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The Arapey group: confining basalts of the Guaraní aquifer in Uruguay

Grupo Arapey: basaltos confinantes del acuífero Guaraní en Uruguay

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Article originally published in:

Agrociencia (Uruguay). 1998;2(1):12-25.

doi: 10.31285/AGRO.2.1006

Abstract

With the increasing demand of drinking water for agricultural use, takes special importance the geological and hydrogeological knowledge of the infrabasaltic aquifer known as Guaraní Aquifer in the South Cone. The different stratigraphic concepts historically managed for the geological formations of the top of Gondwana Supergroup in Uruguay, carrying great volumes of groundwater with thermal potential, agricultural use (irrigation) and urban supply are discussed. Geological units of Guaraní Aquifer are described: Buena Vista, Cuchilla Ombú, Tacuarembó and Rivera Formations.

Geometry and thickness of its confining unit -Arapey group- condition the economic possibilities of profiting from using groundwater from the Guaraní Aquifer. Such group has been divided - according to lithostructural criteria- into six formations, which are briefly described.

A preliminary tridimensional geometry of Arapey group's basaltic lava and its relation with Guaraní Aquifer is shown. This geometry is related to the basaltic thickness to cross in a borehole in order to obtain groundwater with a margin of error of about 30 meters. This is very relevant, especially in lithosol zones of the basaltic area, where the installation of irrigation systems would mean a substantial agrarian improvement of the area.

Keywords: Arapey Group, Guaraní Aquifer, geology, hydrogeology, Uruguay.

Resumen

En función de la creciente demanda de agua potable con fines agropecuarios cobra especial importancia el conocimiento geológico e hidrogeológico de las unidades acuíferas infrabasálticas, conocidas como acuífero Guaraní en el cono Sur. Se discuten las diferentes concepciones estratigráficas manejadas históricamente para las formaciones geológicas del tope del Supergroup Gondwana en el Uruguay, portadoras de enormes volúmenes de agua subterránea con potencial termal, de uso agrícola (riego) y suministro urbano. Se describen las unidades geológicas que conforman - en distinta medida- el acuífero Guaraní: formaciones Buena Vista, Cuchilla Ombú, Tacuarembó y Rivera.

Las posibilidades económicas de aprovechar el agua subterránea del acuífero Guaraní están directamente condicionadas por la geometría y espesor de su confinante: el Grupo Arapey. Dicho grupo se ha compartimentado - siguiendo criterios litoestructurales - en 6 formaciones, de las cuales se brinda una somera descripción.

Se concluye la geometría tridimensional preliminar de las lavas basálticas del Grupo Arapey y su relación con el acuífero Guaraní, en lo que refiere al espesor de basalto a atravesar para poder extraer agua subterránea con un margen de error



de 30 metros, sobre todo en zonas de suelos superficiales y muy superficiales, donde la instalación de sistemas de riego implicaría una mejora agraria sustancial en las áreas consideradas.

Palabras clave: Grupo Arapey, Acuífero Guaraní, geología, hidrogeología, Uruguay

1. Introduction

Drinking water needs are growing at a much faster rate than the world's population. If we take the data provided by the Rector of the University of Paraná (Brazil), Prof. Riad SALAMUNI, in the opening act of the I Mercosur of Groundwater that took place in Curitiba in 1995, it is possible to create table No. 1 demonstrating the aforementioned trend with numbers.

The expected demand of the agricultural sector is the most important for the coming century, associated with the technological development of irrigation systems that can operate with economic profitability in the vast majority of cases.

The knowledge advance of the most important aquifer in South America (ARAUJO and others, 1995; GILBOA and others, 1976; REBOUCAS, 1994) - whose southern portion is located in Uruguay, below the Mesozoic basaltic spills; opens an encouraging prospect for large flows with drilled boreholes in areas where the accumulation of superficial water becomes impracticable. The stratigraphic findings for Uruguayan Gondwana sediments by ANDREIS and FERRANDO (1982), FERRANDO and ANDREIS (1986), led to considerable progress in understanding the functioning of the infra-basaltic aquifer.

thickness of basalt rocks in each place of the country by geological mapping, with an error of the order of ± 30 m.

The joint consideration of the stratigraphic changes and new techniques allowed concluding that it was necessary and appropriate to communicate the progress achieved, for the implications they could have on the agrarian reconversion of the basaltic area, source material of soils in 41,000 km² and especially in the area of superficial and very superficial soils.

The knowledge of the thickness of the basaltic rocks with a predetermined margin of error will be fundamental for the technical and economic planning of the usage of the enormous flows that the underlying aquifer can provide. This data will allow evaluating the cost of drilling, the upwelling possibility and the operation costs, with simple geological research. The proposed contribution is fundamentally linked to the regional geometry of the confining basaltic roof of the largest aquifer in South America. It aims specifically to the detailed knowledge of the isopachs of the basaltic spills at the southern end of the enormous aquifer.

By collecting data on hydraulic parameters of the aquifer, its internal structure with well-known stratigraphy and the geometry of the upper confinement, it is possible to try a process of staggered synthesis, which represents a fundamental objective in natural sciences (ROUTHIER, 1958).

Table 1. Historical and projected world water consumption according to R. SALAMUNJ (1995)

Year	World Population (10 ⁶)	Annual water consumption in km ³			
		domestic	industrial	agricultural	total
1900	1650	140	30	230	400
1975	3650	365	650	1785	2800
2010	7000	650	2600	4500	7750

The development of the Basalt Program from 1967-1973 financed by the Agricultural Plan of the then Ministry of Livestock and Agriculture (BOSSI and HEIDE, 1970), the ECOS project with the Universities of Lyon and Nice (France) between 1994 and 1998 and the Basic Igneous Rocks program of Uruguay financed by CSIC between 1995 and 1997, enabled to develop original photogeological techniques and field criteria, which allow determining the

MATERIAL AND METHODS

The data supporting this study were obtained in field research in selected key areas for photointerpretation. Aerial photographs of 1:40,000 from the Military Geographical Service (1965-1966 mission) were used to determine casting boundaries as well as meso- and macro-scale structures. The current availability of the complete collection of topographic charts of excellent quality with contour lines every 10 m allowed to precisely delimit the photointerpreted limits and calculate the regional dips.

The geometry of each of the castings can be determined in our country since there is an intimate association between the photogeological textures and

each particulate spill; this situation is unique to Uruguay and is not repeated in the other outcropping areas in the Paraná basin (Brazil and Paraguay) where the vegetation prevents the identification of these units.

THE GUARANI AQUIFER

This study will define the aquifer according to the criterion of ARAUJO and others (1995) who consider it to be constituted by sedimentary rocks of the Triassic-Jurassic age confined towards the roof by basaltic plateau spills of the Jurassic-Cretaceous limit, and supported on low permeability Permian rocks. It covers a total area of almost 1,200,000 km² with the following territorial distribution:

839,000 km² in Brazil, 225,000 km² in Argentina, 72,000 km² in Paraguay and 59,000 km² in Uruguay (figure 1).

Figure 1. Distribution of the Guarani Aquifer (gray) in the Southern Cone.



This aquifer has great significance as a high-quality water source for irrigation, thermal stations, industrial use and even for the supply of drinking water to population centers. Although access to the aquifer is expensive due to the need to cross very thick basaltic rocks, flows are normally huge, with values of around 100 m³/hour. GODOY and PAREDES (1995) communicate values of up to 500 m³/hour in areas of confined aquifers captured at depths of around 700 meters and thicknesses of up to 800 meters.

Such thicknesses of sedimentary rocks have regional variations associated with differences in deposit rates, which generate changes in the porosity, permeability and transmissivity of the rocks, modifying the storage capacity and groundwater displacement. ARAUJO and others (1995) point out that the Jurassic strata of wind origin (Botucatú Formations in Brazil, Solari in Argentina, Misiones in Paraguay, Rivera and Cuchilla Ombú in Uruguay) are excellent aquifers throughout the basin. Instead, the Triassic sediments, of fluvio-lacustrine origin (Piramboia, Sanga do Cabral and Santa Maria formations in Brazil, Independencia in Paraguay and Tacuarembó and Buena Vista in Uruguay) are locally too clayey and lose the aquifer nature.

The recharge areas of this huge aquifer are located on the periphery of the outcropping area of the overlying and confining basaltic rocks: Serra Geral Fm. in Brazil, Alto Paraná Fm. in Paraguay and Arapey Group in Uruguay. The levels of the potentiometric surface, which links the heights up to which sediments are saturated in water (static levels) compared to sea level, are very high in Brazil and decrease towards south and west (RAMOS and others, 1990). Thus, a mature basin is configured from the hydrodynamic point of view, with a predominance of centripetal flow regimes. All this regional structuring occurred during the Cretaceous, a period in which the set of basaltic dikes of Punta Grossa (Paraná, Brazil) was also injected, dividing the Guarani Aquifer into two hydrological regimes: one to the north and one to the south of the dike set.

The hydrological regime north of the Punta Grossa arc has potentiometric levels over 600 meters with SW regional flow, gradients of 3 m/km next to recharge areas, falling to 0.2 m/km at distances of a few tens of kilometers from the outcrops. The second hydrological component, south of the dike set, is different from the previous one by high hydraulic gradients and important discharge areas. The potentiometric level in the east is 1200 m and in the west it reaches only 50 m, the regional direction of the flow is SW (ARAUJO and others, 1995).

Next to the recharge area, the hydraulic gradient is 5 m/km falling to 2 m/km in the south of Brazil, Uruguay, and Argentinian Mesopotamia, reaching values of 0.3 m/km in the provinces of Entre Ríos and Santa Fe (Argentina). According to the authors mentioned, this area represents the main discharge area of the aquifer.

LOPES (1984) carried out hydrogeological studies within the aquifer in the state of Sao Paulo (Brazil)

measuring permeabilities of 0.2 to 4 m/day and transmissiveness of

40 to 500 m²/day in the outcrop areas. In areas confined by basalts, both values increase: permeabilities of 3 ± 1 m/day and transmissivities of 1000 ± 200 m²/day. These parameters present great variation according to the predominant lithological type in the studied section. As shown below, for the analysis of the Guaraní Aquifer in Uruguay, the total thickness of sediments involved includes lithologies of such different nature, which favor a very heterogeneous hydrogeological behavior.

THE GUARANI AQUIFER IN URUGUAY

If the criterion adopted for the entire Paraná basin is kept, in Uruguay this aquifer is constituted by the Buena Vista formation sensu ANDREIS and FERRANDO (1982) at the base and the Batoví Dorado group described by FERRANDO and MONTAÑA (1986) at the top. These sedimentary units constitute the top of the Gondwana Supergroup. They lie over clayey fine mudstones and sandstones with low permeability and are covered by the basaltic lavas of the Arapey group that determine the aquifer confines. They have been studied in detail in the northeast region of Uruguay, with abundant publications, but not as much in the northwest, below the basaltic layers. It is precisely because of the lack of outcrops, the relative scarcity of deep wells and percussion drills, that the data available are fragmentary and reduced.

This concept of Guaraní Aquifer is different from the known Tacuarembó Aquifer in Uruguay, and it is essential to dedicate a few lines to explain this difference, being of great importance due to the water reservoir it contains.

From FALCONER (1937) to SPRECHMANN and others (1981) the sedimented unit of the Neo-Gondwana containing the only known wind sandstones accumulated in fossil desert dunes, was called the Tacuarembó formation. Although in detail, the different authors varied the intraformative sequence, a wind episode was recognized at the top and an underwater one with fish fossils at the base. This unit is called the Botucatú formation in Brazil and the Botucatú Aquifer to the hydrogeological reservoir contained in it. By correlation, the Uruguayan infra-basaltic reservoir was called the Tacuarembó Aquifer.

ANDREIS and FERRANDO (1982) discovered the existence of another wind episode of up to 50 meters thick at the base of what BOSSI and others

(1975) called the Tacuarembó Fm. These authors then recognized the possibility of separating a new formation given it is long enough to be mapped and proposed to call it Cuchilla Ombú (FERRANDO and ANDREIS, 1986).

Figure 2. Summary table of the formational units of the top of the Gondwana Supergroup.

GRUPOS	FORMACIONES	ESPESORES	EDAD
Arapey			CRETACICO
Batoví Dorado	Rivera	30-50	JURASICO
	Tacuarembó	100-300	
	Cuchilla Ombú	30-50	TRIASICO
Caraguatá	Buena Vista	50-80	PERMICO
	Yaguari		
	Melo		

Acuífero
Guaraní
en
Uruguay

BOSSI and NAVARRO (1991) created the Batoví Dorado group composed of three mappable stratigraphic units: Cuchilla Ombú Fm. at the base; Tacuarembó formation in the middle and Rivera Fm. at the top.

In that period, the upper member was recognized as an independent and mappable unit, within the Yaguari Fm. FERRANDO (1984) proposed to separate the Buena Vista Fm., composed of medium, thick and conglomeratic sandstones as dominant lithofacies. The base, in contact with the rest of the ex-Yaguari formation, coincides exactly with the limit between the Permian and Triassic periods based on the finding of very characteristic fossil remains (BARBERENA and others, 1985).

Figure 2 provides an illustrative table of the current state of knowledge and its correlation, as a staggered synthesis essay relating various isolated aspects.

The first piece of information on the structure of infra-basaltic sediments was simultaneously due to MACKINON (1967) and HAUSMAN and FERNANDEZ (1967), who described some geological cuts from the study of five depth soundings carried out by ANCAP and the Geological Institute. PADULA (1972) uses data from boreholes in Uruguay and adds the information from the Nogoyá depth sounding (Entre Ríos, Argentina) to create profiles with a larger volume of data. BOSSI and NAVARRO (1991) based on a geological chart of the entire basaltic area (BOSSI and others, 1974) and abundant gravimetric and geoelectrical information, elaborate the first document with the tentative distribution of the Batoví Dorado group in its outcrop area and the

confined area below the basaltic area, both in plant and in a geological cut (Figure 3).

Figure 3.- Tentative distribution of the Batoví Dorado Group in its outcropping area and subsurface sensu BOSSI & NAVARRO (1991).



A significant fact is that the various infra-basaltic sedimentary units increase their thickness to the west and change their lithological composition as a result of a higher subsidence rate. The sequential profiles of the surroundings of Tacuarembó city (SPRECHMANN and others, 1981) undergo important variations to the west. The following information was obtained by J. BOSSI and R. NAVARRO for the company Paycueros and it is possible to publish thanks to the direct authorization of its president, Agr. Conrado Olaso Igoa. Although it refers particularly to the region of upwelling hot springs, its communication seemed relevant since it allows a global vision of the behavior of the Guarani Aquifer in Uruguay (Figure 4).

The Quebracho drilling, in the current Guaviyú hot springs, can be considered as a model of the Guarani Aquifer behavior in western Uruguay. The bore-hole opening is located at an altitude of +33m and the geological profile is described below according to data from MACKINNON (1967), HAUSMAN and FERNANDEZ (1967) and PADULA (1972), reinterpreted:

0m - 102m - Cretaceous sandstones of the Guichón Fm. 102m - 677m - basaltic lavas in 11 overlapping spills

677m - 840m - fine to medium-grained reddish sandstones ($Md=0.2mm$), well-selected with little clay cement. Pelitic levels every 20 to 25

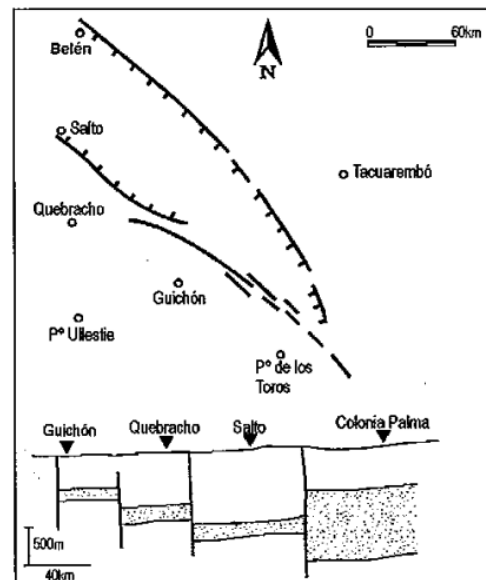
meters representing 15% of the total. A permeability of 2 m/day has been calculated applying TODD's criterion (1973).

840m - 960m - silty sandstones with low levels of fine sandstones. This unit belongs to the Yaguarí Fm. where very fine rocks dominate, with $Md = 0.08mm$. The permeability coefficient is very low, around 17 cm/day.

960m - 1103m glacial and fluvio-glacial rocks of the San Gregario - Tres Islas group.

1103m - 1112m granitic rocks of the Precambrian base.

Figure 4. Location of the drills studied by J. BOSSI & R. NAVARRO (per. comm.), and schematic geological structure of the basaltic area of the NW of Uruguay.



In this sounding, contribution levels are found at 500-540m and 750-900m deep (BUQUET, 1943). The upper aquifer is in the basaltic rocks and the lower covers the Batoví Dorado group and the Buena Vista Fm. The permeability values calculated with TODD's criterion (1973) were confirmed by flow and thickness measures of the contribution level applying DARCY's law. This was done for the five-depth soundings shown in Table 2.

Infrabasaltic sediments supply flows of 200 to 400 m³/hour and have permeability coefficients between 2 and 3 m/day, in all soundings far from the southern edge of the Guarani Aquifer in Uruguay. Table 3 shows lithologies and thickness of the aquifer as well as the flow rate and the permeability coefficient axis.

Table 2. Average thicknesses of the basaltic castings of the Arapey group.

Perforación	Espesor (m)	Nº derrames	Espesor medio (m)
Colonia Palma (Artigas)	518	11	47
Belén (Salto)	160	4	40
Termas Daymán (Paysandú)	946	26	36
Termas Guaviyú (Paysandú)	575	11	52
Paso Ullestie (Paysandú)	361	10	36
Guichón (Paysandú)	506	11	46
Salsipueses (Tacuarembó)	210	8	26
Paso de los Toros (Tacuarembó)	159	8	20
Pelado (Artigas)	160	4	40
Catalán Grande (Artigas)	164	4	41
Catalancito (Artigas)	157	4	39

Table 3. Lithological and hydrogeological characteristics of the Guarani Aquifer in the studied boreholes.

Borehole	Thickness (m)	Sandstones (%)	Silt (%)	Clays (%)	Flow (m ³ /day)	Perm. (m/day)
Arapey	272	83	-	17	800	3.2
Daymán	193	88	6	6	200	1.7
Quebracho	163	85	5	10	400	2
Guichón	128	76	-	24		0.5
P. Ullestie	89	27	41	32	6	0.05

The piezometric levels reached in the different perforations have been directly obtained by J. BOSSI and R. NAVARRO in 1981 (pers. comm.) (Figure 4). As evidenced by the very different flows and depths within the aquifer, the great regional faults generate isolated compartments with different flow directions and hydraulic gradients.

GONZALEZ and DE SANTA ANA (1998) carried out a faciological analysis based on data from soundings of the Eo-Mesozoic continental sedimentation in the NW of the Gondwana basin (southern end of the Chaco - Paraná basin), defining two depositional units in arid conditions. The information they provide, although summarized, represents a significant first contribution to the infra-basaltic sediments of the Guarani Aquifer. The Triassic-Jurassic sediments, up to 1200m thick, are referred to with a predominance of sandy lithofacies. Mudstones develop sporadically and thinner, suggesting -for the authors- conditions of aridity.

The basal unit lies on Permian sediments and is composed of sandy packages of 20 to 40m of individual thickness with thin interspersed mudstone levels whose thickness is not indicated. Sandstones are fine to medium, well selected, quartz, reddish, well rounded and with calcareous cement. There

are stratification plans with dips of up to 30° with respect to the horizontal plane, in sporadically extracted witnesses.

The upper unit is composed of fine to very fine sands, pink to reddish, regular to poorly selected, of variable roundness. Mudstone levels are interspersed more often. The total thickness varies between 300 and 650m. This depositional unit must be linked to a fluvio-lacustrine environment at the base with evolution to a fluvio-wind system. Although the authors do not cite it, they are recognizing in the basal unit the Buena Vista and Cuchilla Ombú formations while in the upper unit, the Tacuarembó and Rivera Fms.

In the currently accepted scheme, the aquifer levels have thicknesses between 30 and 80 m, separated by the Tacuarembó Fm. (with up to 300 meters of power) that due to its petrographic nature can reach an aquitard behavior in much of the area considered.

The dominant lithology of Rivera Fm. are medium sandstones (Md = 0.2 mm), well selected, feldspathic (5 to 10%), with little kaolinitic cement. They present cross-stratification of long stretch with dips of up to 35°. It has been formed by dune fossilization (SPRECHMANN and others, 1981). Granulometry is clearly unimodal in the 0.25 - 0.12mm class (BOSSI, 1966). These are very porous and permeable rocks.

In the Tacuarembó formation, the dominant lithologies are fine to very fine sandstones, well selected, not very rounded, feldspathic and micaceous with abundant clayey cement (FERRANDO and ANDREIS, 1986). These lithologies are interstratified with muscovite limolites and lutites with thicknesses of up to 1 meter and lengths of up to 20 meters. This stratigraphic unit, according to its constituent rocks, would have low values of porosity, permeability and transmissivity as hydraulic properties.

The Cuchilla Ombú Fm. was defined by FERRANDO and ANDREIS (1986) as a lithostratigraphic unit of wind origin, with power under 50 meters in outcropping areas, composed of fine to medium sandstones with predominance of planar curvilinear intersecting structures. Grains are rounded and cement scarce. They are considered fossil dunes of the barjan type due to the unipolar orientation of the paleocurrents towards the SE and the absence of signs of vegetation. This unit constitutes one of the best levels of the Guarani Aquifer, with a porosity of 20% and permeabilities of up to 4.6 m/day if considering data from LOPES (1984) for equivalent units in the state of Sao Paulo.

The Buena Vista Fm. was created by FALCONER (1937), eliminated by BOSSI (1966) and reformulated by FERRANDO (1984). In the original definition, it was composed of coarse-grained red sandstones with frequent cross-lamination, which develop mainly on the surface at the NW of the city of Melo. In the Colonia Palma sounding in the Department of Artigas, it has been crossed between 1530 and 1660 meters deep according to the descriptions of BOSSI and NAVARRO (1991) but the available data are very imprecise. The conditions of fluvial-lacustrine sedimentation have determined very important facies variations that generate different hydraulic behaviors according to the areas. There are no such data for Uruguay and only the values calculated for the entire aquifer by ARAUJO and others (1995) are available: porosity $10 \pm 4 \%$ and permeability 1 ± 0.5 m/day.

The main level of groundwater supply comes from the Cuchilla Ombú Fm. since it has a greater outcropping area and is also supplied by vertical percolation of the aquitard of the Tacuarembó formation. It has great storage capacity and permeability that can reach values of 4.6 m/day. The Rivera formation presents the same characteristics of power, texture and structure, and therefore, the hydraulic properties, but has difficulty recharging because it outcrops in very broken topography areas.

THE BASALTIC CONFINE: METHOD OF STUDY

The possibility of using the Guaraní Aquifer in areas of large flows is associated with drilling the overlapping basaltic layers. It is then of utmost interest to know the basalt thickness to cross and the flows to expect in each area. Flows, in general, are very important and do not constitute a limiting factor for most of the usage objectives, including irrigation.

The precise data of the perforations and electrical vertical soundings do not allow establishing acceptably precise contact plans for the determination of the thickness of the basaltic spills of the Arapey group, which represents an important limitation to evaluate the technical and economic feasibility of a borehole project that always implies a considerable investment.

BOSSI and HEIDE (1970) discovered the photogeologic possibility to define on the 1/40,000 scale, contacts of each spill, by the difference of behavior between the vesicular and massive levels. This discovery allowed establishing the rigorous

stratigraphic sequence at any point in the outcrop area, spill by spill, when the topography is moderately broken.

The thickness of each spill is variable and grows from east to west, with values of 35 ± 5 meters on the eastern edge and 42 ± 5 meters in the deep pores of the western region (see figure 4). The shapes of the contacts are also variable, including or not thin levels of sandstones, but in general terms, the average thickness of the individual spills can be estimated at around 40 meters.

In 1994 an ECOS cooperation agreement was signed between the Universities of Lyon and Nice (France) and the Universidad de la República (Uruguay) to renew the studies of the basaltic area of northwestern Uruguay, due to the importance from several points of view of the exhaustive scientific knowledge of an enormous magmatic phenomenon that can be studied spill by spill. This new approach to the problem provided aerial photos at 1/20,000 and 1/40,000 scale, topographic charts at 1/50,000 scale and the values of Bouguer gravimetric anomalies of the entire area, in public documents of very good quality of the Military Geographic Service. With such precise basic documents available, it became possible to gather quantitative information on each spill.

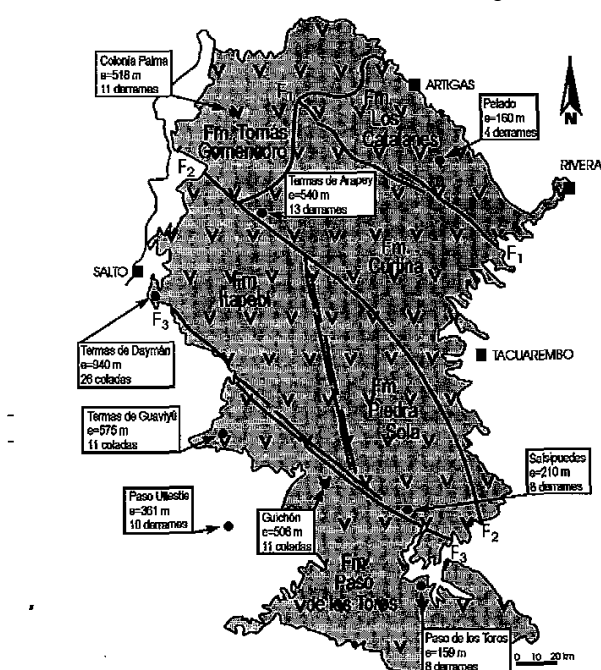
ARAPEY GROUP

The systematic application of the method throughout the basaltic area allowed recognizing the existence of 6 blocks of distinctly different behavior, taking into account several fundamental parameters: type of rock, slope angle and direction, presence or absence of intertrappean sandstones, development of large faults, total basalt thickness.

This new lithostructural compartmentalization suggested the convenience of proposing a group in order to assign formation hierarchy to each of the 6 blocks mentioned above. This approach seeks to highlight the differences in structure, lithological nature and surface morphology of each unit. On the other hand, each unit is perfectly mappable, even at very small scales (g.v. 1/2,000,000).

The proposal to create the Arapey group consisting of 6 formations called Los Catalanes, Curtina, Piedra Sola, Paso de Los Toros, Itapebí, and Tomás Gomensoro, is shown graphically in Figure 5 where the main perforations are added, with the thickness of basalt and the number of crossed castings.

Figure 5. Lithostructural compartmentation of the Arapey Group, indicating perforations, basalt thickness and number of crossed castings.



The separation of formations between each other is fundamentally based on the existence of 3 large NW faults, indicated in figure 5 as F1-F1, F2-F2 and F3-F3 from north to south, respectively. Another major fault has N10W direction and separates the Itapebí and Piedra Sola formations. The contact relationships of the Tomás Gomensoro Fm. seem to be instead of simple stratigraphic overlap, at least of the upper castings.

The most notorious characteristics of each of the proposed formations within the Arapey group are briefly described below to emphasize the current heterogeneity of behavior of the enormous magmatism of the Mesozoic plateau in the NW of Uruguay.

Los Catalanes Formation: In this unit BOSSI and CAGGIANO (1974) recognized the existence of 6 overlapping spills studying the geological structure of the Department of Artigas. They determined maximum dips of 0.3% and total thicknesses from 10-20 meters in contact with the underlying sandstones up to 170m in the sounding at Mr. O. Brum's property in Catalan Grande. Figure 6 shows the surface distribution of these spills between Masoller and Javier de Viana to account for the currently accepted structure. The basalts contain between 56 and 56% silica by weight (strictly speaking, andesites) and contain geodetic levels filled with agate and amethyst.

Curtina Formation: It is defined as a succession of fine to very fine grain spills, with geodes filled with siliceous material, frequent levels of intertrappean

sandstones and a regional structure dipping 0.5% towards the NW. Thirteen superposed castings have been recognized whose regional distribution is graphically expressed in Figure 7, extracted from BOSSI and HEIDE (1970). From the petrographic point of view, afiric rocks dominate, with a grain size between 0.03 and 0.1mm with intersertal texture, less than 10% glass, with opaque sub-automorphic minerals and little presence of olivine. The size of the fine grain and the regional dips of the structure generates landscapes with flat, slightly inclined areas and strong, concave slopes between them, responding to the existence of vesicular levels that are not very resistant to weathering, on which massive basalt levels of fine grain that resist the action of atmospheric agents are supported.

Piedra Sola Formation: It is composed of 9 superposed spills up to the edge of the Cretaceous sediments that cover it. The regional structure shows a dip of 0.4% towards the WSW as can be inferred from Figure 8 where an important portion of the outcrop area is exposed. From the petrographic point of view, most of the castings are micro-porphyric with very fine grain size (0.008 - 0.15mm), intergranular texture, about 10% glass, automorphic to sub-automorphic phenocrysts, opaque late minerals, micro phenocrysts of plagioclase and/or pyroxene with matrix in which the amounts of pyroxene and plagioclase are the same.

Paso de los Toros Formation: This lithostratigraphic unit brings together 11 overlapping basaltic spills, individually not very thick (average 20 meters), dips of 0.7% towards the SW and textures of coarse or porphyric grain, purely dominant. All these factors determine a barely wavy surface morphology, with few outcrops. These spills were described petrographically by FERNANDEZ and LEDESMA (1974) and GANCTO and APPRATIO (1993). The relationship between the 7 base spills is shown in Figure 9.

Itapebí Formation: This unit presents several notorious properties. It is an almost horizontal block in which practically a single casting emerges in 4800 km² (BOSSI and others, 1969). Secondly, it is the only block that contains 27 overlapping spills, generating strongly positive gravimetric anomalies. The resulting topography is very flat and the elevated areas are made up of resistant vesicular basalt, while the massive basalt - from medium to coarse grain - presents easy weathering. Figure 10 reproduces (simplified) the geological chart extracted from BOSSI and others (1969) and BOSSI and HEIDE (1970). The massive basalts of casting #26 possess interstitial texture without phenocrysts. The plagioclases are between 0.2 and 0.3 mm long and the

pyroxenes' diameter is 0.1 mm; labradorite and augite appear in equivalent proportions; the titaniferous magnetite is the only accessory. The percentage of glass is very small. Iddingsite is a sporadic accessory.

Formation Tomás Gomensoro: This lithostratigraphic unit was separated by very particular geomorphology, with large flat extensions, deep soils and exceptionally coarse-grained basaltic subsoil. It occupies 6600 km² at the NW end of Uruguay. It is

the only formation whose edges are neither rectilinear nor defined by faults, but by spill fronts, with curved limits (see figure 5). Petrographically it is a plagioclase -porphyritic basalt of labradorite - bytownite crystals (An70) with large opaque minerals (0.5mm edge). The plagioclases of the matrix are 0.4 - 0.5 mm long, present andesine composition (An45) and dominate over the pyroxenes in the modal composition. The texture is interstitial with areas where the glass reaches values of 20% in volume.

Figure 6. Geological chart of the "Los Catalanes" Formation.

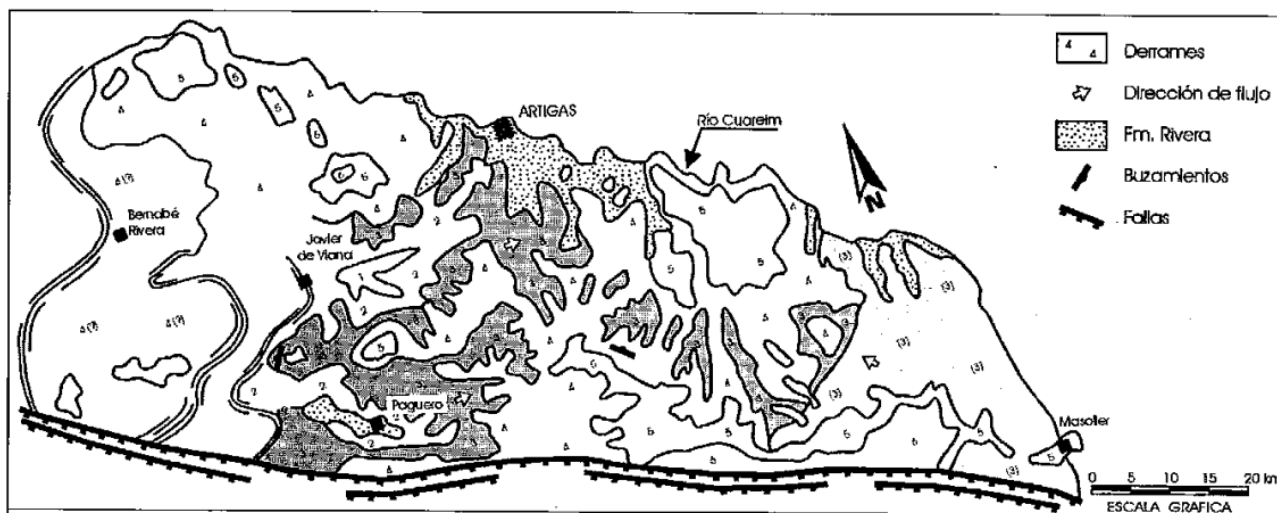


Figure 7. Geological chart of the "Curtina" Formation

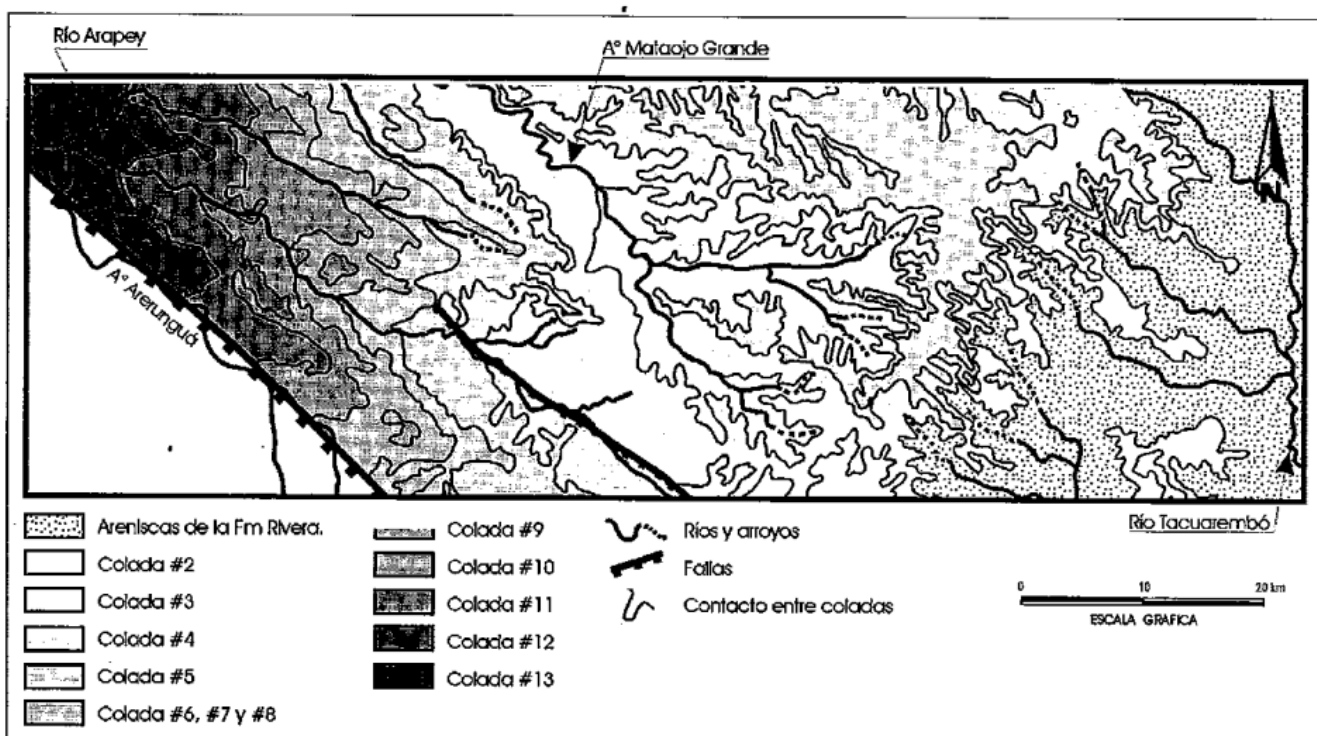


Figure 8. Partial geological map of the "Piedra Sola" Formation.

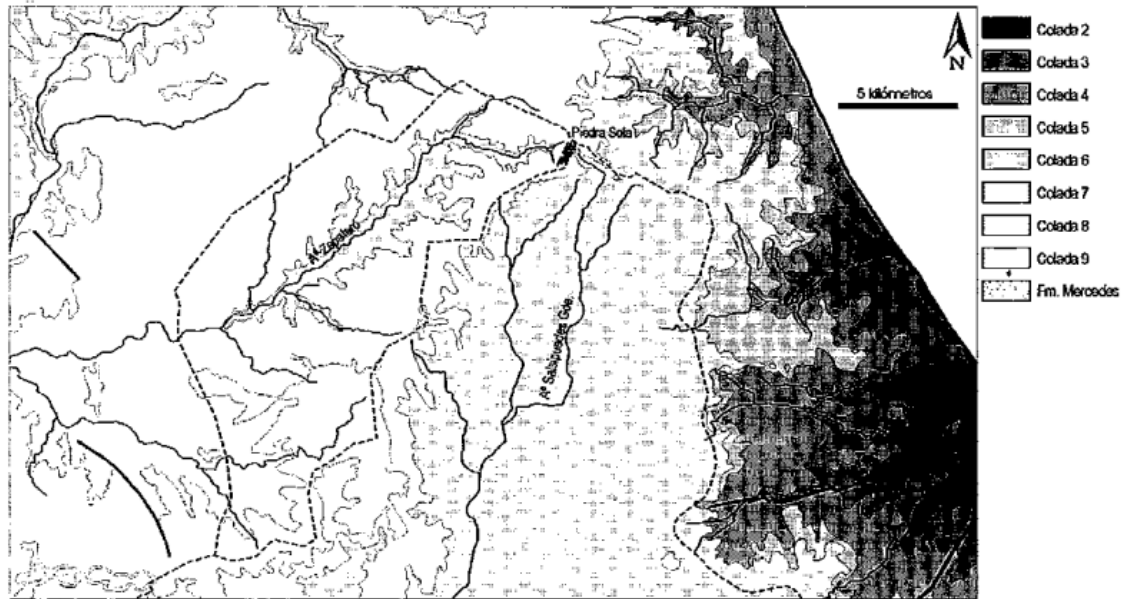


Figure 9. Geological chart of the "Paso de los Toros" Formation.

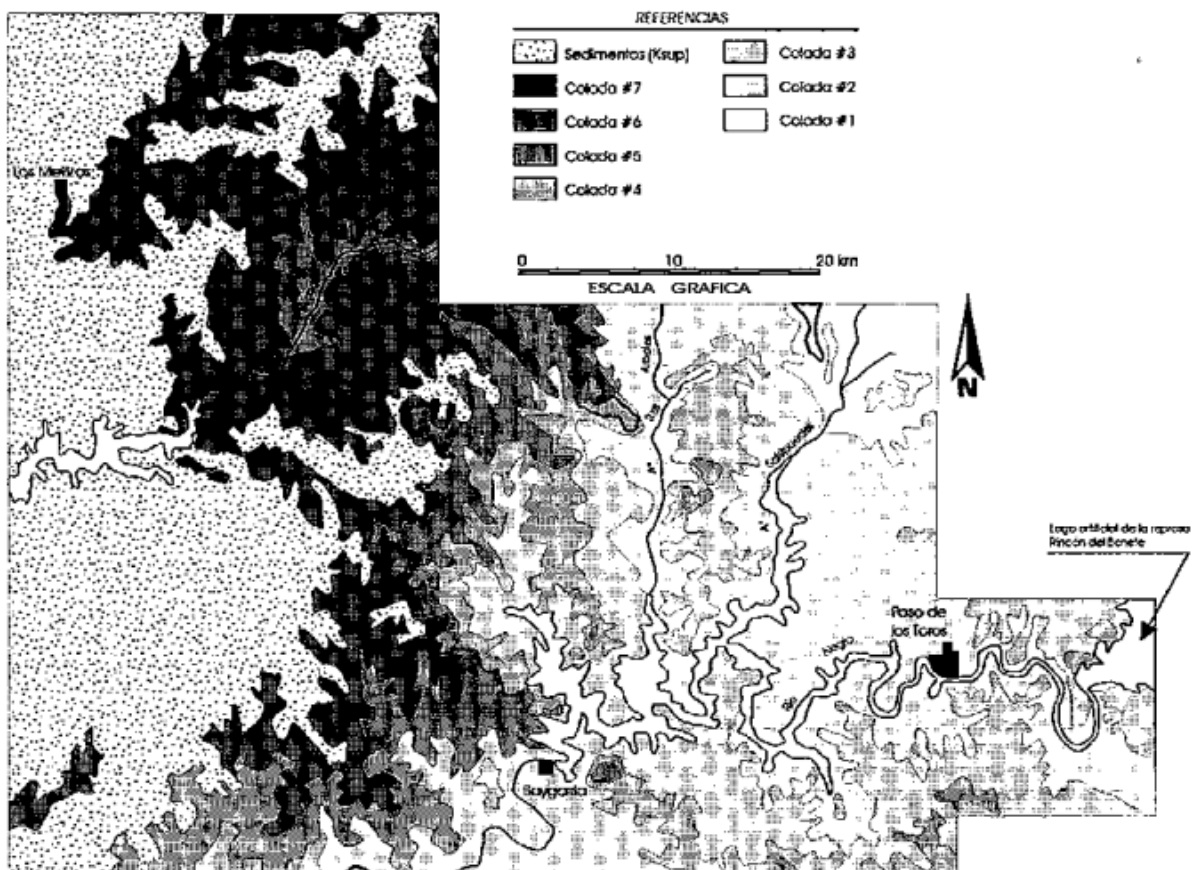
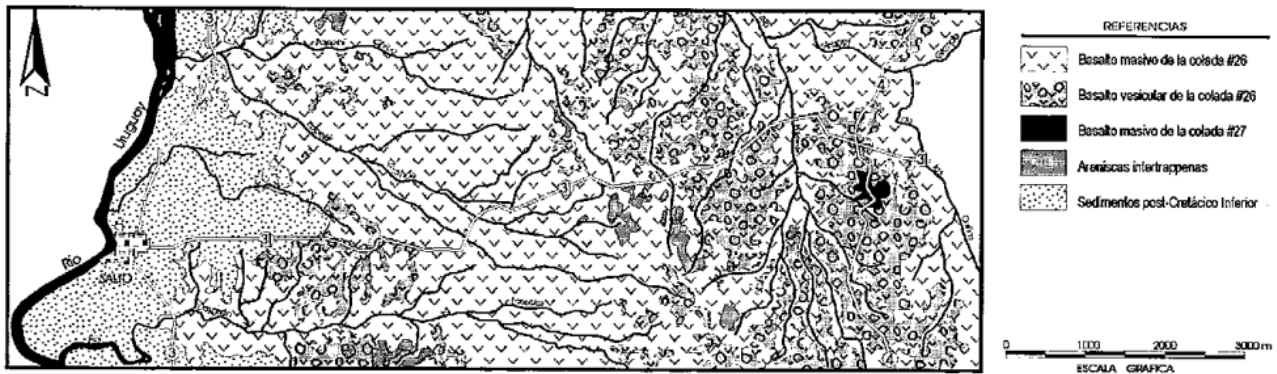


Figure 10. Geological chart of the "Itapebí" Formation.

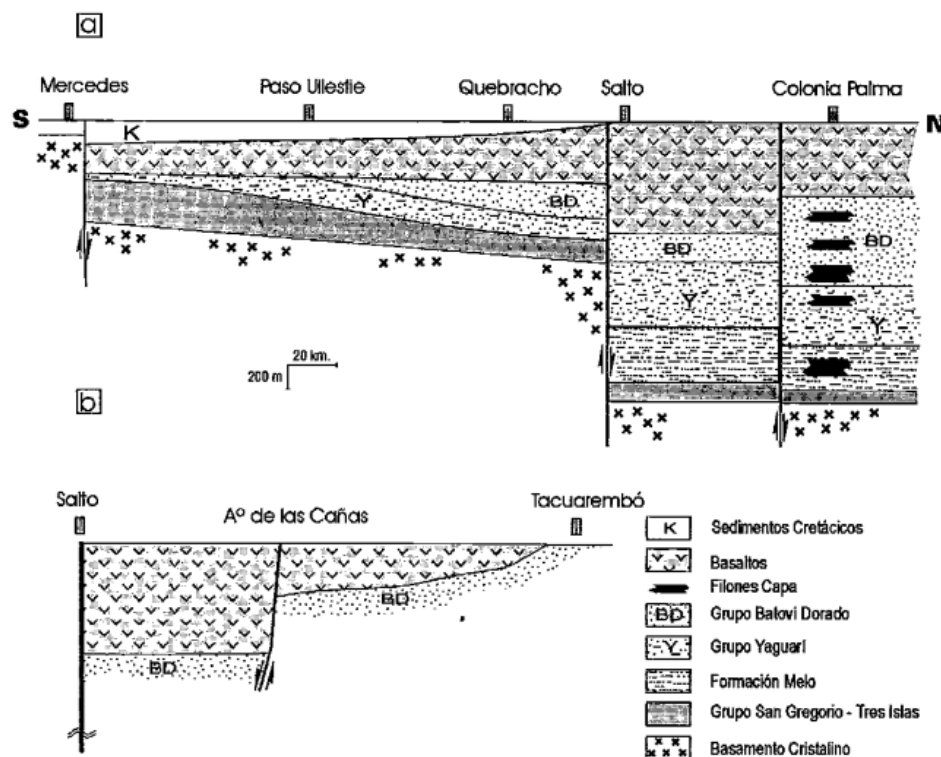


CONFINING BASALT GEOMETRY

The application of the photogeological and cartographic method to determine the number of overlapping castings in each zone, the individual thickness

of each of them and the regional dip, allowed to establish the three-dimensional geometric shape of the basalts of the Arapey group.

Figure 11. (a) geological cut north-south "Mercedes - Colonia Palma". (b) geological cut east - west by the parallel of Tacuarembó (geological scheme due to absence of drilling in the area).



Precision is relatively high in the eastern region where the number of overlapping castings is reduced and the method cannot be applied in the case of absolutely horizontal structures such as the Itapebí Fm. whose thickness can only be inferred from the data of the well drilled in the hot springs of Paso de Las Piedras of the Dayman River.

In general terms, the thickness of the basaltic rocks as a whole increases from east to west according to inclined levels and/or fault steps. These faults

present very significant rejections, reaching several hundred meters on both the northeast and south-west sides of the Itapebí Fm.

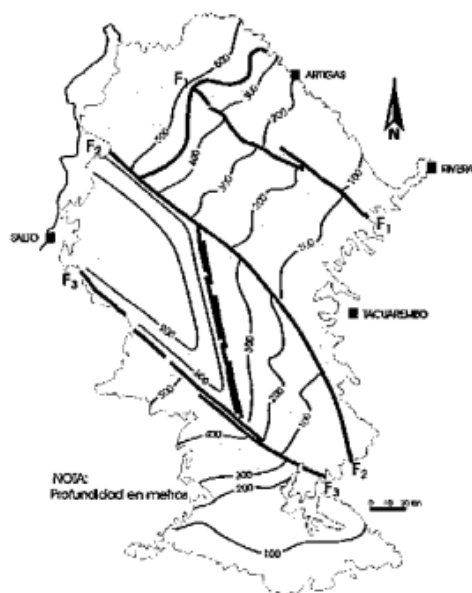
In a schematic cut of practically north-south direction, from the city of Mercedes in the Department of Soriano to the town of Colonia Palma in the Department of Artigas, using the data of the drilling in Paso Ulleste, Quebracho, Salto (Paso de las Piedras of the Dayman river) and Colonia Palma, it is possible to illustrate the behavior in blocks of different

thicknesses of the Arapey Group, as shown in figure 11a. In another geological cut, perpendicular to the previous one - approximate course east-west - (figure 11b) in the parallel of the city of Tacuarembó, it is possible to illustrate the behavior of the confining basalt increasing its total thickness towards the west.

Gathering all the available information described in this essay: perforations, geologic charts at 1/100,000 scale of almost the entire area and detailed topographic profiles in 1/50,000 scale charts, it became possible to present a first document in which the lines of equal basalt thickness (isopach) of the Arapey group are graphically shown.

These lines were drawn for each block based on the number of overlapping spills, the regional dip and the thickness measured for each casting in the areas closest to which it was accessed, thus presenting, an error of ± 30 meters in its evaluation (Figure 12).

Figure 12. Isopachs of the Arapey Group. They are shown as thin lines to facilitate the observation and interpretation of the document, but in reality, they should be tapes a few millimeters thick to quantitatively express their degree of uncertainty.



DISCUSSION

Defining the formations as independent units limited to each other by faults of increasing rejections towards the NW, the methodology of separating casting by casting gave positive results in several aspects of Geology Application, but one of the most significant has been the ability to predict the total

basalt thickness in every point of the area with an error less than or equal to 30 meters.

The possibility of knowing the basalt thickness at any point in the area occupied by the Arapey group with an appropriate degree of precision, allows knowing at what depth important groundwater flows can be obtained. This has the transcendental importance of enabling the quantitative planning of the profitability of investment in such a work to increase or modify agricultural production, in areas where the surface water resource is not easily accessed.

Average values of the thickness of the castings can currently be measured with great precision as topographic charts are available at 1/50,000 scale with contour lines every 10 meters. This allows evaluating the value of the regional dip or inclination with respect to the horizontal plane with very low errors (5% of the most probable value) applying the three-point method (BONTE, 1958) and the thickness of each casting with errors of less than 5 meters.

The degree of accuracy was verified by comparing the values obtained by the application of the cartographic method with real data of drilling carried out by the Geological Institute of Uruguay and ANCAP in Catalán Grande, Catalancito, Pelado and Yacaré (Dept. of Artigas), Paso de Los Toros and Salsipuedes (Dept. of Tacuarembó) and Guichón in the Department of Paysandú.

In all cases, differences of less than 30 meters have been obtained in areas where up to 9 spills overlap, which represents the entire area where it can be important to calculate the total basalt thickness with inexpensive techniques.

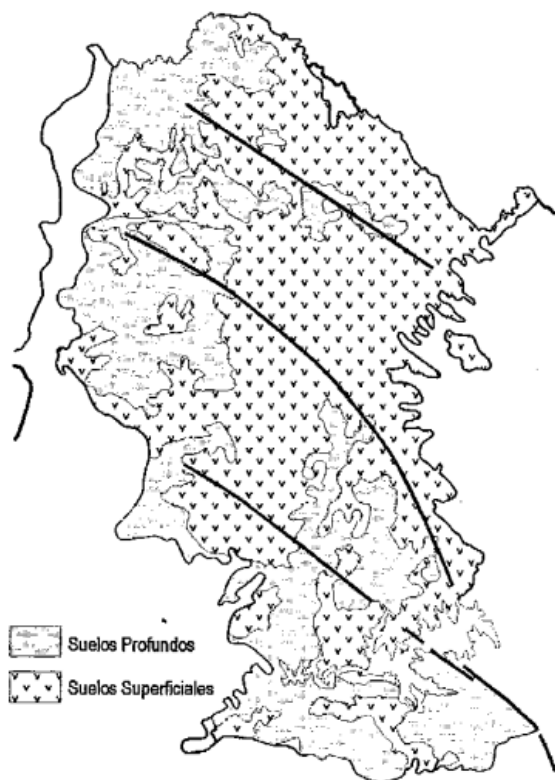
In the case of soil associations with a predominance of lithosols, which cover a large proportion of the total basaltic area, this method may be of decisive importance to generate an increase in production when it depends on irrigation at certain times of the year (Figure 13).

It shows that in the Curtina and Los Catalanes formations the superficial and very superficial soils clearly dominate, developed on fine-grained rocks, high relative silica tenor, dipping structures and/or areas of negative gravimetric anomalies that suggest blocks in isostatic ascent, in which erosion dominates over weathering.

For these lithosol areas, the "Basalt Program" was developed in agreement between the Agronomy College and the Agricultural Plan of the Ministry of Livestock and Agriculture between 1968 and 1973 with the express objective of installing meadows plowing with footings (SACCONE, 1971). The

clover meadows were installed with great vitality, but the summer temperatures in the rainless seasons prevented the reinstallation of the meadow the following year.

Figure 13. Association of surface soils in the basaltic area, taken from the 1/1,000,000 scale Soils chart from the Soil and Fertilizer Division of the MGAP (1976).



From the systematic results obtained from the experiences of meadow implantations in lithosols, it can be inferred that the irrigation possibility during summer droughts could satisfactorily solve the re-implantation problem.

The basaltic area supplies two types of aquifers, according to HAUSMAN and FERNANDEZ (1967):

- a fissured aquifer within the basaltic rocks properly mentioned with flows of 3 to 10,000 l/h at depths between 30 and 50m.
- a porous aquifer in infra-basaltic sandstones with flows with higher drilling and commissioning costs.

Being raised the issue in these terms, it is essential to know the expected depths and flows in order to decide the type of exploitation to plan: without irrigation; irrigation with small flows of the intra-basaltic aquifer; irrigation using significantly higher flows of the infra-basaltic aquifer.

Conclusions

Studies carried out on the basaltic area of the NW of Uruguay, which covers 41,000 km² with great internal heterogeneities, allowed improving the knowledge of several parameters and drawing some conclusions of interest, both in theoretical and applied aspects, which are described below:

1. It was convenient to increase the stratigraphic hierarchy and create the Arapey group composed of 6 formations with particular lithological and tectonic characteristics, different from each other and separated by regional faults of important rejections.
2. All surface drilling and surveys verify the overlap between 6 and 13 castings in each block except for the one corresponding to the Itapebí Fm. that presents 27 spills.
3. The thickness of each spill and the total overlapping spills grows from east to west, with average values of 35 ± 5 m to 42 ± 5 m, respectively.
4. The current level of knowledge makes it possible to measure the number of overlapping castings at each point of the outcropping basalt area and to establish the thickness of each casting with an error of less than 5 meters.
5. As a corollary of the previous conclusion, it is possible to know the total thickness of basalt at each point, with an error of less than 30m, verified by comparing the data obtained by the application of the photogeological - cartographic method with the real values of 7 perforations.
6. For the first time, this information allowed making a chart with contour lines of basaltic rocks of equal thickness (isopach), which turned out to be the most important conclusion of the study due to the possible economic repercussions in the short and medium-term.
7. Knowing the thickness of basaltic rocks to cross in order to reach the Guaraní Aquifer with flows of at least 50,000 l/h, means the possibility of planning technological modifications in the basaltic area, especially including the area of superficial and very superficial soils (lithosols), with approaches of economic feasibility on quantitative bases.

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