THE DEVELOPMENT OF THE THERMAL CENTERS ALONG THE BORDER ARGENTINA - URUGUAYAN

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INTRODUCTION

The origin of balneology in the region is associated with oil exploration efforts that began about 60 years ago, but during the last six years, the commercial exploitation of thermal (30-50ºC) aquifers along the Argentine and Uruguayan sides of the Uruguay River has grown significantly. The establishment of therapeutic and recreational facilities such as Chajarí, Federación, Concordia, Villa Elisa and Colón in Argentina, and Arapey, Daymán, Guaviyú and Almirón in Uruguay (Figure 1) are contributing considerably to the local economy.

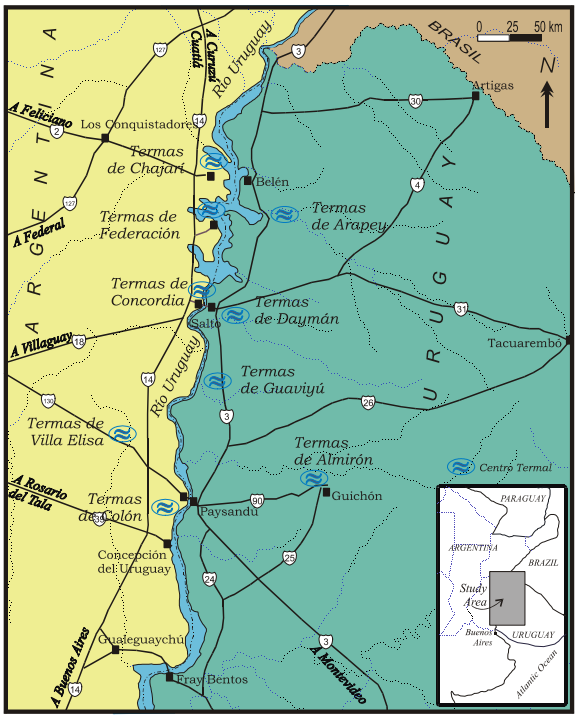

Figure 1. Location of study area and of thermal spas in northeastern Argentina and western Uruguay

The low-temperature geothermal resources are found in a vast volcanic-sedimentary basin hosted in an intercratonic region of low-to-normal thermal gradient. Three thermal aquifers with large potential for direct geothermal applications have been identified and characterized [1]. The governments of both countries have recognized the importance of these hot waters and are promoting the development of spas and tourist centers around the wells tapping them.

The wells supplying thermal water to the spas produce from different levels of the Guaraní Aquifer System (GAS), depending on location (Table 1). The lower aquifer exploited at Almirón, Paso Ullestie in Uruguay and at Villa Elisa in Argentina, is quite saline; it is in Lower Carboniferous-Middle Permian glaciomarine deposits. The middle and most important thermal aquifer, is in Lower Triassic to Lower Jurassic sedimentary rocks (eolian at the top, fluvial, deltaic and lacustrian toward the bottom). Generally, this highly productive aquifer is of low salinity, however as it deepens towards the east-southeast its salinity increases. The spas at Chajarí, Federación, Concordia, Arapey, Dayma and Guaviyú tap into this aquifer. The upper aquifer is in Lower Jurassic to Upper Cretacic sedimentary rocks that are interlayered with thick basaltic flows, particularly toward the bottom. The spa at Colón extracts water from this low salinity water-bearing unit.

Well	Latitude (S)			Longitude (W)			Approx. Elev. (m.a.s.l.)	Top Serra Geral Fm. (r.n.m.)	Top Rivera– Tacuarembó Fms. (r.n.m.)	Top Carbonif.-Permian Fms. (r.n.m.)	Top Basamento (r.n.m.)	Total Depth (m.b.b.p.)	Temp. (° C)	Flow Rate (L/min)
	Deg.	Min.	Sec.	Deg.	Min.	Sec.								
Colón	32	12	31	58	08	50	25	-209	-	-	-765	1500	33	2250
Arapey	30	57	36	57	31	48	60	60	-477	-	-	?	41	5800
Chajarí	30	44	46	58	00	46	55	-57	-611	-	-	811	38	6100
Federación	30	58	32	57	55	41	35	-7	-776	-	-	1301	41	7500
Concordia	31	17	41	58	00	16	48	-20	-935	-	-	1175	43	4400
Daymán	31	32	24	57	53	24	20	20	-935	-2000	-2155	2206	45	5166
Guaviyú	31	51	36	57	53	24	33	33	-642	-	-	958	38	6800
Paso Ullestie	32	27	00	57	58	48	25	-235	-	-875	-950	?	-	-
Almirón	32	39	36	57	11	24	68	10	-	-568	-860	?	34	312
Villa Elisa	32	07	40	58	27	18	50	-309	-	-898	-	1032	41	216

Table 1. Guaraní Aquifer System. Thermal well data

ORIGIN AND EVOLUTION OF THE BASIN

The GAS of central-eastern South America extends over the Chaco-Paraná basin of Argentina, Uruguay and Paraguay, and over the Paraná basin of southeastern Brazil. It spans across a 1,750,000 km^2 area of Phanerozoic sedimentation, in a epicratonic basin located above the Rio de la Plata Craton-Brazilian Massive unit which became a craton during the Brazilian Cycle [2]. It corresponds to a tectonic basin filled with 5,000 m or more of sedimentary rocks and basaltic flows.

The basins extend over a Cambro-Ordovician craton (i.e. consolidated basement) and fractured zones created during the late stages of intracratonic trough formation [3]. The basin formed during slow regional subsidence as evidenced by the extensive Early Paleozoic fine sediments overlying crystalline basement, and the lack of coarse sediments near an hypothetical rift zone. Cambrian-Ordovician marine sediments deposited in the northeastern part of the basin. During the Silurian, the sea level dropped and the volume of deposited detridal materials diminished. The Devonian corresponds to a transgressive time. Probably during the time between the Lower and Middle Carboniferous the region was uplifted, as indicated by the erosional discordance obsverde at the top of the Early Paleozoic sequence.

During the Upper Carboniferous-Early Permian, predominantly continental (fluvial, lacustrian and glacial) sediments were deposited in an intracratonic basin, which formed the sequence that corresponds to the lower level of the GAS. At the end of the Permian, the regional subsidence in the central basin resulted in the sedimentation of more continental units. This was followed by regional uplift and subsequent erosion (indicated by a slight Middle Triassic discordance). During the Upper Triassic and Upper Jurassic, fluvial and eolian sandstones were deposited which host the middle level of the GAS.

At the end of the Jurassic significant tectonic extension occurred, mainly in the NNE and NW directions, creating numerous faults and folds. The deposition of continental sandstones during this time might have been controlled by a rifting episode which ended after the effusion of large volumes of basalts related to the Upper Jurassic and Lower Cretaceous opening of the Atlantic Ocean. At lower levels these volcanics present continental sediment interlayers that correspond to the upper SAG.

In the southern part of the basin a marine transgression occurred during the Cretaceous-Tertiary transition. Also during those times the first uplifts related to the Andean Orogeny resulted in an erosional period that ended in the Eocene with the deposition of continental units. Another marine transgression occurred during the Miocene. At the end of this epoch, movements of the Quechua Phase produced a discordance between the top of the Pliocene and the Quaternary sedimentary units.

THE GUARANÍ AQUIFER SYSTEM OF ARGENTINA AND URUGUAY

The GAS has three levels of thermal aquifers that correspond to separate hydrogeologic systems.

Lower GAS level. Montaño and Collazo [4] described the lower level of the GAS in Uruguay where it is found in glacial and fluvioglacial units corresponding to the Lower Permian San Gregorio Formation which correlates to the Sachajoy and Charata Formations of Argentina (Figure 2). The sedimentary rocks, fine to medium sandstones and conglomerates of the Tres Islas Formation (similar to the Chacabuco Formation of Argentina), were deposited in continental to littoral environments. In Argentina, in the western part of the basin, the lower level is represented by the Chacabuco, Charata and Sachajoy Formations. At the bottom of this level there are sedimentary rocks deposited during a marine transgression. The top corresponds to an Early Permian regression period (Chacabuco and Charata Formations). The Chacabuco Formation [5], and Charata and Sachayoj Formationes [6] presents hard, micaceous, gray-to-dark-gray clays and sometimes bituminous shales, as well as gray limestone and medium-to-fine sandstone interlayers. The Charata Formation, representing Upper Carboniferous glacial and fluvioglacial environments, is formed by silty, gray clays; tillite intercalations are abundant near the base of the formation.

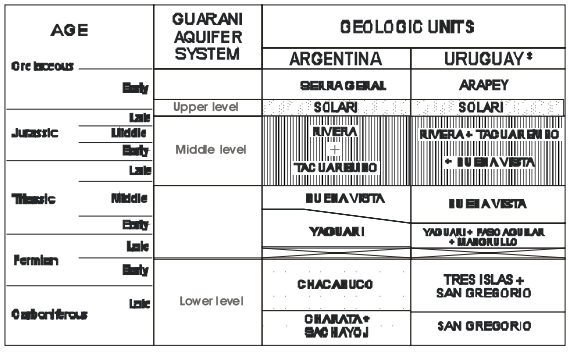

Figure 2. Stratigraphy for the Guaraní Aquifer System

The thickness of the lower GAS level varies between 292 m in the southeastern part of the basin (i.e., in the Almidón well; Table 1) and 95 m toward the south (i.e., in the Paso Ullestie well). Near the Uruguay River this level was not deposited because of a basement high in that region. It is not encountered in the wells at Colón and Concepción del Uruguay, but it is found to the west in the Villa Elisa well.

Middle GAS level. Because of its productivity, the middle level is the most important one in the GAS. [4] mention that the aquifer outcrops in some areas. It is found in the Rivera and Tacuarembó Formations [7] y [8] which form the largest known eolian deposit that may extend over a 1.5 million square kilometer area [9]. The outcrops, restricted to Uruguay, occur along a north-south band that starts east of the city of Rivera, and ends at the Negro River to the south, passing through the city of Tacuarembó. These large outcrops are the main recharge areas of the middle GAS which is exploited on both sides of the Uruguay River.

The wells drilled at Arapey, Belén, Federación, Charají and Concordia show that the Rivera and Tacuarembó Formations extend toward the west into Argentina [1]. The southern limit of the middle level is north of the Almirón, Colón and Villa Elisa wells. The total thickness of this level could only be determined in the Belén well (i.e., 526 m) that had been drilled looking for oil. All the other wells which were exploring for thermal waters only penetrated the upper few meters of the two units.

The lithologic and sedimentary characteristic of the Early-to-Lower Jurassic Rivera Formation (e.g., sandy dunes, eolian and ephemeral torrential fluvial deposits) indicate that it was deposited in a desert environment. It is composed mainly by fine-to-medium, well-sorted, cross-bedded quartzitic

sandstones of eolian origin. Drill cuttings from the Chajarí wells show that they have no or little cement, and a porosity of about 30%.

The sedimentary rocks of the Middle Triassic-to-Early Jurassic Tacuarembó Formation are mainly of fluvial type (i.e., river bed, alluvial plain, and overflow deposits). It is composed by very fine-to-medium grained, well-to-regularly sorted, feldspar, quartz and micaceous (mainly muscovite) sandstones with clay cement, and by green, redish siltstones and mudstones, friable muscovite shales, and intraformational conglomerates.

Upper GAS level. The upper aquifer of the GAS is hosted in continental sandstones of the Solari Formation [10] interstratified with the lower basalts of the Serra Geral Formation [11]. At present, this thermal aquifer is only being penetrated by the Colón well, west of the Uruguay River, at 795 m below sea level (Figure 3). In this part of the basin the basement presents a structural high, the Colón-Concepción del Uruguay Horst, that did not allow the deposition of the formations corresponding to the lower and medium GAS levels. Fine and medium grained quartz sandstones and some coarse psammitic interlayers predominate the lithology of the upper GAS level. Some basalt flows are also found. There is evidence of alternating basaltic effusions, and erosion and deposition events occurring under arid conditions. Sediments are predominantly eolian, with smaller amounts of subaqueous deposits.

The north-south profile along the Uruguay River (Figure 3) was prepared using the information from the Chajarí, Federación, Concordia, Colón, Concepción del Uruguay and Gualeguaychú wells. The Colón-Concepción del Uruguay Horst that had an important effect on sedimentation, is clearly discernable. Its highest part (at 686 m below sea level) was encountered by the Concepción del Uruguay well. Toward the north and south where the basin becomes deeper, the lower and medium GAS levels are found in the wells. The lower level occurs south of the horst (i.e., at Gualeguaychú).

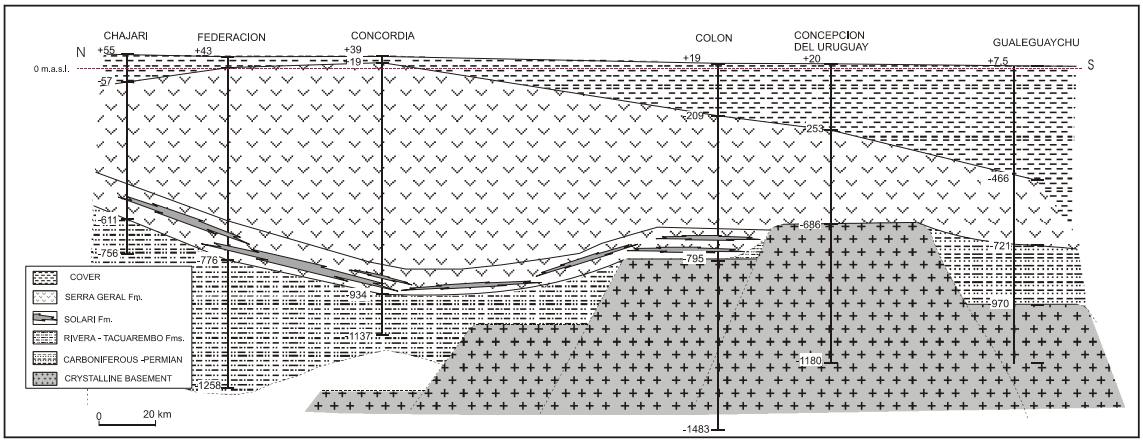

Figure 3. North-South geologic section along the Uruguay River (showing the Colón-Concepción de Uruguay Horst). Elevations given in meters

In the southern and central part of the area under study the upper and medium level of the GAS produced the thermal fluids. The western and eastern edges of the horst and the southern limits of the medium and lower levels have been established by correlating the Almirón, Colón, Paso Ullestie, Concepción del Uruguayand Villa Elisa wells (Figure 3).

HYDROLOGY

The GAS is confined over 90% of its area. In the remaining 10%, where the aquifer is unconfined, most of the recharge occurs [12]. The chemical characteristics of the GAS waters are given in Table 2.

Montaño and Collazo [4] mentioned that the waters in the Rivera and Tacuarembó Formations are potable everywhere. The waters are of calcium chloride and calcium bicarbonate type. The concentration of calcium is higher than that of sodium which could be related to the poor cementation of the Tacuarembó Formation that some times is calcareous [4]. The mean total hardness, expressed as $CaCO_3$, is 45 mg/L; the average dry residue is 120 mg/L.

The GAS presents three confined aquifer levels. The top of the system corresponds to the upper and mid parts of the Serra Geral Formation; in some areas and because it presents fractures the formation behaves as an aquitard [13].

As indicated earlier, the GAS deepens toward the east-southeast where it presents a remarkable number of reactivated regional faults [14] that permits the infiltration of waters from overlying units. Since in the western part of the basin these units are Tertiary marine formations, there is an increase in total dissolved solids toward the west [1].

Geothermal Area	pH	EC [µS/cm]	TDS [mg/L]	Na^+ [mg/L]	Ca^{++} [mg/L]	Mg^{++} [mg/L]	Cl^- [mg/L]	SO_4^{--} [mg/L]	HCO_3^- [mg/L]	CO_3^{--} [mg/L]	SiO_2 [mg/L]	K^+ [mg/L]	Fe^{++} [mg/L]	F^- [mg/L]	B [mg/L]	NO_3^- [mg/L]	Li^+ [mg/L]	Al^{+++} [mg/L]	Mn^{++} [mg/L]	As^{+++} [mg/L]	Water Type
U P P E R L E V E L																					
Colón	8.5	1180	620	235	1.4	0.5	105	74	318	12	22	0.7	0	3.1	1.4	n.d.	0.03	<1	0	0.01	Sodium Bicarbonate-Sodium Chloride
M I D D L E L E V E L																					
Arapey *	8.2	416	297	98	19	10	33	20	175	49		6.3	0	0.2		0.1			0		Sodium Bicarbonate
Chajarí	8.2	918	569	175	11	5	120	40	238 *	< 5	----	5	0.01	0.6	0.17	n.d.	< 0.1	0.017	< 0.005	0.021	Sodium Bicarbonate-Sodium Chloride
Federación	8.5	1250	698	240	16	5.8	199	92	236	2.6	7.9	4.3	0.2	0.5	0.23	4	0.04	0	< 0.05	0.03	Sodium Bicarbonate-Sodium Chloride
Concordia	8.5	554	326	118	4.6	1.8	21	8.4	290	3.8	9.6	2.5	< 0.2	0.7	0.17	3.1	0	0	0	0.06	Sodium Bicarbonate
Daymán *	7.8	806	455	140	7	2	32	28	295.24	0		2	0	0		0			0		Sodium Bicarbonate
Guaviyú *	8.7	997	712	245	1.8	0.4	80.97	70	302	88		2	0	1		0.1			0		Sodium Bicarbonate
L O W E R L E V E L																					
Paso Ullestie *		3000	2803	900	41.5	5.8	911.68	602	129.32	0		10	0	0		0			0		Clorurada-Sódica
Almirón *	7.2	8000	8044	2000	233	2.9	2933.95	1215	37	0		15.01	0	0		0			2.9		Clorurada-Sódica
Villa Elisa	7.7	18900	14,500	4900	191	70	5070	4800	98	0	15	13	0.4	1.1	4.1	n.d.	0.47	<1	<0.05	0	Sodium Sulfate-Sodium Chloride

Table 2. Chemical analysis of waters from the three levels of the Guaraní Aquifer System

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The lower level of the GAS is exploited in the extreme southern part of the basin where three wells have been drilled (i.e., at Almirón, Paso Ullestie and Villa Elisa). The Almirón well reaches the San Gregorio Formation at less that 568 m depth; at Paso Ullestie, at less than 855 m; and at Villa Elisa (Argentina), the Chacabuco Formation is found at less than 897 m depth, indicating that the lower GAS level

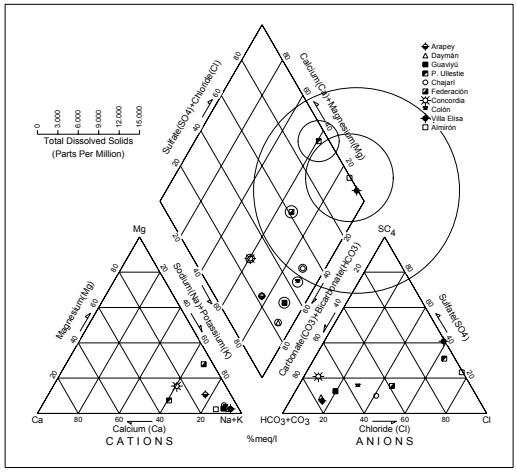


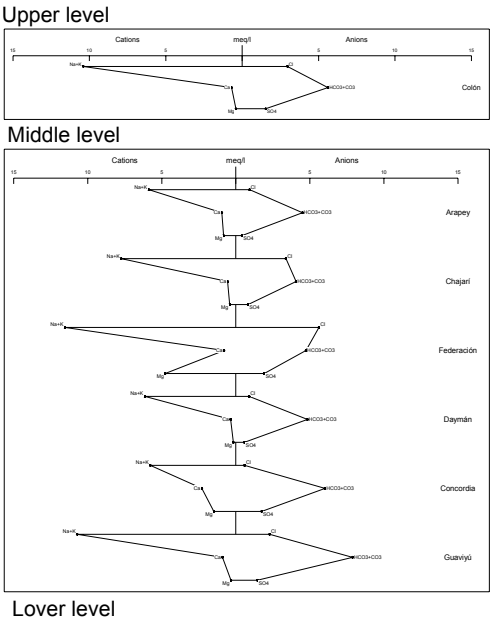
Figure 4. Pipper diagram for the Guaraní Aquifer System waters.

deepens toward the west. According to the Pipper diagrams (Figure 4), the waters are of sodium sulfate-chloride type. The amount of total dissolved solids (TDS) increases toward the west (i.e., the average TDS is 5423 mg/L in the east and 14,500 mg/L in the west. The amount of magnesium in the waters also

increases in that direction. The average pH of the waters is 7.5. The electrical conductivity varies between an average of 5500 µS/cm in Uruguay to 18,900 µS/cm in Argentina.

The middle level is being produced in the south-central part of the region under study, where the Rivera-Tacuarembó can be found (i.e., in the Guaviyú, Daymán, Concordia, Arapey, Federación and Chajarí wells). The major ions in the thermal waters of this level are mainly of sodium bicarbonate type. The wells in Federación and Chajarí produce high chloride content waters, as shown by the Stiff diagrams (Figure 5). This can be explained by the hydrogeologic model for this aquifer that shows the groundwaters moving from east to west.

The temperatures in the middle level vary between 38º and 46ºC; the pH (i.e., 8.3) is almost constant throughout this level. The average TDS is 509 mg/L; it varies between 455 mg/L (Arapey) and 712 mg/L (Guaviyú)



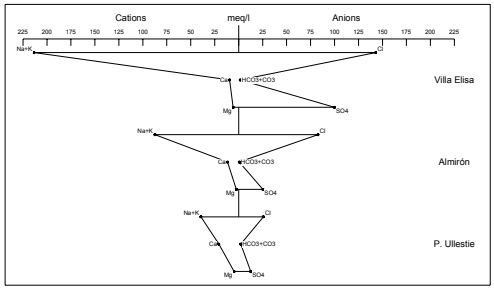


Figure 5. Stiff diagrams for the waters of the three levels of the Guaraní Aquifer System

The waters in the upper GAS level (only produced at Colón) have a temperature of 33ºC, a pH of 8.5 and TDS of 620 mg/L; they are mainly of sodium bicarbonate-chloride type. Sodium and potassium concentrations are higher than that of calcium and magnesium, and the flour content is high. The waters' electrical conductivity is 1180 µS/cm.

GEOTHERMAL DEVELOPMENT

In the mid-1990s a number of people, witnessing the successful spa industry in Uruguay, proposed similar developments on the Argentine side of the Uruguay River. This led to the drilling of the 1260 m deep Federación well which produced 43°C waters and the opening of the first thermal spa in northeastern Argentina in January 1997.

After that successful well, others were drilled at Concordia, Colón, Villa Elisa, Concepción del Uruguay and Gualeguaychú. Unfortunately because of lack of appropriate exploration data and bad completion, some did not encountered thermal waters, like the ones at Concepción del Uruguay and Gualeguaychú, and others were drilled too deep (e.g. the 1502-m deep Colón well than penetrated more than 600 m of crystalline basement). Note that all the thermal wells on both sides of the Uruguay River are flowing artesian wells.

The integrated study of the basin and the economic success of the spas is resulting in the rapid development of the region's low-temperature geothermal resources. Five additional wells and associated spas are being

planned in Argentina and two new ones in Uruguay. This shows the important role of these developments in the economy of the region.

The growth of economic activity is made obvious by the fast increase in the number of hotel beds in towns having spas. For example, at Federación that number went from 182 in 1994 to 2150 in 2001. The opening of a spa tends to be reflected by a jump in the number of beds in town.Statistics collected by the government of the Province of Entre Ríos where for all of the thermal spas located in northeastern Argentina, show a constant growth in the number of tourists visiting the spas; a record number visited during Easter 2002. In the case of Federación the increase of tourist activity is surprisingly high; during the January-June 2002 period more than 210,000 people visited the spa, compared to 150,840 for the twelve months of 2001. Part of this increase is related to the recent devaluation of the Argentine peso which lowers the costs for visitors from neighboring countries. It is estimated that only 10 % of the visitors are locals, the rest are from other parts of Argentina and from abroad. The drop in unemployment from 25 % to 7 % reflects the importance of these centers on the economy of the region over a four-year period.

The data collected from wells drilled during the development of the low-temperature geothermal resources of northeastern Argentina and western Uruguay has allowed to get a better understanding of the Guaraní Aquifer System, reducing the risks associated with drilling new wells and developing new spas in the region. The popularity of the thermal centers along both sides of the Uruguay River will lead to a further development of these geothermal resources and the construction of new tourist centers, contributing to the growth of the regional economy.

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