical corrosion deepens and it is possible to find collapsed blocks from deeper sectors in the depressed sector. These depressed structures were classified as "well" type dolines; several are uncovered and others have been taken advantage of by the native forest to implant and develop in these deep cavities (**Figure 9**).

Figure 8. Distribution of depression structure of the terrain (cup-type dolines), accompanying the N 45° E. East Syncline, Treinta y Tres. Cup-type dolines observed in plan (1 and 2). Sequence of "cup-type" Dolinas observed with drone images (3) (coordinates: X: 32°50′22″, Y: 54°24′10″, date: 19/9/15).

Figure 9. Diversity of forms of karst relief forming "well" type dolines.

For 1 and 2 it was not possible to reach the base of the depression. In 3, the base of the hole is observed near the surface, generating the conditions for the implantation of native forest sprouts. In 4, the surface corrosion of the limestones is observed, with sectors of collapse in the structure, and in the background the development of native forest can be seen over this type of structure. The dark gray color characteristic of limestones is observed.

3.1.2 Region II

The Polanco Formation is characterized by millimetric to centimetric intercalation rhythmites of limestones and dolomites in this region. On these lithologies there are springs that are recorded in the mapping. Thrust structures are developed with near-vertical or low-angle dips, predominantly NE–SW strike, which affected the sedimentary sequence (**Figure 10**). The lineaments map shows the main structural directions over the drainage network (**Figure 11**). A NW-SE geological section was also performed, parallel to the development of the stream channel, to survey the carbonate outcrops that are disposed in that direction (**Figure 12**).

The direction of greatest presence is N 50° to 60° E. This pattern is observed parallel to the interstratification of the outcropping carbonates. This phenomenon is a favorable indication of water circulation, since carbonate di-solution is observed in these planes. Less frequently, lineaments of N 60° W and N–S direction are found, associated with faults observed on the drainage network (**Figure 13**). These orientations are probably associated with the action of the NW-verging thrusts, which act to the NW and SE of this area and notoriously generate an intense structuring pattern.

The distribution of structural features over the carbonates of this formation allows intense fracturing to be generated at the surface. These structures were recorded on the ground with plan and drone images (**Figure 14**). Digital terrain models allow us to visualize the exokarstic structures that develop on the rock surface as a consequence of water erosion, taking advantage of fractures and diaclases.

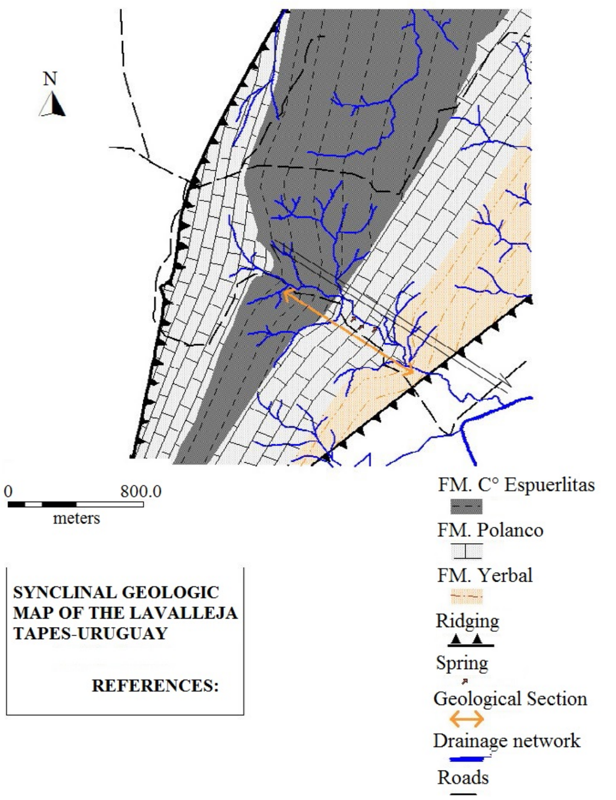

Figure 10. Geological map of Region II (Tapes Grande Syncline), Lavalleja.

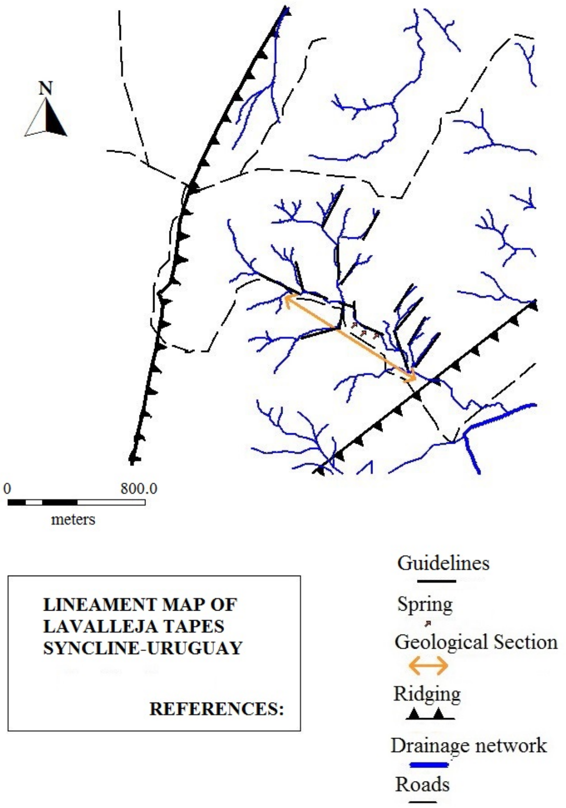

Figure 11. Lineaments map of Region II (Tapes Grande Syncline), Lavalleja.

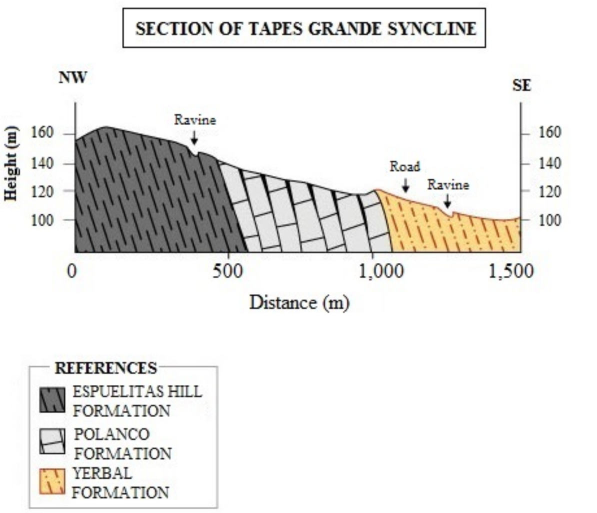

Figure 12. NW–SE geological section (Tapes Grande Syncline), Lavalleja.

The N 50°–60° E direction is the most present and coincides with the surface and is probably associated with the thrust acting in the SE of the area. The N 60° W value corresponds to transcurrent faults that direct the drainage network. The N–S lineaments correspond to the thrust to the NW of the area.

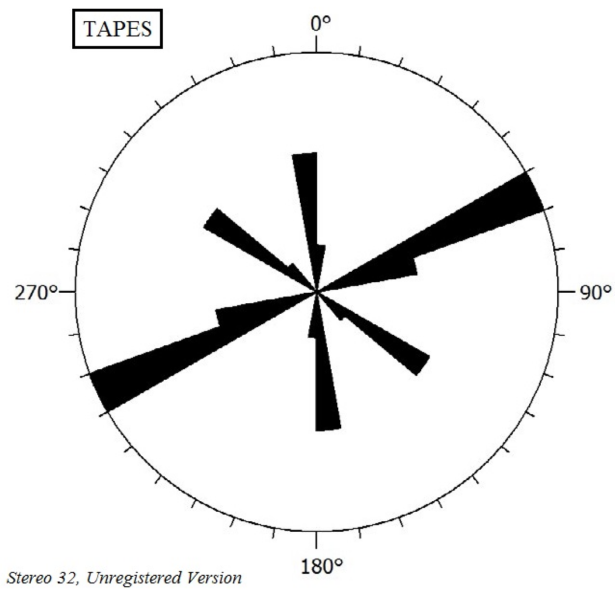

Figure 13. Lineament compass rose for Region II, Tapes Grande Syncline, Lavalleja.

The N 60° W lineaments surveyed on the drainage network are associated with transcurrent faults. The N 60° E alignment coincides with the orientation of the thrust to the SE of the area and corresponds to the stratification of the carbonate rhythmites. This characteristic favors the development of a lapiaz-type karstic relief. This form of karst dissolution is characterized by an irregular relief on the surface, as a result of the corrosion of water through the discontinuities (**Figure 15**).

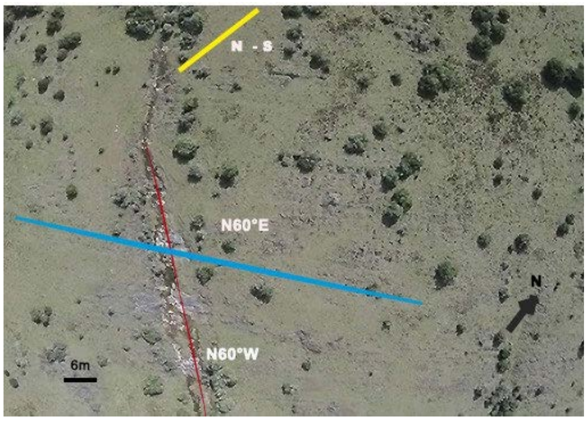

Figure 14. Drone image where the structural lineaments are visualized on the surface and the N 60° E layering and the N 60° W fault are clearly observed. The N–S structures are smooth on the upper end of the photo. Tapes Grande Syncline, Lavalleja (coordinates of the center of the photo: X: 33°57′59″, Y: 54°57′36″, date: 19/9/15).

This superficial karst form is generated by dissolution of the calcareous rock and causes parallel and longitudinal grooves that can interfere with the diaclases and give rise to arborescent structures. The absence of soil cover and a slope greater than 10° favor the dynamics of the system (**Figure 15**; photo 2). Cylindrical pits and niches are also found concentrated in sectors where the N 60° E and N 60° W structures intersect (**Figure 15**; photos 1, 3 and 4).

Figure 15. Karst structures surveyed in outcrops.

The concordance of the structure with the orientations is shown; N 60° E coincides with lineaments and stratification; N 60° W corresponds to faults that favor the development of karst structures (photos 1 and 4). Karstic relief of irregular surface features associated with diaclases (photo 2). Karst structure of fracture by diaclases (photo 3).

It shows the occurrence of the sedimentary sequence of the GAS, particularly the outcrops of the carbonates of the Polanco Formation. Enlargement of the map presented by Gaucher *et al.*[12]

3.1.3 Region III

The photointerpretation survey was carried out with the support of Google Earth images; no premises were obtained to apply other techniques. South of the city of Minas, the transitional passage of the Yerbal, Polanco and Cerro Espuelitas Formations (Ediacaran) was observed with intrusions of the Minas Granite and in tectonic contact with other units (**Figure 16**). Large elevations of NS (ZCSY) and N 30° E (Arroyo La Plata Lineament) were recognized in this region and intense folding where the sedimentary sequence of the GAS is affected.

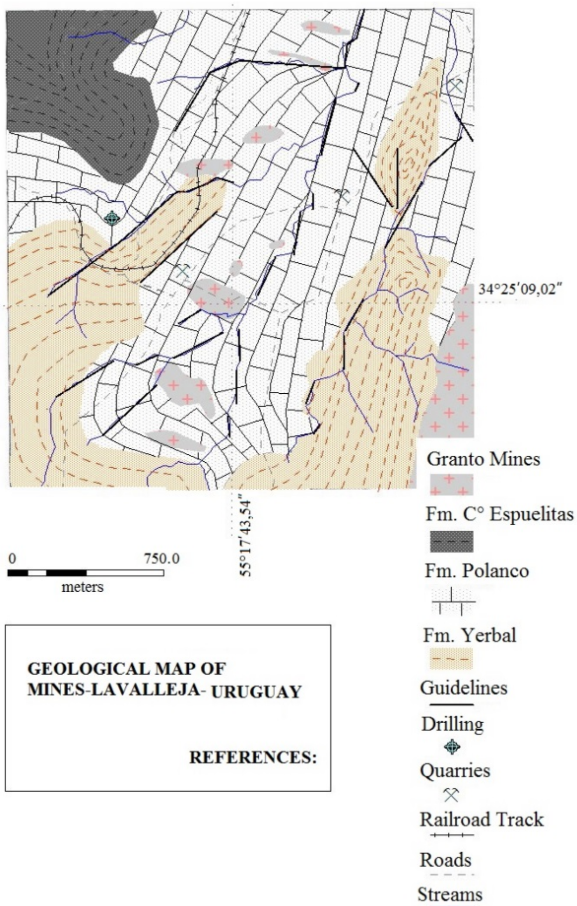

Figure 16. Geological-structural map of Region III (Minas).

3.2 Hydrogeology

Water level measurements were taken from each well for a period between March 2012 and August 2015. These data were plotted, showing the behavior of the water level in each well (**Figure 17**). Water level variations in the wells were compared with the standardized precipitation index that measures the excess or deficit of precipitation for a given location over a period of time and compares it with historical values for the period between 1981 and 2010 (**Figure 18**) (Instituto Uruguayo de Meteorologia, [s.d.])[17].

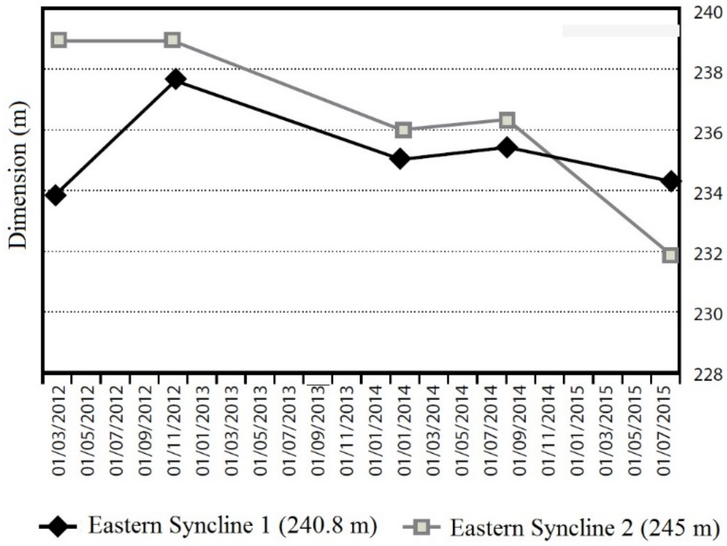

Figure 17. Water level graph in two wells of the East Syncline, Treinta y Tres.
Note: The ground elevation for Eastern Syncline 1 is 240.8 m and for Eastern Syncline 2 is 245 m.

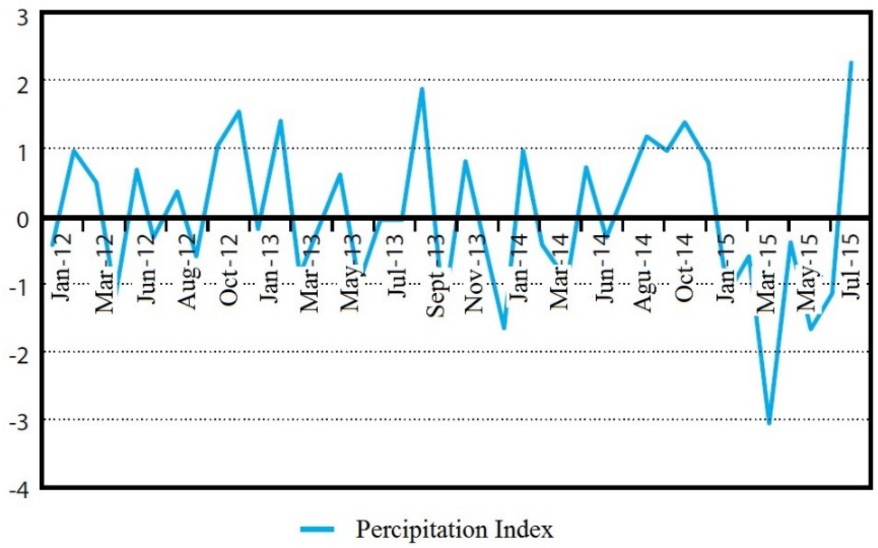

Figure 18. Graph of standardized precipitation index for Treinta y Tres, between 1/12 and 8/15.

Values greater than zero indicate that precipitation was above the normal value for the site, values less than zero indicate that precipitation was less than the standard value.

It was observed that there is a relationship between the recharge of the wells. During the period (December 2012–September 2014), recharge between the two systems remained constant. Then, recharge decreased significantly: between February and May 2015 there was a fluviometric decrease recorded in the region and it was observed that the water level in well 2 decreased more steeply than in well 1. This is consistent with the hydrodynamics of karst systems: rapid initial response to recharge and evolution conditioned by the circulation circuits in each case. In region II, a system of springs was recorded, which arise on the sides of the drainage network in the levels of fine limestone and dolomite rhythmites. The drainage network responds to a fault system of N 60° W direction that overlies the N 60° E layering and a third event of N–S direction affects these lithologies. Between the intersection of the N 60° W and N 60° E structures, karstic relief structures such as pits and cylindrical niches are generated. In the levels of limestone and dolomite interstratification, natural groundwater emergence occurs (**Figure 19**). For this system, the flow rate of the upwelling was measured, yielding a value of 1,200 l/h in September 2014 and in June 2015 these groundwater levels did not appear on the surface. The decrease in water level that was recorded at the wellhead in the East Syncline Region was also observed, with less precision, in the Tapes Syncline Region with the absence of upwellings.

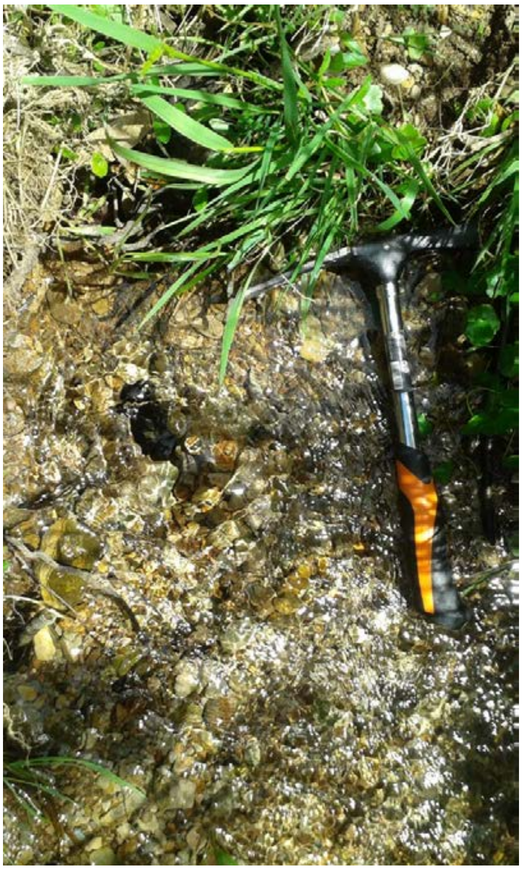

Figure 19. Spring emergence in Region II, Tapes.

4. Discussion and conclusions

In the three regions analyzed, the sedimentary sequence of the GAS is represented by the Yerbal, Polanco and Cerro Espuelitas Formations, from the base to the top, with the transitional passage between each unit.

The carbonates of the Polanco Formation in Region I (East Syncline) and III (Minas) are characterized by limestones, dolomitic limestones and calcarenites. On the other hand, for Region II (Tapes) the Polanco Formation is represented by millimetric to centimetric interbedded rhythmites of limestones and dolomites.

In Region I, the Polanco Formation forms a syncline with axial plane N 45° E between two ridges, one to the NW and the other to the SE of the outcrop area. This structure coincides with the lineaments recorded on the drainage network, which range from N 35° to 45° E. The Yerbal and Cerro Espuelitas Formations behave as levels with very low hydrogeological permeability levels ly. In particular, the Yerbal Formation, which is located in the highest topographic levels of the area, generates surface depressions in which temporary water bodies develop. The results of the SEV indicate that they do not correspond to surface manifestations of groundwater, since the substratum presents a level that exceeds 20 m with high resistivity values.

It should be noted that this study defines, for the first time, karstic structures in the carbonates of the Polanco Formation, whose characteristics are detailed below. A karstic relief is developed on the Polanco Formation, where "cup" type dolines are identified with N 45° E direction, in the same direction of the fold axis, the main structures and the main lineaments. Open "well" type dolines were found with collapse of the structures of which the base was not reached and that allowed, in turn, the implantation of native forest in the cases where the holes were filled. Morpho-structurally, the fold constitutes a depressed relief, harboring in the vicinity of the axial plane, from N 40° to 45° E, karstic depressions, circulation structures and groundwater accumulation. It is estimated that the karst in folded limestones develops taking advantage of the axial plane drainage and it is in this structure where the 30 m^3/h borehole is located.

In Region II, NE–SW trending thrusts are developed that affect the sedimentary sequence. However, the N 50° to 60° E lineaments are dominant and correspond to the So of carbonate layering. N 60° W and N–S faults are also found. From these structures, a karstic lapiaz-type relief is identified with the development of pits and cylindrical niches, which are concentrated in sectors where the N 60° E and N 120° structures intersect, and three springs where the So and its intersection with the N 60° W fault, which allow the emergence of groundwater. In this case, a different behavior is observed than in the pure limestones, where the karst takes advantage of the axial plane cleavage. In the more dolomitic carbonates, faults seem to play an important role in karst development. This is possibly due to the different rheology of calcite and dolomite. The stress required for dolomite to flow at low temperatures (-200℃) is 10 orders of magnitude higher than calcite[18]. This means that at low temperatures dolomite will show brittle deformation, but calcite can deform plastically. At temperatures of 550–600 °C, however, both show similar flow stress values[18].

In all regions, the water deficit recorded between February and May 2015 affected the upwelling, preventing it from being recorded at the surface. In the boreholes in the Eastern Syncline, the well with the highest flow rate was more stable in the face of the variation in climatic conditions. Considering the difference in elevation in the static level of the East Syncline wells, it is estimated that there is independence in the karstic system of well 1 with respect to well 2.

This work represents a significant step towards the prospection of water sources with special emphasis on table mineral waters, which constitute one of the mineral resources of Uruguay and its exploitation is in growing national, regional and worldwide development.

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Conflict of interest

The authors declared no conflict of interest.

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