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CHARACTERIZATION OF GROUNDWATER IN THE CARIRI (CEARÁ, BRAZIL) BY ENVIRONMENTAL ISOTOPES AND ELECTRIC CONDUCTIVITY

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ABSTRACT. The Cariri region is the largest sedimentary basin in the state of Ceará, Brazil. Located in the southern portion of the state, it comprises the Araripe Plateau and the Cariri Valley on its northern foot. The region's groundwaters are being heavily exploited. Using electric conductivity (EC) and ^{18}O, ^{14}C and ^{3}H data, we differentiate groundwaters from various origins. We identified three horizons of springs on the slope of the Plateau through their geologic environment and the EC of their waters. Groundwaters from wells in the Cariri Valley are classified according to the aquifers exploited as indicated by the drilling profiles. However, strong tectonic features and intense fracturing in the Valley produce a great many horizontal discontinuities, which result in a mixing of groundwaters from different aquifers. Mixing systems are described in terms of δ^{18}O–^{14}C and EC–^{14}C linear trends.

INTRODUCTION

The Cariri region is located in the southern portion of the state of Ceará in the semiarid northeast of Brazil. The area is a green "oasis" embedded in a barren landscape of mostly crystalline bedrock outcroppings. The region consists of a sedimentary plateau (the Araripe Plateau) with a mean elevation of 750 m and an area of *ca.* 7500 km^2, and a sedimentary basin (the Cariri Valley), measuring *ca.* 3500 km^2, on its northern foot.

Rich groundwater resources are the driving agents for the region's important economy, which is second only to that of the capital of the state. The resources provide an exclusive water source for cattle raising and domestic, industrial and agricultural water supplies and are being intensively exploited mainly for large-scale irrigation of sugar cane. However, the origin of the groundwater and its recharge areas are still largely unknown.

Our research in the Cariri was initiated because of popular complaints denouncing the environmental damage caused by deforestation at the top of the Araripe Plateau, as well as overexploitation of the Cariri Valley aquifers. The discharge from one of the major springs emerging from the cliffs of the Plateau has dropped during the period from 1920 to 1993 from *ca.* 1300 m^3 h^{-1} to 380 m^3 h^{-1} (Kemper *et al.* 1995). In years with poor rainfall the water table in the Valley lowered dramatically. A great number of private wells (with depths <20 m) fell dry and natural lakes disappeared without returning to their normal extension in the following years. Based on environmental isotope data (^{14}C, ^{18}O, ^{3}H) and EC measurements, we have characterized the waters from the different aquifers to evaluate regional groundwater dynamics.

DESCRIPTION OF THE AREA

The area of this study comprises mainly the townships of Crato, Juazeiro do Norte, Barbalha and Missão Velha (Fig. 1). In this part of the Cariri, mean annual rainfall is *ca.* 1000 mm, surpassing that of many coastal areas of the state. Differing from the rest of Ceará, where the southerly shifting of the Zone of Intertropical Convergence causes the single rainy period around April (lasting three to four months), the Cariri is favored with two distinct rainfall regimens that produce a two-humped distribution of precipitation: in addition to the main peak in April, a precursing one appears in January. This is due to cyclonic events penetrating from the south. Because of this, the growth period of vegetation is greatly increased as compared to the central and northern parts of Ceará.

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Structurally, the Cariri region is characterized by pronounced tectonic features. Mont'Alverne *et al.* (1995) describe successive grabens and horsts along sections AB and CD in Figure 1A. Chignone *et al.* (1986) individualized seven structural blocks in the Cariri Basin, the most important of which are: 1) the block of Crato/Corredores, with arched grabens and horsts; 2) the graben of the Serra das Cacimbas; and in between these, 3) the regional, central horst of Mauriti.

A drilling (P1 in Fig. 1B) by Petrobras in the township of Araripina/Pernambuco, on the Plateau, revealed the following sequence of formations (thicknesses are in parentheses): Exu (228 m), Arajara (165 m), Santana (112 m), Rio da Batateira (198 m), Abaiara (124 m), Missão Velha (190 m), Brejo Santo (431 m) and Mauriti (41 m). Exu, Arajara, Santana and Rio da Batateira are all from the Middle Cretaceous Period, Abaiara is from the Cretaceous, Missão Velha and Brejo Santo from the Upper Jurassic and, finally, Mauriti, which is in contact with the crystalline basement, is from the Silurian/Devonian Period. The first three formations constitute the Araripe Plateau and are absent in the Cariri Valley. Arajara, Santana and Brejo Santo formations are aquitards and the others are aquifers.

A drilling by the Departamento Nacional de Produção Mineral (DNPM) in the township of Bodocó/Pernambuco, *ca.* 15 km southwest of the Petrobras, showed that the formations Abaiara, Missão Velha and Mauriti are absent at this location. Sequence and thicknesses are as follows: Exu (190 m), Arajara (40 m), Santana (242 m), Rio da Batateira (59 m), Brejo Santo (380 m) and Mauriti (32 m). The piezometric level for the Rio da Batateira Formation was 370 m by this drilling.

Due to sandy soils on top of the Plateau and, possibly, open fractures in the Exu Formation, infiltration occurs very quickly there. A surface drainage system is only faintly developed. Even several hours after heavy rainfall, no accumulation of surface water is found. There are no producing deep wells on the Plateau, with the exception of one in the Fazenda Janaguba, near the edge of the Plateau, that taps the saturated layer (possibly 60 m thick) at the contact of the formations Exu and Arajara. However, there are some localized perched aquifers, such as in a settlement called "Cacimbas". (The name refers to a type of shallow, dug well found in the area.)

The Exu/Arajara and Arajara/Santana contacts constitute discontinuities (from high to low) of hydraulic conductivity and define the horizons of some hundreds of springs that emerge at roughly half of the height of the Plateau above the Basin. They appear mainly in gorges and other locations affected by erosion where resistance to water flow is reduced. Their total discharge is roughly 50 m^3 min^{-1} (Gaspary 1967). The allocation and use of the waters from some of these springs have been legally established for over a century.

The exploitation of aquifers in the Cariri Basin is intense. The depths of wells studied range from 32 to 240 m, with pumping rates reaching 300 $m^3 h^{-1}$; their water generally derives from contributions from various aquifers. Wells are often arranged in batteries, specially along the alluvial zones of the rivers Rio da Batateira (in Crato), Riacho dos Macacos (in Juazeiro do Norte), Rio Salamanca (in Barbalha) and Riacho dos Porcos (in Milagres). Due to excessive pumping of wells, in some of these rivers during the dry season, the natural runoff has not been replaced by returning waste water from households and factories.

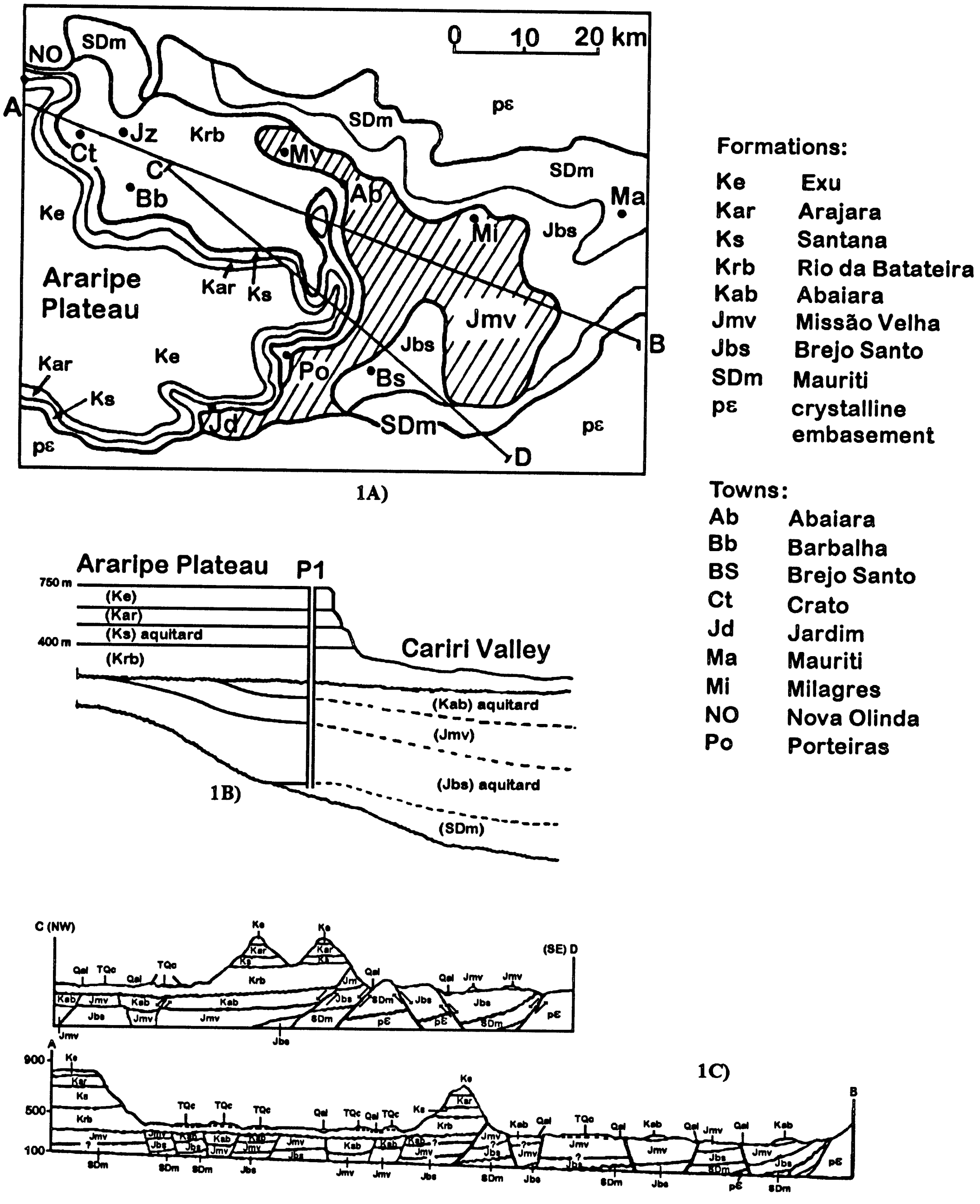


Fig. 1. A) The area of study; B) Geological sketch; C) Stratigraphic of the Araripe Plateau and Cariri Valley.

METHODS

^{14}C and ^{18}O measurements were made on groundwater, and ^{3}H and ^{18}O were analyzed in water from springs. The discharge from two springs was monitored for *ca.* 3 yr using NaCl dilution after instantaneous injection. ^{14}C and ^{3}H were measured in our (Physics Department) laboratory and ^{18}O was measured by Hydroisotop (Schweitenkirchen, Germany). Electric conductivity (EC) was measured in the field. Geographic coordinates were assigned through GPS.

^{14}C values were obtained by gas-proportional counting of acetylene (864 ml at 760 Torr, corresponding to *ca.* 1 g of carbon). The standard used was HOxI. An error of ±1 σ applies to the counting statistics of background, samples and modern standard. Some of the ^{14}C data were published previously (Santiago *et al.* 1994). Tritium was measured in our laboratory with a Packard Tri-Carb® 2000 CA/LL liquid scintillation spectrometer after electrolytic enrichment by a factor of 40, starting with a sample volume of 500 ml, and using Insta-Gel® as scintillator. The detection limit was 0.3 TU.

RESULTS

In Table 1, 19 springs are listed together with their locations (township, coordinates), EC, $\delta^{18}O$ (‰, SMOW) and the approximate discharge (Q). The last column indicates the environment (formation or interface of formations) as assigned by us using a spring's elevation together with the stratigraphic column. Three groups can be distinguished.

1. The first set comprises the first 12 springs (from Batateira through Santa Rita), listed in Table 1 in order of decreasing discharge. They originate from the Exu/Arajara contact. Their waters are very weakly mineralized, with EC $\leq 30\,\mu S\ cm^{-1}$.
2. The second set is made up of three minor springs from the Arajara Formation (Angélica, Olho d'água and Recanto). Their discharge is much smaller and diffuse and has therefore not been measured. Mineralization is significantly higher (EC from *ca.* $80\,\mu S\ cm^{-1}$ to $130\,\mu S\ cm^{-1}$) than in the first group.
3. The third set comprises the springs Solzinho and Macauba, which we attribute to the contact of the formations Arajara and Santana. Their EC is $234\,\mu S\ cm^{-1}$ and $266\,\mu S\ cm^{-1}$, which is two to three times that of the second set.

We added two springs to Table 1 that do not originate from the Plateau but are located in the Cariri Valley: Rosário and Ciciaca. Rosário is located on the cliff of the horst of Mauriti, and Ciciaca where the Mauriti Formation meets the crystalline basement. We measured $\delta^{18}O$ for some springs: Pendência in Missão Velha yielded −3.4‰; Boca da Mata and Solzinho in Jardim, −2.9‰ and −3.5‰, respectively. The two springs in the Valley, Rosário and Ciciaca, measured −3.4‰ and −2.9‰.

Results from wells in the Cariri Valley show a wide range of values reflecting the opulence of tectonic features of the region. We group them according to the main aquifers exploited as indicated by the drilling profiles. Tables 2–5 represent, respectively, wells in the aquifers Rio da Batateira, Rio da Batateira in combination with Missão Velha, Missão Velha, and, finally, Mauriti. However, we must emphasize that we deal with production wells where all water entries are utilized, irrespective of their origin. Thus, we cannot expect a clear-cut separation of the different groups. Nevertheless, EC is a fairly good parameter for characterizing the water produced by each group:

- The Rio da Batateira wells have EC below $200\,\mu S\ cm^{-1}$ if we eliminate a subgroup of five wells (at the end of Table 2) that are located in areas where fluvial deposits along riverbeds are directly connected with the Rio da Batateira aquifer;

- The Rio da Bateteira/Missão Velha wells produce waters with EC between 200 μS cm^{-1} and 300 μS cm^{-1} (excluding P6 and P10, see comments below) (Table 3);
- The Missão Velha wells have from 300 μS cm^{-1} to 580 μS cm^{-1} (Table 4);
- The Mauriti wells have from 600 μS cm^{-1} to 980 μS cm^{-1} (Table 5).

TABLE 1. The Major Springs in the Cariri Basin, their Coordinates, EC and Discharge (*Q*)

Locality	Township*	Lat. S	Long. W	EC (μS cm^{-1})	*Q*† (m^3 h^{-1})	δ^{18}O (‰)	Origin
Springs on the Slope of the Plateau							
Batateira	Ct	7°15′35″	39°28′17″	28	376		Exu/Arajara
Pendência	MV	7°24′35″	39°12′46″	25	352	−3.4	Exu/Arajara
Bica do Farias	Bb	7°19′50″	39°24′45″	27	348		Exu/Arajara
Sítio Cocos	Bb	7°22′36″	39°17′14″	19	182		Exu/Arajara
Sítio Saco	Po	7°29′38″	39°09′45″	20	182		Exu/Arajara
Bom Jesus	Bb	7°22′39″	39°17′19″	30	180		Exu/Arajara
Sozinho	Ct	7°19′15″	39°24′48″	17	154		Exu/Arajara
Coqueiro	Ct	7°17′02″	39°25′57″	23	140		Exu/Arajara
Boca da Mata	Jd	7°33′20″	39°16′21″	26	132	−2.9	Exu/Arajara
Camelo	Bb	7°22′23″	39°20′33″	15	120		Exu/Arajara
Água Grande	Ct	7°17′15″	39°24′58″	25	113		Exu/Arajara
Santa Rita	Bb	7°21′21″	39°18′48″	15	102		Exu/Arajara
Angélica	Ct	7°12′46″	39°26′33″	69			Arajara
Olho d'água	BS	7°28′05″	39°04′49″	77			Arajara
Recanto	Ex	7°25′33″	39°50′25″	118			Arajara
Solzinho	Jd	7°34′43″	39°16′17″	234		−3.5	Arajara/Santana
Macauba	MV	7°12′46″	39°39′06″	266			Arajara/Santana
Springs in the Cariri Valley							
Rosário	Mi	7°18′20″	39°58′05″	118		−3.4	Mauriti
Ciciaca	NO	7°06′11″	39°38′22″	339		−2.9	Mauriti/basement

*Bb = Barbalha; BS = Brejo Santo; Ct = Crato; Ex = Exu; Jd = Jardim; Mi = Milagres; MV = Missão Velha; NO = Nova Olinda; Po = Porteiras.

†After Mont'Alverne *et al.* (1995)

DISCUSSION

Based on the values given in Tables 1–5 and previous isotope measurements from springs (Santiago *et al.* 1992) and rain (Frischkorn *et al.* 1990) we designed the following conceptual model for groundwaters on the Araripe Plateau and in the Cariri Valley.

Infiltrated rainwater from the top of the Araripe Plateau percolates the Exu sandstone and feeds a group of *ca.* 300 springs. As shown in Table 1, and in a previous publication (Santiago *et al.* 1988), the springs with the highest discharge are situated at an elevation of *ca.* 700 m and have EC <30 μS cm^{-1}. According to its drilling profile, a well in Fazenda Janaguba (elevation 730 m, depth 50 m) produces water from the contact of the formations Exu and Arajara. Its water has an EC of 32 μS cm^{-1} and a tritium concentration of 1.3 TU, which is comparable to values for the first group of springs, which lie between 0.3 TU and 1.3 TU (Santiago *et al.* 1990). Thus, these values verify that springs with EC <30 μS cm^{-1} discharge from the Exu/Arajara contact.

δ^{18}O for one of these springs (Batateira in Crato) was monitored for 10 months and was found to follow seasonal rainfall variations of ^{18}O with a lag of *ca.* 5 months (Frischkorn *et al.* 1990). The discharge from two springs in Barbalha (Studart *et al.* 1992) was monitored for >2 yr. In this case, we

TABLE 2. Wells that Exploit the Rio da Batateira Aquifer*

No.	Locality	Town-ship†	*P* (m)	Lat. S	Long. W	$\delta^{18}O$ (‰)	EC ($\mu S\ cm^{-1}$)	^{14}C (pMC)
P5	Rch. Macacos 2	Jz	150	7°13′37″	39°18′26″	−3.1	168	74.6 ± 0.9
P26	Conj. Mirandão	Ct	102	7°14′11″	39°23′51″	−3.0	198	91.4 ± 0.8
P27	Lagoa Seca 10	Jz	91	7°14′51″	39°19′19″	−3.3	98	80.8 ± 0.5
P28	Lagoa Seca 11	Jz	115	7°14′56″	39°19′22″	−3.3	186	66.6 ± 0.5
P29	Lagoa Seca 16	Jz	129	7°14′34″	39°18′51″	−3.0	182	88.7 ± 0.6
P34	Rch. Macacos 2a	Jz	32	7°13′38″	39°18′22″	−3.2	154	124.8 ± 0.9
P40	Lagoa Seca 17	Jz	180	7°14′23″	39°18′04″	−3.1	162	80.5 ± 0.6
P47	Cafundó 5	Ct	110	7°14′26″	39°24′20″	−3.0	183	98.8 ± 0.8
P54	SENAI	Ct	95	7°13′34″	39°23′49″	−2.9	199	--
P63	Lagoa Seca 15	Jz	130	7°15′43″	39°19′20″	−3.1	157	--
P67	Floresta	Ct	129	7°14′29″	39°24′59″	−3.1	113	--
P69	São Raimundo Novo 2	Ct	100	7°13′47″	39°25′31″	−2.8	169	--
P70	Café da Linha	Ab	60	7°17′54″	39°02′05″	−2.9	79	--
P77	Rosário	Mi	50	7°18′29″	38°57′54″	−3.5	98	--
P79	Sizani	Ct	120	7°13′20″	39°25′20″	−3.1	174	--
P80	Recanto 1	Ct	130	7°14′37″	39°24′56″	−3.1	134	--
P15	São Raimundo 2	Ct	126	7°13′47″	39°25′31″	--	219	111.5 ± 1.1
P20	St. Monte Alegre	Ct	60	7°12′25″	39°24′37″	--	497	121.4 ± 1.1
P22	V. Padre Cícero	Ct	98	7°13′08″	39°21′32″	--	88	108.3 ± 0.8
P41	Batateira - lav.	Ct	32	7°13′25″	39°25′31″	−3.2	312	115.5 ± 1.1
P55	São Raimundo N1	Ct	130	7°13′49″	39°25′37″	−3.1	144	104.2 ± 1.1

*For Tables 2–5: No.= well number; P (m) = well depth; $\delta^{18}O = \delta^{18}O$ (SMOW); EC = electric conductivity; pMC = percentage of modern carbon.

†Ab = Abaiara; Ct = Crato; Jz = Juazeiro do Norte; Mi = Milagres.

TABLE 3. Wells that Exploit the Rio da Batateira and Missão Velha Aquifers

No.	Locality	Town-ship*	*P* (m)	Lat. S	Long. W	$\delta^{18}O$ (‰)	EC ($\mu S\ cm^{-1}$)	^{14}C (pMC)
P4	Lagoa Seca, 9	Jz	119	7°14′27″	39°19′22″	−3.3	291	64.2 ± 0.7
P6	Rch. Macacos 8	Jz	191	7°12′36″	39°18′08″	−3.9	522	35.4 ± 0.6
P10	Poço 2	MV	86	7°15′32″	39°17′46″	−3.6	375	30.3 ± 0.4
P19	Sítio S. Pedro	Bb	78	7°17′50″	39°17′12″	−3.2	226	99.2 ± 0.5
P33	Barro Branco	Bb	76	7°18′50″	39°15′22″	−3.4	288	88.0 ± 0.8
P35	Rch. Macacos 3	Jz	140	7°13′35″	39°18′12″	−3.2	243	92.0 ± 0.7
P36	Rch. Macacos 4	Jz	140	7°13′25″	39°18′13″	−3.4	291	78.2 ± 0.5
P38	Rch. Macacos 7	Jz	200	7°12′46″	39°18′20″	−3.2	281	75.1 ± 0.7
P39	Lagoa Seca 14	Jz	82	7°14′38″	39°19′03″	−3.5	299	61.0 ± 0.5
P46	Vila Alta 2	Ct	107	7°13′24″	39°24′43″	−3.2	232	93.7 ± 1.1
P58	Rch. Macacos 1	Jz	120	7°13′48″	39°18′24″	−3.4	258	77.5 ± 0.7
P71	Lagoa Seca 12	Jz	126	7°15′08″	39°19′21″	−3.4	253	72.4 ± 1.1
P72	Lagoa Seca 13	Jz	102	7°15′20″	39°19′23″	−3.5	213	79.1 ± 0.7

*Bb = Barbalha; Ct = Crato; Jz = Juazeiro do Norte; MV = Missão Velha.

found a delay of 6–8 months with relation to monthly rainfall amounts. These results indicate a surprisingly quick hydraulic response, certainly due to percolation in fractures of the Exu sandstone. As "modern" rainfall has 3.2 TU, the 0.3–1.3 TU for springs are, according to a modified exponential model for the horizontal flow at the Exu/Arajara contact, compatible with times of transit between 4 and 26 yr (Silva *et al.* 1992).

TABLE 4. Wells that Exploit the Missão Velha Aquifer

No.	Locality	Town-ship*	*P* (m)	Lat. S	Long. W	$\delta^{18}O$ (‰)	EC (μS cm^{-1})	^{14}C (pMC)
P9	Alto da Alegria	Bb	113	7°18′27″	39°08′12″	−3.2	349	93.2 ± 0.7
P31	Usina, prof. 200	Bb	200	7°18′08″	39°14′09″	−3.2	363	84.5 ± 0.7
P37	Rch. Macacos 5	Jz	160	7°13′14″	39°18′15″	−3.6	380	48.9 ± 0.4
P48	Abaiara - lav.	Ab	130	7°21′10″	39°02′47″	−3.8	417	44.9 ± 0.6
P50	CAGECE 7	Mi	118	7°18′54″	38°56′20″	−5.1	569	--
P53	Bela Vista	Bb	88	7°19′40″	39°17′46″	−4.3	456	28.1 ± 0.5
P59	Rch. Macacos 6	Jz	200	7°13′02″	39°18′17″	−3.6	438	54.2 ± 1.1
P68	Sítio S. Paulo	Bb	144	7°18′07″	39°17′49″	−3.0	332	--

*Ab = Abaiara, Bb = Barbalha, Jz = Juazeiro do Norte, Mi = Milagres.

TABLE 5. Wells that Exploit the Mauriti Aquifer

No.	Locality	Town-ship*	*P* (m)	Lat. S	Long. W	$\delta^{18}O$ (‰)	EC (μS cm^{-1})	^{14}C (pMC)
P1	R. M. Ferreira	NO	80	7°05′21″	39°41′32″	−3.6	967	--
P2	Poço 2	NO	128	7°06′32″	39°41′02″	−3.4	752	62.9 ± 0.6
P3	Baixio 3	NO	130	7°06′58″	39°41′19″	−3.8	976	3.6 ± 0.4
P42	SESI	Ct	63	7°13′37″	39°23′46″	−3.1	639	99.1 ± 0.7
P44	Hp. S. Vicente	Bb	150	7°18′39″	39°18′03″	−2.9	602	90.8 ± 0.8
P73	Abaiara 1	Ab	130	7°21′20″	39°02′40″	−3.5	776	59.7 ± 0.7
P74	Jacu	NO	127	7°05′42″	39°41′10″	−3.5	866	--
P76	Pedras Cariri	NO	50	7°05′43″	39°40′35″	−3.0	631	--
P78	Vila Esperança	Ma	80	7°26′33″	38°57′14″	−2.8	670	--

*Ab = Abaiara; Bb = Barbalha; Ct = Crato; Ma = Mauriti; NO = Nova Olinda.

A second group of springs that emerges from the slope of the Plateau, characterized by EC between 69 μS cm^{-1} and 118 μS cm^{-1}, comprises mostly discharges of groundwater from the Arajara Formation that are not well concentrated but resemble seepage areas. Their discharge is difficult to evaluate. A well at the Colégio Agrícola (agricultural school) in Crato, at an elevation of 630 m and a depth of 45 m, produces, following the drilling profile, water from the Arajara Formation. EC of this well is 71 μS cm^{-1} and tritium concentration is 0.9 TU, which confirms the attribution of this second group of springs to the Arajara Formation.

At still lower elevation, on the slope of the Plateau, there is another horizon of springs at the Arajara/Santana contact with higher mineralization (with EC *ca.* 250 μS cm^{-1}). Their discharge is much smaller than that of the first group and normally diffuse. Solzinho Spring, which belongs to this group, shows a $\delta^{18}O$ of −3.5‰, which is the lowest value measured for springs. The scattering of $\delta^{18}O$ between −2.9‰ and −3.5‰ demonstrates that, even at an elevation of *ca.* 200 m below the Plateau, the amount effect that marks rainfall is still perceptible without being blurred much by mixing. Even though, due to a very low water table at *ca.* 100 m deep, access to groundwater is difficult on the Plateau, some isolated clayey lenses produce perched aquifers that are being exploited in some places through dug wells. We determined EC for two of them and found 169 μS cm^{-1} (at Semião) and 526 μS cm^{-1} (at Romoaldo). The fact that these conductivities are considerably higher than those of the springs far below is still another indication of a vertical flow in fractures in the Exu Aquifer.

Tectonic fracturing is very intense in the Cariri Valley. This causes a varying sequence of formations in the sedimentary basin (Fig. 1C) and produces local mixtures of waters that are difficult to interpret. In our discussion, we adopt the new stratigraphic column proposed by DNPM (Mont'Alverne *et al.*

1995) in our assignments of isotopic characteristics to hydrogeologic structures. This column distinguishes, in the area of interest of the Cariri Valley, the formations, from top to bottom, Rio da Batateira (aquifer), Abaiara (aquitard), Missão Velha (aquifer), Brejo Santo (aquitard) and Mauriti (aquifer).

Phreatic waters from the Rio da Batateira Formation (Table 2) are weakly mineralized (EC <200 μS cm^{-1}). Figures 2A and 3A show pMC between 67 and 125 and δ^{18}O from −2.8‰ to −3.5‰, with a mean of −3.1‰, which corresponds roughly to the mean value for rainfall in the area. The scattering of δ^{18}O around the mean reflects seasonal and annual fluctuation in rainfall (amount effect). It is noteworthy that wells in zones of fluvial deposits exhibit special features: EC increases with pMC in a very good correlation (EC = 22.7 pMC − 2295) with a correlation coefficient of R = 0.94, different from the "traditional" decrease of EC with increasing pMC as shown by the other groups of wells. This behavior can be explained as a mixing line of very young, yet highly mineralized water from the fluvial deposits with young recharge from the unconfined Rio da Batateira aquifer.

Waters from wells that simultaneously exploit the aquifers Rio Batateira and Missão Velha (Table 3) are characterized by EC from 200 μS cm^{-1} to 300 μS cm^{-1} (with the exceptions of wells P6 and P10; see below). They comprise pMC from 30 to 99 and δ^{18}O from −3.2‰ to −3.9‰. The following correlations were obtained (Figs. 2B and 3B):

$$\text{EC} = -3.21\ \text{pMC} + 524\ (R = -0.83) \quad \text{and} \tag{1}$$

$$\delta^{18}\text{O‰} = 0.008\ \text{pMC} - 3.96\ (R = 0.81)\ . \tag{2}$$

These correlations describe mixtures of young and weakly mineralized waters from the Rio da Batateira with a older and more mineralized water from the Missão Velha Formation. Wells P6 and P10 occupy an extreme position in this group. Even though their drilling profiles integrate them into the Rio da Batateira/Missão Velha wells, their δ^{18}O and pMC values are the lowest of the group; their conductivities are the highest. As a result, these two wells seem to be "strangers" in an otherwise rather homogeneous group. In fact, mathematical simulation using MODFLOW of the dynamic levels for the battery of wells they are part of, and also the evaluation of pumping tests (Mendonça 1995), confirm that at least P6 is situated exactly upon a leak that, bridging the Abaiara aquitard, directly connects the aquifers Rio da Batateira and Missão Velha. Thus, for wells P6 and P10, pMC of 35.4 and 30.3 (with uncorrected ages of 7840 and 9600 yr, respectively) and δ^{18}O levels of −3.9‰ and −3.6‰ may be taken as characteristic for this old component of the Missão Velha aquifer.

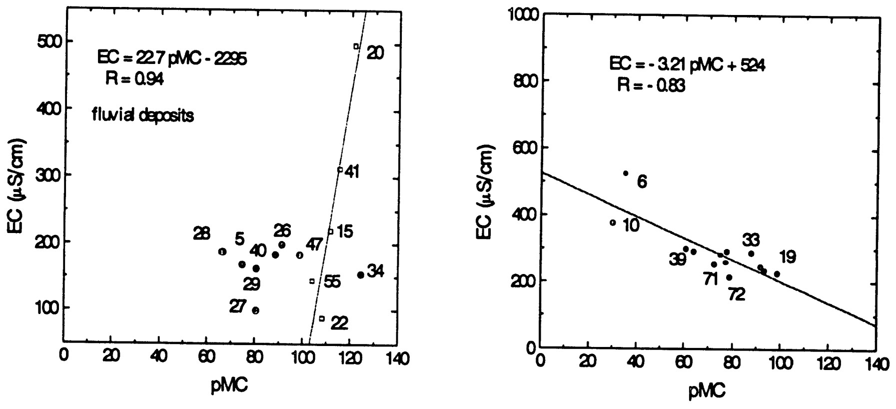
Wells that produce water from the Missão Velha aquifer (Table 4) are represented in Figures 2C and 3C. EC ranges from 330 μS cm^{-1} to 570 μS cm^{-1}, pMC from 93.2 (corresponding to an uncorrected age of 564 yr) to 28.1 (10,185 yr), and δ^{18}O from −3.0‰ to −5.1‰. The correlations obtained are

$$\text{EC} = -1.50\ \text{pMC} + 489\ (R = -0.87) \quad \text{and} \tag{3}$$

$$\delta^{18}\text{O (‰)} = 0.016\ \text{pMC} - 4.54\ (R = 0.94)\ . \tag{4}$$

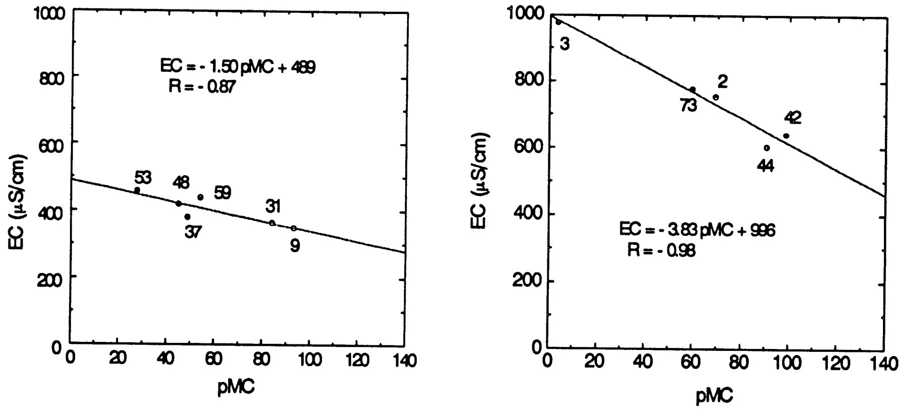
Again, we understand them as mixing of a young component, originating from recharge by rainfall, and an ascending paleo-component. It is noteworthy that P31, P37, P48 and P59 were flowing wells at the time of drilling; now levels are some meters below surface.

The measurement −5.1‰ for δ^{18}O of P50 is the lowest value for all the wells. It clearly indicates a strong contribution of paleo-waters dating back to a colder and more humid climate than at present in the northeast of Brazil. In previous research (Frichkorn *et al.* 1984; Frischkorn and Santiago 1992; Stute *et al.* 1995) on the deep aquifers in Piaui State we could prove that, at *ca.* 10,000 BP, temperature rose by roughly 5°C in the region, causing δ^{18}O to rise from *ca.* −6‰ to present day −3‰. Thus, the same paleoclimatic effect should be found in the Cariri. The fact that no values <−5.1‰ have



2A: Rio da Batateira (circle) and Rio da Batateira / fluvial deposits (square)

2B: Rio da Batateira / Missão Velha



2C: Missão Velha

2D: Mauriti

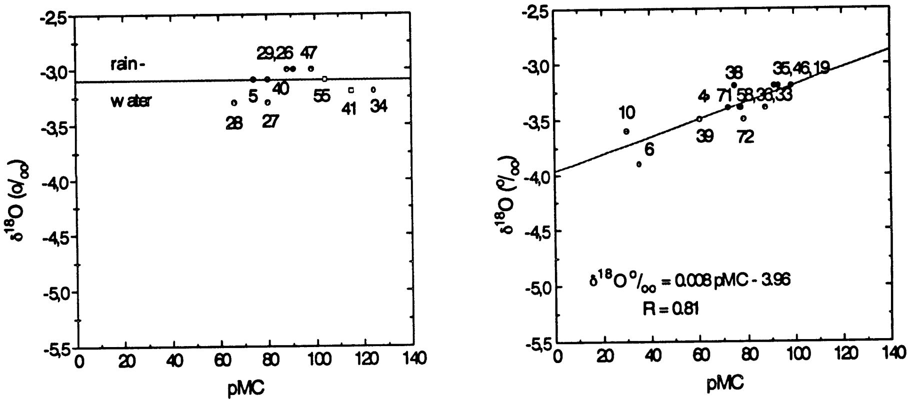
Fig. 2. Electrical conductivity as a function of pMC for wells in the Cariri Valley. The exploited aquifers are listed below each graph.

been found is an indication of mixing with components younger than *ca.* 10,000 yr (unfortunately, we do not have ^{14}C for P50 as it is installed with an air-lift pump). Waters from the Mauriti Formation (Table 5) exhibit EC rates from 600 to 980 $\mu S\ cm^{-1}$, pMC from 99.1 to 3.6 (corresponding to uncorrected ages from modern to 26,800 yr) and $\delta^{18}O$ from −2.8‰ to −3.8‰ with mixing lines:

$$EC = -3.83\ pMC + 996\ (R = -0.98) \quad \text{and} \tag{5}$$

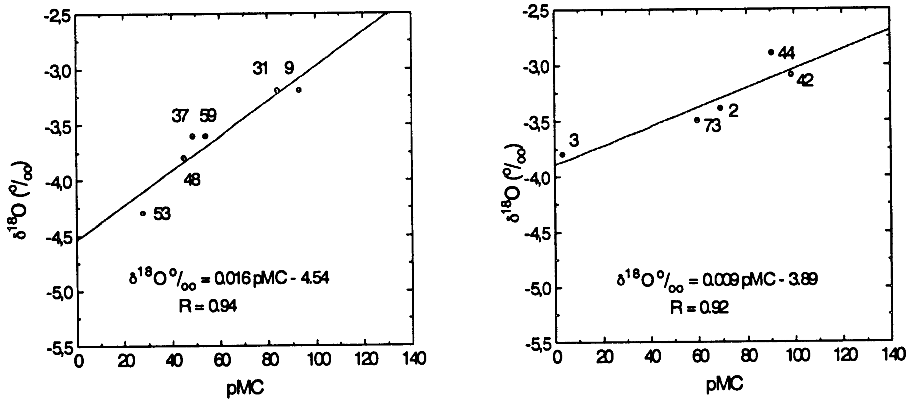
$$\delta^{18}O = 0.009\ pMC - 3.89\ (R = 0.92)\,. \tag{6}$$

P42, with EC = 639 $\mu S\ cm^{-1}$, pMC = 99.1 and $\delta^{18}O = -3.1‰$, can stand for the young contribution, originating from infiltration in the recharge area of the Mauriti aquifer. P3, with EC = 976 $\mu S\ cm^{-1}$, pMC = 3.6 and $\delta^{18}O = -3.8‰$, which exploits the Mauriti aquifer where confined by the aquitard Brejo Santo, may represent the aged component.



3A: Rio da Batateira (circle) and Rio da Batateira / fluvial deposits (square)

3B: Rio da Batateira / Missão Velha



3C: Missão Velha

3D: Mauriti

Fig. 3. $\delta^{18}O$ (‰) as a function of pMC for wells in the Cariri Valley. The exploited aquifers are listed below each graph.

Summing up our results, we conclude that the predominant presence of young waters in all aquifers of the Cariri Valley makes them suitable for sustainable exploitation. However, at the same time, our findings reflect a high vulnerability to contamination of these aquifers due to easy infiltration in the sedimentary basin. This is of special importance because of the intense large-scale agricultural activity, mostly from sugar cane plantations, in the basin.

On the other hand, the Cariri Basin constitutes a sedimentary lens engraved in the crystalline basement, with aquifers outcropping on its border and submerging, in the area of this study from north to south, confined by aquitards. Accordingly, one expects the existence of a regional flow pattern for deep groundwaters leading from the margin to the center of the basin. In fact, we detected the presence of a paleo-component of >10,000 yr, marked by a lower atmospheric temperature than at present (as may be seen from the $\delta^{18}O$ values of the paleowaters). This component may have a favorable influence on the exploitation of Cariri Valley aquifers as it can smooth down the influence of drought periods that affect the region.

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