

Full Length Research Paper

Hydrogeochemical characterization of the coastal Paleocene aquifer of Togo (West Africa)

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This paper presents a hydrogeochemical characterization of the Paleocene aquifer in the coastal basin of Togo. During the dry season (March, 2005), piezometric measurements were made on inventoried water wells. Fifty nine (59) water samples were taken for chemical analysis and the results subjected to statistical study. The quantitative variables considered for this purpose were temperature, pH, electrical conductivity, the major and some minor elements. The results showed that the water samples were weakly mineralized. The electrical conductivity did not exceed 1000 $\mu\text{S}/\text{cm}$, but it increased considerably in the sulphate rich samples. Hydrochemistry was dominated by calcium and bicarbonate except where important values of sulphate (967 mg/L) were obtained. The results of chemical analysis allowed the definition of four different hydrochemical facies. The calcic and magnesian bicarbonated facies was the most important. A sodic and potassic bicarbonated facies identified was mainly due to the residence time of water in the reservoir. Principal component analysis showed one pole of mineralization with strong correlations between sulphate, carbonate, magnesium and calcium.

Key words: Hydrochemistry, aquifer, chemical facies, residence time, Paleocene, Togo.

INTRODUCTION

The focus of this study is the aquifer system hosted by the Paleocene limestone formations. This aquifer is intensely exploited for diverse uses (domestic, industrial and agricultural). As a matter of fact, the coastal basin is the most populated part of Togo. One third of the nation's population is accommodated in this encompassing 3450 km² (Bourgeois, 1981), which is about 6% of the total area of the country. It is a region of important economic activities and the home of nascent industry. The concentration of population and industries in such a small area leads to major disequilibria between water supply and demand. Besides the Mono River, the other rivers in the basin are seasonal with extremely low flows. The aquifer is potentially threatened by anthropogenic pollution but it is not well known chemically. The purpose

of this study is to determine the hydrogeochemical characteristics of the Palaeocene aquifer. To fulfil the objectives of this study, chemical analyses were conducted on samples collected from piezometers. This characterization allows one to ensure the conservation and the durability of this resource.

STUDY AREA

The study area forms part of the vast Gulf of Benin basin which stretches from East to West along the Atlantic coast from Nigeria to Ghana. In Togo, it is bounded in the North by outcrops of the crystalline basement of Pan-African age, and in the South it opens up to the offshore basin under the Atlantic Ocean. It widens from West to East from the Ghana border to the Mono River which forms the frontier with the Republic of Benin.

Geomorphologically, the coastal basin appears as a collection of inclined plateaus separated by river valleys

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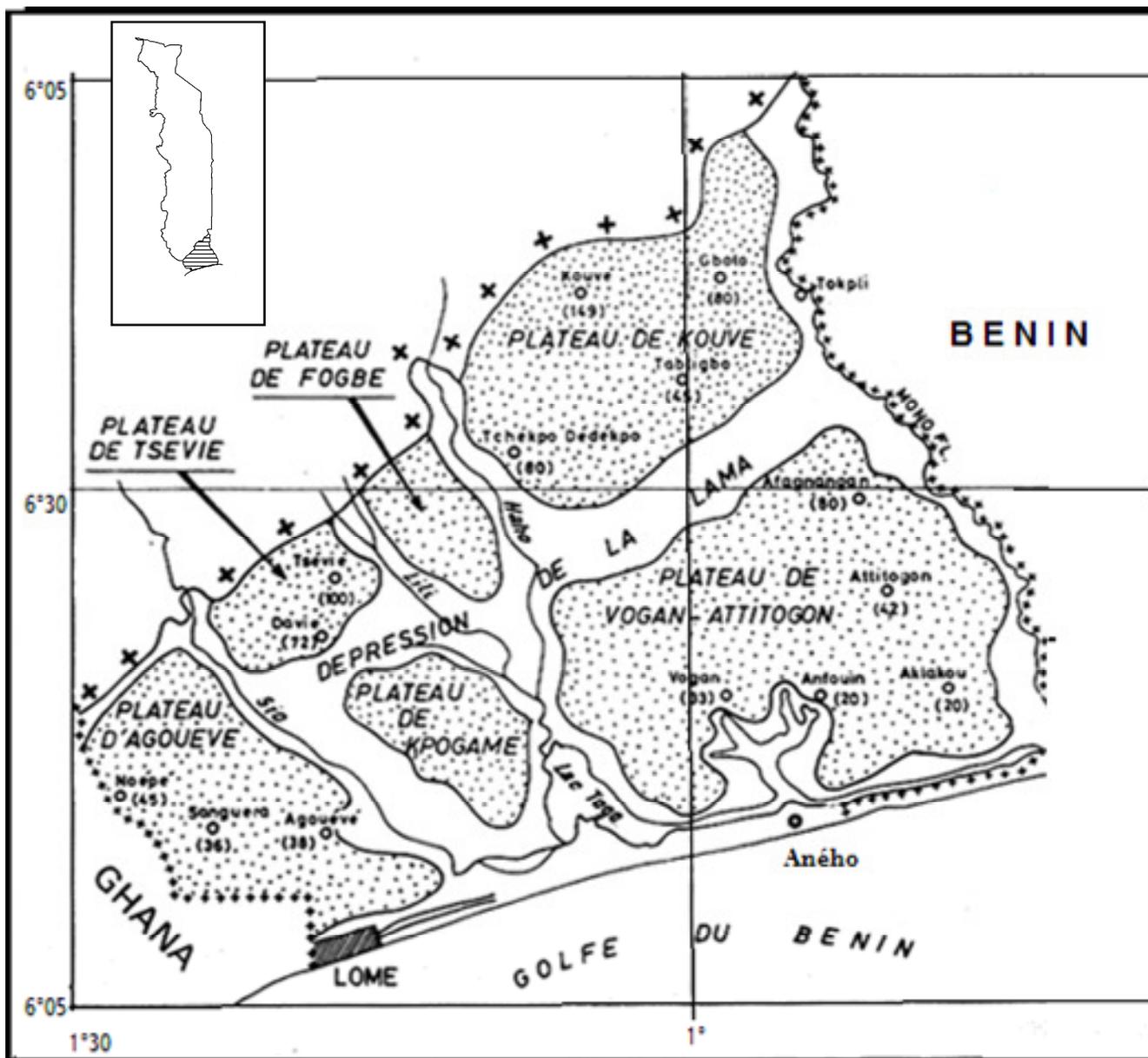


Figure 1. Study area location: hydrological and geomorphological settings (PNUD, 1982).

and located on both sides of a median depression oriented NNE-SSW, known as the “Lama depression”. A system of lagoons stretches along the coastal plain. It consists of small lagoons; the most important one is the Lake Togo (Figure 1).

The region, with a subequatorial climate, is characterized by two distinct rainy seasons related to the movement of the “intertropical front”. Rainfall in the basin is not uniformly distributed and decreases significantly from NE (1445 mm in Tabligbo) to SW (864 mm in Lomé). The average monthly temperature varies between

25 and 29°C in Lomé (Gnazou, 2008).

The geology of this part of Togo is known thanks to the numerous hydraulic and petroleum wells drilled in the area, during geophysical and mining surveys (Sylvain et al., 1986). The Post-Paleozoic sedimentary series thus constituted is known from the Maastrichtian to the Quaternary (Johnson, 1987; Da Costa, 2005) (Figure 2).

The Maastrichtian deposits are dominated by quartz-detrital clayey facies rich in organic matter. The sands found in the North of the basin, may or may not be clayey. In the South, the detrital character diminishes and

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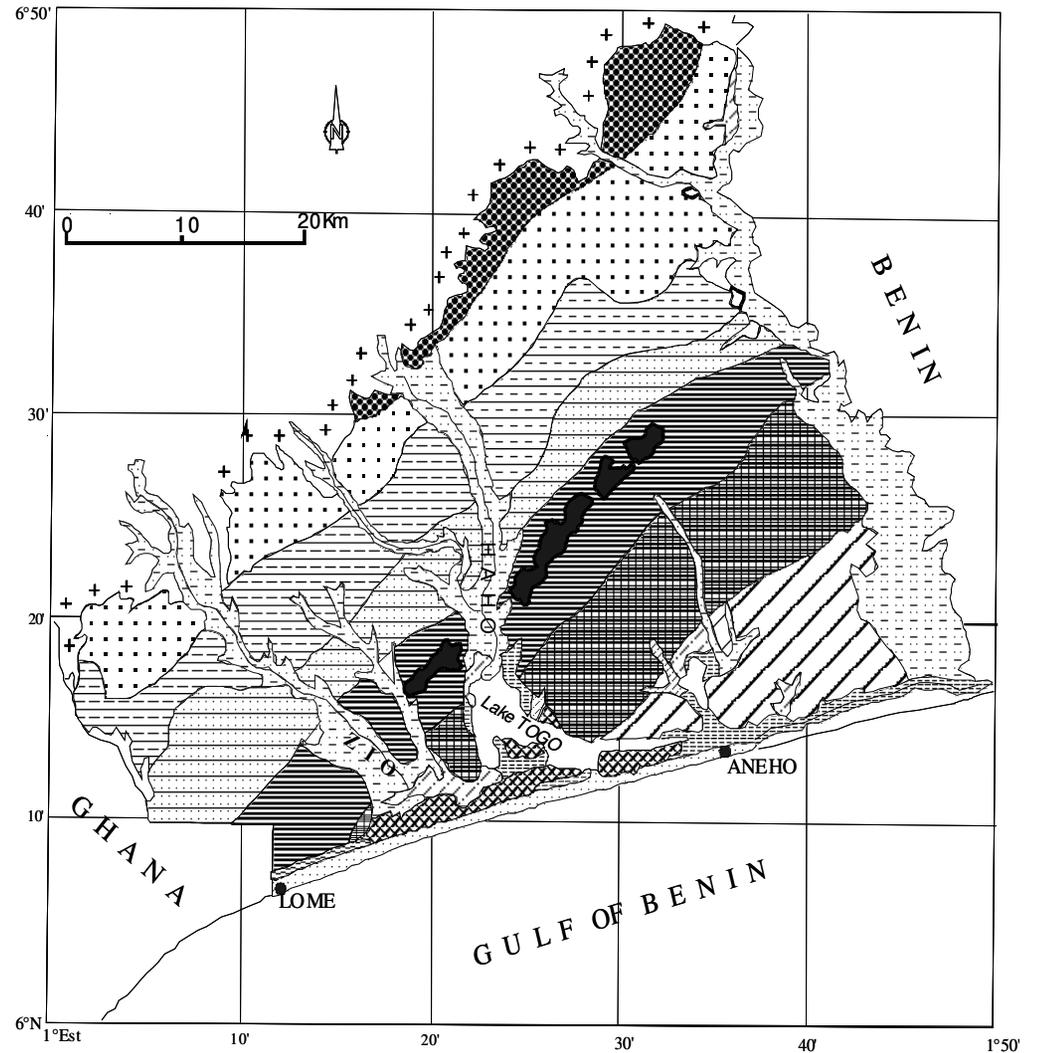
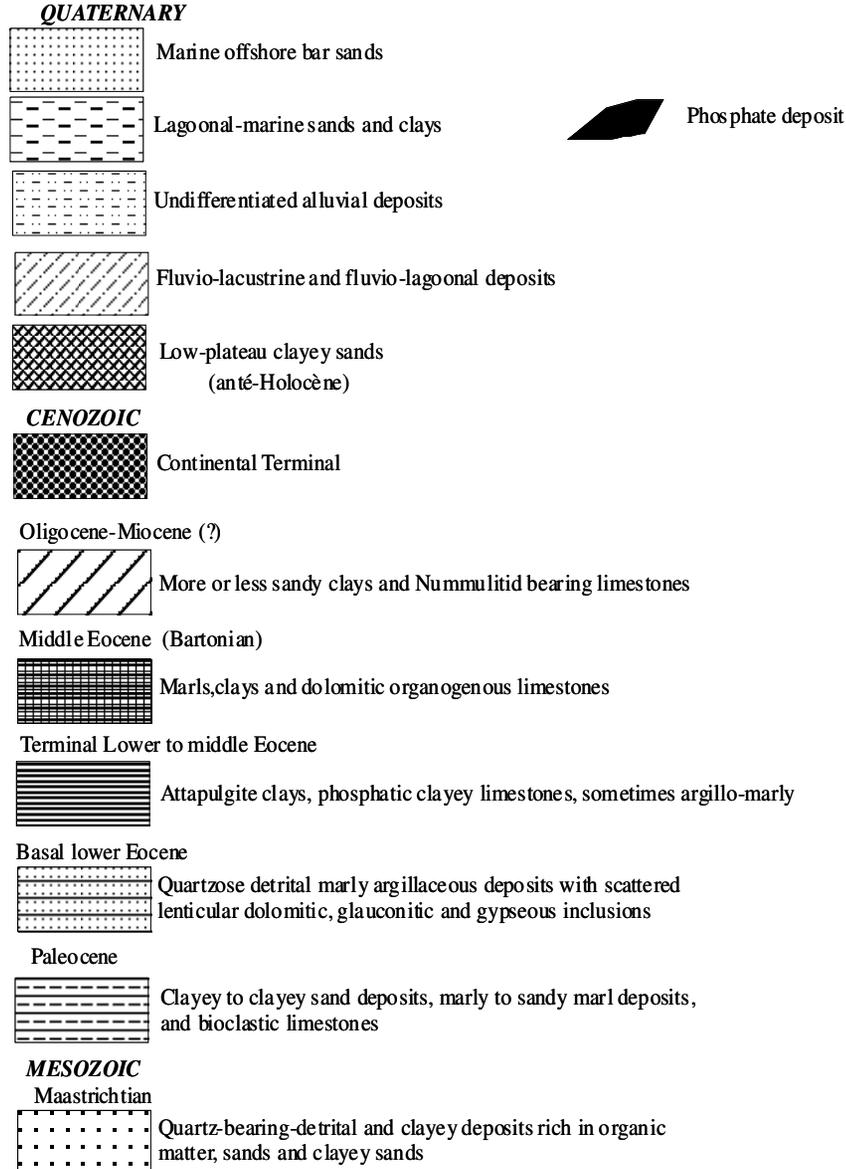


Figure 2. Geological map of the Togo coastal sedimentary basin (Sylvain et al., 1986).

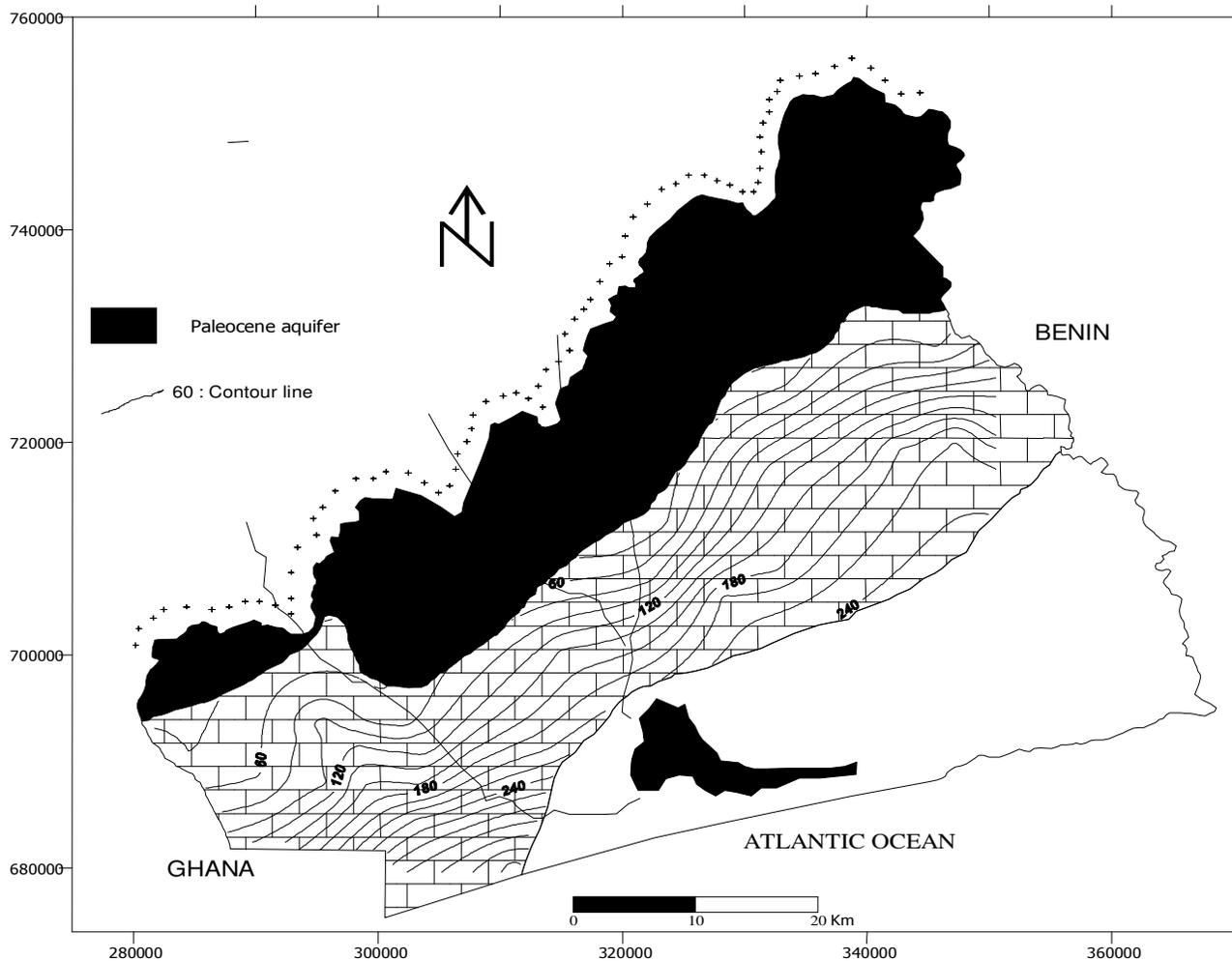


Figure 3. Extension of Paleocene aquifer and substratum geometry (Gnazou, 2008).

is progressively replaced by marls, clayey limestones and dolomites. Glauconite, gypsum and phosphate grains occur in small quantities. The thickness of the Maastrichtian formations increases from NW to SE (Johnson, 1987).

Paleocene sedimentation is characterized by a dominance of biochemical deposits. In the North, it is reduced to slightly organogenous clayey and clayey sand deposits. In the South, it may begin with marly and sandy marl facies. The *Togocyamus seefriedi* bearing limestone overlies this basal facies. A series of often laminated clayey marls rich in organic matter succeeds the limestones.

The Eocene consists of clayey-marl deposits with glauconite, gypsum and phosphates. The Oligocene formations include nummulitic limestone and sandy clay facies. The Continental terminal consists of sands and

clayey silts.

Finally the Quaternary formations are made of beach sands and fluvio-lacustrine deposits.

In the coastal basin formations, four aquiferous horizons are exploited. These productive levels are separated by thick aquicludes. The aquifers are the upper Cretaceous, Paleocene, Continental terminal and the Quaternary coastal sands.

The Paleocene aquifer is sandwiched between clayey and marly Eocene and Maastrichtian formations. From West to East, it forms a 10 to 20 km wide SW to NE trending band along the entire basin. Its northern boundary corresponds to the end of the limestones. In the south, this boundary, situated in Lomé on the Atlantic, rises gradually up to the Mono River in the NE (Figure 3). The top of the limestone is very heterogeneous and consists of Eocene clays and marl. Its depth in the SW

varies between 30 and more than 200 m. The reservoir, with a thickness between 5 and 35 m is made mainly of limestone. In some cases, sand may be found at the base of the limestone. Like the top, the substratum, made mainly of Maastrichtian clays, is inclined from North to South.

The Paleocene aquifer is recharged mainly in the North of the basin where it is in contact with the shallow aquifer of the Continental terminal (BCEOM/BRGM, 1983). Water flows in the Paleocene are from the North toward the South and are considered to be specific to the aquifer, because of the morphology of the substratum which plunges in the direction of the Atlantic Ocean (Gnazou, 2009).

METHODS

Fifty nine (59) groundwater samples were collected from the Palaeocene aquifer in March 2005 to investigate the chemical quality of the water. The data on the location of water wells that tap the Paleocene were collected from the data bank of the Hydraulics Department of Togo. In order to render each sample representative, we took a number of precautions. Thus a sufficient pumping time preceded sampling (Rodier et al., 2005). Water samples were pre-treated in the field before storage. All samples taken were passed through a 45 µm diameter filter. Filtration allowed the removal of contained particle and bacteria that could modify contents (Atteia, 2005). To the samples destined for cation analysis, we added the nitric to maintain the metals ions in solution (Rodier et al., 2005). The geographic locations of the sampling sites with a global positioning system (GPS) are shown in Figure 4.

Field parameters such as temperature, pH, turbidity and electrical conductivity were measured at each site using WTW (Wissenschaftliche Technische Werkstätten) type instruments. Water samples were stored in a refrigerator at a temperature of 4°C and analyzed within 72 h of sampling. The employed analytical methods, summarized in Table 1, were based mainly on the French association standards (AFNOR, 1986).

The data were analysed using appropriate computer programs and software: Xlstat (Fahmy, 2006), Excel, Golden Software Surfer. Piper and binary diagrams and statistical methods were utilized to characterize the Paleocene aquifer hydrogeochemically. Piper's diagram allowed a global visualization of the hydrochemical facies by identifying the chemical evolution of the different parameters used. The statistical study by principal component analysis allowed to determine the relations between the different parameters, while the binary diagrams allowed, by simple correlation between two elements, to investigate the processes responsible for the mineralization.

RESULTS AND DISCUSSION

Physicochemical characterization of Paleocene waters

The detailed results of the analysis are shown in Table 2. To facilitate interpretation the results are regrouped in statistical form in Table 3. Minimum, maximum, mean, and standard error values of the physical and chemical

parameters identified for the purpose of this study are summarized in Table 2. These results showed that the water temperature varied between 29.0 and 34.0°C. These values, higher than air temperature (27.4°C), reflect the high confining nature of this aquifer. This is explained by the deeper occurrence of the aquifer (50 to more than 200 m). The highest temperatures (>33°C) were recorded in the SW part of the basin where the aquifer depth exceeds 250 m.

The pH values varied between 6.6 and 8.5 with a mean near to the neutral value. The tendency toward alkalinity in some of the samples may be explained by the dissolution of carbonates composing the reservoir rock. Electrical conductivity values oscillated between 244 and 3213 µS/cm with a mean of about 1000 µS/cm. These values are representative of waters experiencing slight to excessive mineralization. Furthermore, the high value of the electrical conductivity standard error illustrates the important variations in the aquifer mineralization.

Areas with conductivities exceeding 1000 µS/cm are located mainly in the Eastern part of the basin and are associated with high sulphate content (Figure 5). Considering the hydrogeological context, the potential sources of salinity are the evaporitic deposits present in the surrounding geological formations (gypsum in the Eocene). This is possible because of the leakage observed in the basin aquifers (PNUD, 1975).

Nitrate concentrations were observed to be low throughout the sampled area; the maximum value was 20 mg/L.

These observations may be due to the confined and deep nature of the aquifer which limits the downward migration of surface nitrogen compounds to the aquifer. On the other hand, the confinement of the aquifer system favours anoxic conditions that enhance denitrification with a reduction in nitrate concentration. This is responsible for the relatively higher nitrite and ammonium ion contents observed in the deepest wells. From the point of view of toxicity, nitrite, like nitrate can cause a methemoglobinizing effect (Rodier et al., 2005).

Sulphate concentrations varied between 5.2 and 962 mg/L. In the western part of the basin, these concentrations varied between 130 and 225 mg/L. The highest concentrations (greater 250 mg/L) were observed in the Eastern part of the basin (Figure 6), the main source of sulphate being the dissolution of evaporites such as gypsum (CaSO₄, 2H₂O) contained in Eocene formations, or in the laminated Paleocene argillites that make up the top of the aquifer.

Chloride contents fluctuated between 20 and 450 mg/L (Figure 7). Since the investigated wells are located far from the ocean, this high chloride content in the Paleocene aquifer can be explained by paleosalinity (Akouvi, 2000).

Fluoride and cadmium analyses were indispensable to defining the impact of the Eocene phosphate deposit

Table 1. Analytical materials and methods.

| Parameters | Methods | AFNOR Norms | Method accuracy | Material |
|-------------------------------|-------------------------------------|-------------|-----------------|---|
| Turbidity | Nephelometry | NFT90-33 | ±0.01NTU | DRT100B, model 20012 turbidimeter |
| Temperature | Electrometry | NFT90-100 | ±0.1 °C | WTW Cond 330i Conductimeter |
| pH | Electrometry | NFT90-008 | ±0.01 | pH 330i pH-meter WTW |
| Electrical conductivity | Conductimetry | NFT90-031 | ±0.5% | WTW Cond 330i Conductimeter |
| Cl ⁻ | Argentimetry | NFT90-014 | ±0.5 mg/L | - |
| HCO ₃ ⁻ | Acidimetry | NFT90-036 | ±0.25 mg/L | - |
| SO ₄ ²⁻ | Nephelometry | NFT90-009 | 1 to 2% | GENESYS 10 Spectrophotometer |
| NO ₃ ⁻ | Molecular Spectrophotometry | NFT90-012 | 1 to 2% | GENESYS 10 Spectrophotometer |
| NO ₂ | Molecular Spectrophotometry | NFT90-013 | 1 to 2% | GENESYS 10 Spectrophotometer |
| NH ₄ ⁺ | Molecular Spectrophotometry | NFT90-015 | 1 to 2% | GENESYS 10 spectrophotometer |
| Ca ²⁺ | Complexometry EDTA | NFT90-016 | -±0.5 mg/L | - |
| Mg ²⁺ | Complexometry EDTA | NFT90-016 | ±0.24mg/L | - |
| Na ⁺ | Atomic absorption spectrophotometry | NFT90-020 | ± 0.04mg/L | Perkin-Elmer, model 2380 Spectrophotometer. |
| K ⁺ | Atomic absorption spectrophotometry | NFT90-020 | ±0.02 mg/L | Perkin-Elmer, model 2380 Spectrophotometer |
| SiO ₂ | Molecular Spectrophotometry | NFT90-007 | 1 to 2% | GENESYS 10 Spectrophotometer |
| F ⁻ | Potentiometry | NFT90-004 | ± 0.2mV | JENWAY Ion meter 3345 Potentiometer |
| Fe | Molecular Spectrophotometry | NFT90-017 | 1 to 2% | GENESYS 10 Spectrophotometer |
| Cd ²⁺ | Atomic absorption spectrophotometry | T90-112 | 0.02mg/L | Perkin-Elmer, model 2380 Spectrophotometer. |

(Ca₅(PO₄)₃F) on the underlying Paleocene waters. Phosphate ore is composed mainly of fluorapatite with fluoride and cadmium contents of 0.15% and 49 ppm respectively (Gnandi, 1998; Tchangbédji et al., 2003; Bawa et al., 2006). Fluoride and cadmium, if present in the Paleocene would constitute indicators of groundwater pollution by the overlying Eocene phosphate and exchange between aquifers (Continental terminal, Eocene and Paleocene). Fluoride concentrations in the groundwater varied from 0.1 to 0.7 mg/L. These concentrations are below the recommended World Health Organization drinkable water standard of 1.5 mg/L (WHO, 2006). This is an indication that phosphate has no impact on the Paleocene aquifer water quality. Furthermore cadmium concentrations were below the limit of detection (<0.02 mg/L).

Regarding the alkaline-earth elements, groundwater calcium content varied between 28 and 380 mg/L while that for magnesium was between 4.8 and 164 mg/L. One notes a similarity in the spatial distribution of these elements with high localized concentrations in the East of the basin (Figures 8 and 9).

The presence of those elements in high concentration increases water hardness. Using Langelier's empirical method, thirty two (32) samples were identified to exhibit a hard and five (5) a corrosive character. The remaining three samples reveal a character close to calco-carbonic equilibrium. For domestic consumers hard water means increased soap use for cleaning.

Silica concentrations in the water samples lay between 3.1 and 42.0 mg/L. These low concentrations are due to the carbonated nature of the aquifer and the very low solubility of silica in natural water (Banton and Bangoy, 1997). The silica present in the samples results from the dissolution of the clays (silicates) that form the top and the bottom of the aquifer, or that are contained in the carbonated matrix. One other possible source of silica in the Paleocene waters is its recharge by the sandy of the Continental terminal.

Iron contents varied between 0.0 and 4.4 mg/L, the iron presence is often associated with high water turbidity. High concentrations were often obtained in abandoned wells. This situation favours casing corrosion.

Groundwater chemical facies

Groundwater chemical facies were determined from the Piper diagram using the computer software "Diagrammes" (Simler, 2005). The advantage of using this diagram is that it allows many analyses to be represented on a single graph and facilitates their grouping by family. From these analyses the following observations emerged. The ternary diagrams of anions and cations indicated that the majority of samples were oriented towards the bicarbonate and calcic poles respectively. Projection of these points in the lozenge allowed the identification of the following pattern (Figure 10):

Table 2. Physico-chemical parameters of the Paleocene groundwaters.

| Localities | N°IRH | Coordinates | | | Physico-chemical parameters | | | | | | | | | | | | | | | | |
|-------------|-------|-------------|--------|------|-----------------------------|------------|------|-------------------------|-----------|--------------------------------------|-------------------------|----------|------------------------|------------------------|-------------------------------------|-------------------------|------------------------|-----------------------|-------------------------|-----------------|-------------------------|
| | | X (m) | Y (m) | T °C | EC (µs/cm) | Turb (NTU) | pH | HCO ₃ (mg/L) | Cl (mg/L) | SO ₄ ²⁻ (mg/L) | Ca ²⁺ (mg/L) | F (mg/L) | NO ₃ (mg/L) | NO ₂ (mg/L) | NH ₄ ⁺ (mg/L) | Mg ²⁺ (mg/L) | Na ⁺ (mg/L) | K ⁺ (mg/L) | Cd ²⁺ (mg/L) | Fe total (mg/L) | SiO ₂ (mg/L) |
| Atiémé II | 14513 | 293975 | 691673 | 29.5 | 437.7 | 0.65 | 7.59 | 244 | 32.04 | 18.88 | 66 | 0.14 | 0.25 | 0.00 | 0.09 | 17 | 19.00 | 3.60 | < 0.02 | 1.81 | 17.05 |
| Madjikpéto | 14511 | 293915 | 692120 | 31 | 459.8 | 0.84 | 7.73 | 244 | 40.04 | 14.49 | 84 | 0.17 | 0.22 | 0.00 | 0.10 | 4.8 | 23.08 | 4.03 | < 0.02 | 1.11 | 16.36 |
| Apessito | 14753 | 294015 | 695220 | 30 | 526.3 | 2.59 | 7.78 | 207.4 | 45.05 | 18.63 | 61 | 0.3 | 1.70 | 0.00 | 0.21 | 4.8 | 22.68 | 3.39 | < 0.02 | 2.45 | 13.20 |
| Yohonou | 15059 | 296374 | 693224 | 30.5 | 498.6 | 0.02 | 7.95 | 305 | 35.04 | 12.29 | 86 | 0.27 | 0.88 | 0.22 | 0.02 | 12 | 17.80 | 4.74 | < 0.02 | 0.84 | 13.52 |
| Sogbos EPP | 14506 | 298033 | 692758 | 30 | 1351.8 | 0.3 | 7.82 | 378.2 | 110.12 | 14.88 | 91 | 0.34 | 3.89 | 0.01 | 0.35 | 38.4 | 73.90 | 10.61 | < 0.02 | 0.95 | 19.45 |
| Sogboss | 14767 | 298109 | 691311 | 33 | 714.7 | 0.08 | 7.77 | 329.4 | 80.09 | 38.39 | 72 | 0.31 | 3.53 | 0.09 | 0.31 | 55.2 | 38.94 | 6.15 | < 0.02 | 0.74 | 14.78 |
| Nyamassi | 14524 | 298355 | 691865 | 34 | 687.0 | 0.1 | 7.94 | 323.3 | 85.09 | 18.15 | 56 | 0.31 | 2.83 | 0.19 | 0.03 | 33.6 | 47.10 | 9.27 | < 0.02 | 0.83 | 13.77 |
| GuénouKopé | 14514 | 304121 | 693136 | 32 | 797.8 | 0.11 | 7.93 | 381.25 | 82.09 | 10.59 | 48 | 0.28 | 1.76 | 0.00 | 0.04 | 38.4 | 54.38 | 5.09 | < 0.02 | 0.92 | 21.98 |
| Fidokpoe | 14516 | 303870 | 691601 | 32.5 | 675.9 | 0.32 | 7.73 | 353.8 | 62.07 | 18.15 | 40 | 0.31 | 3.45 | 0.06 | 0.23 | 33.6 | 37.72 | 5.86 | < 0.02 | 1.52 | 13.45 |
| Zongo | 14519 | 302287 | 692560 | 31 | 692.5 | 0.4 | 7.86 | 359.9 | 65.07 | 15.71 | 64 | 0.31 | 2.31 | 0.04 | 0.56 | 28.8 | 39.34 | 6.74 | < 0.02 | 1.49 | 13.01 |
| Apedokoe | 14504 | 293030 | 687158 | 32 | 1263.1 | 0.41 | 7.73 | 402.6 | 175.19 | 15.95 | 104 | 0.29 | 2.59 | 0.18 | 0.43 | 57.6 | 79.18 | 6.56 | < 0.02 | 0.41 | 23.11 |
| Logopé | 14772 | 298922 | 688493 | 32 | 886.4 | 0.8 | 7.74 | 305 | 107.12 | 23.76 | 84 | 0.15 | 2.87 | 1.91 | 0.11 | 36 | 55.16 | 13.33 | < 0.02 | 0.22 | 15.93 |
| Vakpo | 14771 | 296968 | 687168 | 32 | 864.2 | 0.6 | 7.77 | 366 | 88.10 | 29.37 | 72 | 0.21 | 1.16 | 0.03 | 0.30 | 28.8 | 39.96 | 7.56 | < 0.02 | 0.70 | 19.97 |
| Akoin | 14773 | 300840 | 693818 | 32 | 642.6 | 4.15 | 7.68 | 366 | 55.06 | 13.00 | 124 | 0.32 | 4.63 | 1.53 | 0.02 | 9.6 | 34.43 | 10.42 | < 0.02 | 0.90 | 14.92 |
| Akepe | 14219 | 284120 | 690923 | 31 | 626.0 | 0.5 | 7.91 | 366 | 58.06 | 14.24 | 72 | 0.29 | 1.44 | 0.41 | 0.06 | 14.4 | 26.13 | 7.84 | < 0.02 | 0.26 | 17.95 |
| Alinka | 14525 | 299853 | 694805 | 30 | 542.9 | 0.2 | 8.06 | 298.9 | 60.07 | 13.27 | 72 | 0.30 | 1.95 | 0.45 | 0.05 | 9.6 | 23.14 | 8.72 | < 0.02 | 0.18 | 16.69 |
| Alinka | 13934 | 297975 | 693986 | 34 | 831.0 | 8.89 | 7.67 | 340 | 63.00 | 20.83 | 76 | 0.24 | 1.32 | 0.17 | 0.01 | 13 | 28.00 | 4.32 | < 0.02 | 0.21 | 19.00 |
| Rama | 14671 | 305480 | 696472 | 33 | 609.4 | 0.5 | 7.72 | 366 | 39.04 | 29.12 | 88 | 0.19 | 3.22 | 0.01 | 0.12 | 21.6 | 24.29 | 3.55 | < 0.02 | 0.48 | 21.49 |
| Kladjémé | 14862 | 313057 | 697571 | 34 | 675.9 | 0.53 | 7.77 | 390.4 | 42.05 | 23.27 | 80 | 0.16 | 1.32 | 0.00 | 0.10 | 12 | 31.66 | 3.06 | < 0.02 | 0.00 | 15.18 |
| Adodo | 15050 | 306635 | 700439 | 33 | 637.1 | 0.5 | 7.06 | 240.2 | 20.02 | 11.80 | 76 | 0.14 | 0.22 | 0.00 | 0.02 | 9.4 | 12.31 | 1.57 | < 0.02 | 0.24 | 25.03 |
| Tonoukouti | 14756 | 305331 | 695811 | 35 | 880.9 | 0.35 | 7.79 | 335.5 | 45.05 | 20.59 | 80 | 0.15 | 0.89 | 0.00 | 0.01 | 19.2 | 26.33 | 3.56 | < 0.02 | 0.00 | 13.91 |
| Sewouvi | 14669 | 307901 | 695445 | 31 | 903.0 | 0.5 | 7.7 | 402.6 | 80.09 | 24.98 | 96 | 0.26 | 0.85 | 0.00 | 0.01 | 31.2 | 44.63 | 5.68 | < 0.02 | 2.46 | 21.49 |
| Kpotavé | 14363 | 303491 | 697951 | 34 | 321.3 | 7.5 | 7.03 | 146.4 | 22.02 | 12.05 | 60 | 0.33 | 1.00 | 0.00 | 0.04 | 24 | 12.77 | 2.23 | < 0.02 | 1.18 | 21.74 |
| Adidome | 14766 | 284950 | 690100 | 30 | 243.8 | 0.56 | 6.64 | 134.2 | 20.02 | 7.17 | 56 | 0.22 | 2.41 | 0.00 | 0.04 | 9.6 | 11.70 | 1.21 | < 0.02 | 0.19 | 27.55 |
| ESTAO | Etao | 300859 | 681972 | 34 | 819.9 | 0.54 | 7.92 | 305 | 100.51 | 25.46 | 56 | 0.35 | 4.11 | 0.61 | 0.02 | 28.8 | 63.73 | 12.32 | < 0.02 | 0.00 | 19.22 |
| Hopital | Hop | 301672 | 679611 | 35 | 919.6 | 0.62 | 7.93 | 305 | 125.14 | 21.56 | 52 | 0.21 | 6.51 | 0.61 | 0.14 | 16.8 | 81.62 | 15.08 | < 0.02 | 0.13 | 31.09 |
| SALT | Salt | 306197 | 682875 | 34.5 | 952.9 | 0.53 | 7.98 | 334 | 140.35 | 9.85 | 48 | 0.41 | 8.45 | 0.00 | 1.70 | 26.4 | 89.73 | 22.12 | < 0.02 | 0.06 | 14.92 |
| Présidence | PR | 302676 | 683054 | 33.5 | 842.1 | 0.4 | 8.47 | 346.48 | 109.12 | 11.56 | 29 | 0.16 | 4.53 | 0.00 | 1.50 | 33 | 85.00 | 13.79 | < 0.02 | 0.09 | 23.26 |
| Libye | Lib | 303258 | 684689 | 34 | 842.1 | 0.68 | 8.06 | 329.4 | 116.13 | 16.20 | 88 | 0.64 | 4.78 | 0.00 | 1.20 | 43.2 | 71.05 | 14.84 | < 0.02 | 0.03 | 19.72 |
| Klobatémé | 14762 | 307407 | 690376 | 32 | 736.8 | 0.32 | 7.97 | 329.4 | 75.08 | 35.71 | 48 | 0.60 | 4.75 | 0.57 | 0.35 | 19.2 | 48.94 | 17.67 | < 0.02 | 0.29 | 18.96 |
| Lowé | 13778 | 309742 | 694747 | 31 | 847.6 | 0.61 | 7.88 | 377.4 | 80.39 | 46.93 | 81 | 0.09 | 1.30 | 0.03 | 0.10 | 29 | 48.00 | 6.62 | < 0.02 | 0.66 | 30.08 |
| Abao | 14761 | 313382 | 694538 | 31 | 775.6 | 0.46 | 8.04 | 366 | 79.09 | 37.17 | 100 | 0.26 | 1.62 | 0.04 | 0.11 | 4.8 | 45.03 | 8.21 | < 0.02 | 0.39 | 25.78 |
| AkodesseEPP | 14538 | 322655 | 701048 | 32 | 964.0 | 0.07 | 7.67 | 362 | 105.12 | 36.44 | 104 | 0.4 | 3.48 | 0.31 | 0.02 | 16.8 | 71.00 | 17.00 | < 0.02 | 0.10 | 19.89 |
| Zéglé | 14549 | 312642 | 695016 | 30 | 819.9 | 0.47 | 7.79 | 411 | 76.08 | 30.59 | 68 | 0.26 | 1.27 | 0.00 | 0.11 | 38.4 | 50.71 | 11.00 | < 0.02 | 0.09 | 16.10 |
| Akadjamé | 13332 | 315678 | 699745 | 38 | 714.7 | 1.97 | 8.21 | 274.5 | 88.10 | 5.71 | 72 | 0.19 | 2.97 | 0.00 | 0.38 | 7.2 | 54.70 | 11.08 | < 0.02 | 1.89 | 16.67 |

Table 2. Cont.

| | | | | | | | | | | | | | | | | | | | | | |
|-------------|-------|--------|--------|------|--------|-------|------|--------|--------|--------|-------|------|-------|------|------|--------|--------|-------|--------|------|-------|
| Agbleta | 14553 | 322445 | 700135 | 32 | 797.8 | 0.33 | 8.03 | 311 | 76.58 | 77.00 | 64 | 0.17 | 3.86 | 0.11 | 0.04 | 33.6 | 66.04 | 15.00 | < 0.02 | 0.07 | 21.09 |
| Akodéssewa | 14536 | 322445 | 700951 | 35 | 858.7 | 0.12 | 7.89 | 358 | 109.62 | 36.20 | 104 | 0.54 | 3.16 | 0.06 | 0.94 | 7.2 | 54.30 | 17.00 | < 0.02 | 0.03 | 13.39 |
| Vodze | 14570 | 322446 | 707146 | 29 | 775.6 | 0.23 | 7.67 | 417 | 33.54 | 24.00 | 92 | 0.21 | 1.29 | 0.06 | 0.07 | 24 | 45.00 | 11.00 | < 0.02 | 0.40 | 13.20 |
| Kpakpladzev | 14554 | 332329 | 708523 | 32 | 759.0 | 0.4 | 7.58 | 658.8 | 34.04 | 26.20 | 120 | 0.09 | 0.78 | 0.11 | 0.06 | 40 | 30.00 | 7.60 | < 0.02 | 0.60 | 13.01 |
| Tokamè | 14550 | 331685 | 709414 | 31 | 709.1 | 0.27 | 7.55 | 414.8 | 36.04 | 17.66 | 96 | 0.11 | 0.50 | 0.06 | 0.02 | 9.6 | 19.00 | 4.60 | < 0.02 | 0.46 | 13.96 |
| Kpotémé | 14602 | 343240 | 722318 | 31 | 897.5 | 0.34 | 7.74 | 451.4 | 58.06 | 41.32 | 96 | 0.16 | 1.52 | 0.00 | 0.01 | 28.8 | 77.00 | 10.54 | < 0.02 | 1.00 | 15.92 |
| Dévémé | 14594 | 346991 | 716201 | 30.5 | 609.4 | 3.09 | 7.16 | 183 | 73.08 | 34.73 | 84 | 0.37 | 2.45 | 0.02 | | 9.6 | 45.00 | 6.22 | < 0.02 | 0.19 | 15.67 |
| Gbodjomé | 14649 | 350571 | 721287 | 31.3 | 886.4 | 0.05 | 7.57 | 402.6 | 46.05 | 68.88 | 76 | 0.27 | 1.72 | 0.02 | 0.36 | 60 | 28.00 | 11.00 | < 0.02 | 0.43 | 10.24 |
| Akladjénou | 14633 | 346927 | 730171 | 30.7 | 797.8 | 0.08 | 7.51 | 500.2 | 40.04 | 37.90 | 80 | 0.24 | 0.33 | 0.00 | 0.03 | 7.2 | 46.00 | 6.35 | < 0.02 | 0.83 | 8.85 |
| Ahlemeyi | 14624 | 343657 | 729741 | 31.0 | 952.9 | 0.18 | 7.56 | 475.8 | 58.06 | 24.98 | 116 | 0.23 | 5.39 | 0.00 | 0.01 | 52.8 | 57.00 | 7.84 | < 0.02 | 0.00 | 14.91 |
| Sonou Djog | 14853 | 343038 | 728033 | 30.2 | 865.0 | 0.4 | 7.28 | 414.8 | 56.00 | 42.00 | 92 | 0.31 | 6.20 | 0.50 | 0.00 | 43.2 | 58.00 | 9.00 | < 0.02 | 0.39 | 3.10 |
| CCI | Cci | 343036 | 727833 | 33.7 | 839.0 | 0.5 | 7.17 | 317 | 94.00 | 9.00 | 28 | 0.19 | 3.70 | 0.00 | 0.00 | 31 | 95.00 | 16.00 | < 0.02 | 0.40 | 18.05 |
| Klikamé | 13126 | 290471 | 691184 | 31.0 | 421.0 | 65.6 | 6.79 | 207.4 | 47.06 | 25.82 | 57.22 | 0.16 | 3.10 | 0.00 | 0.00 | 6.27 | 19.63 | 3.37 | < 0.02 | 2.29 | 14.24 |
| Anonkui | 14528 | 298282 | 690105 | 32.1 | 1309.0 | 1.9 | 7.2 | 390.4 | 153.54 | 197.23 | 131.9 | 0.45 | 0.80 | 0.00 | 0.00 | 58.59 | 87.86 | 9.59 | < 0.02 | 4.38 | 22.16 |
| Sokomé | 13927 | 331986 | 703202 | 31.4 | 3213.2 | 0.45 | 7.02 | 530.2 | 450.50 | 737.56 | 380 | 0.13 | 0.82 | 1.48 | 0.17 | 144 | 77.00 | 10.54 | < 0.02 | 0.44 | 13.45 |
| Dagbati | 13170 | 333776 | 716621 | 30.8 | 2105.2 | 0.29 | 7.89 | 658.8 | 226.25 | 777.56 | 212 | 0.32 | 0.22 | 0.10 | 0.03 | 132 | 282.00 | 38.24 | < 0.02 | 0.00 | 18.57 |
| Logové | 14868 | 343624 | 711112 | 31.4 | 1529.0 | 0.3 | 7.35 | 878.4 | 137.65 | 293.66 | 144 | 0.23 | 0.98 | 0.42 | 0.00 | 67.2 | 281.00 | 35.60 | < 0.02 | 0.00 | 31.51 |
| Hélépémé | 14568 | 340183 | 721026 | 30.5 | 2603.8 | 0.83 | 7.51 | 445.3 | 321.35 | 722.93 | 268 | 0.21 | 0.22 | 0.05 | 0.02 | 156 | 126.00 | 13.00 | < 0.02 | 3.18 | 16.68 |
| Nyékonakpoe | 14567 | 339468 | 721521 | 30.6 | 1551.2 | 0.76 | 7.66 | 610 | 283.31 | 16.20 | 176 | 0.50 | 0.22 | 0.02 | 0.01 | 52.8 | 59.00 | 8.11 | < 0.02 | 1.67 | 16.19 |
| Ouatchidomé | 14560 | 338700 | 720211 | 31.1 | 2991.6 | 0.43 | 7.6 | 488 | 257.28 | 961.95 | 316 | 0.14 | 0.22 | 0.00 | 0.05 | 164.64 | 289.00 | 39.19 | < 0.02 | 0.51 | 15.54 |
| DjokotoF1 | 14571 | 337811 | 715148 | 31.7 | 2204.9 | 0.14 | 7.71 | 447.74 | 187.21 | 476.59 | 216 | 0.36 | 16.28 | 0.00 | 0.01 | 115.2 | 182.00 | 24.73 | < 0.02 | 3.14 | 18.95 |
| KpessouM493 | 13932 | 342769 | 721621 | 30.1 | 1795.0 | 0.22 | 8.35 | 463.6 | 189.21 | 211.97 | 162 | 0.57 | 7.58 | 0.47 | 0.02 | 83 | 81.89 | 7.01 | < 0.02 | 1.30 | 26.65 |
| Mome Hagou | 14610 | 345826 | 728846 | 31.5 | 2170.0 | 0.027 | 7.9 | 833 | 203.00 | 87.00 | 219 | 0.30 | 19.80 | 0.00 | 0.01 | 79.5 | 101.00 | 8.00 | < 0.02 | 0.19 | 42.00 |
| Klo-Gagnon | 14592 | 342712 | 711178 | 30.4 | 1561.0 | 0.8 | 7.85 | 746 | 149.00 | 61.00 | 197 | 0.30 | 20.00 | 0.00 | 0.11 | 59 | 73.00 | 8.00 | < 0.02 | 0.51 | 36.00 |

Table 3. Minimum, maximum, mean, and standard error values of the physico-chemical parameters measured.

| Parameters | T °C | pH | EC (µS/cm) | Turbidity NTU | HCO ₃ mg/L | SO ₄ ²⁻ mg/L | Cl ⁻ mg/L | NO ₃ mg/L | F ⁻ mg/L |
|----------------|----------------------|-----------------------|-----------------------|----------------------|-----------------------|------------------------------------|----------------------|-----------------------|-----------------------------------|
| Minimum | 29.0 | 6.6 | 243.8 | 0.03 | 134.2 | 5.7 | 20 | 0.20 | 0.1 |
| Maximum | 34.0 | 8.5 | 3213.2 | 65.6 | 878.4 | 962 | 450.5 | 20.0 | 0.7 |
| Mean | 31.4 | 7.7 | 1003.5 | 2 | 388.6 | 97.1 | 100.51 | 3.2 | 0.3 |
| Standard error | 1.3 | 0.4 | 610.4 | 8.5 | 143.6 | 205.4 | 79.6 | 4.1 | 0.2 |
| Parameters | NO ₂ mg/L | Ca ²⁺ mg/L | Mg ²⁺ mg/L | Na ⁺ mg/L | K ⁺ mg/L | SiO ₂ mg/L | Fe mg/L | Cd ²⁺ mg/L | NH ₄ ⁺ mg/L |
| Minimum | 0.0 | 28.0 | 4.8 | 11.7 | 1.2 | 3.1 | 0.0 | <0.02 | 0.0 |
| Maximum | 1.9 | 380.0 | 164.6 | 289.0 | 39.2 | 42.0 | 4.4 | <0.02 | 1.7 |
| Moyenne | 0.2 | 103.1 | 38.8 | 64.6 | 10.5 | 18.6 | 0.8 | <0.02 | 0.2 |
| Standard error | 0.4 | 67.0 | 37.1 | 59.0 | 8 | 6.5 | 0.9 | <0.02 | 0.4 |

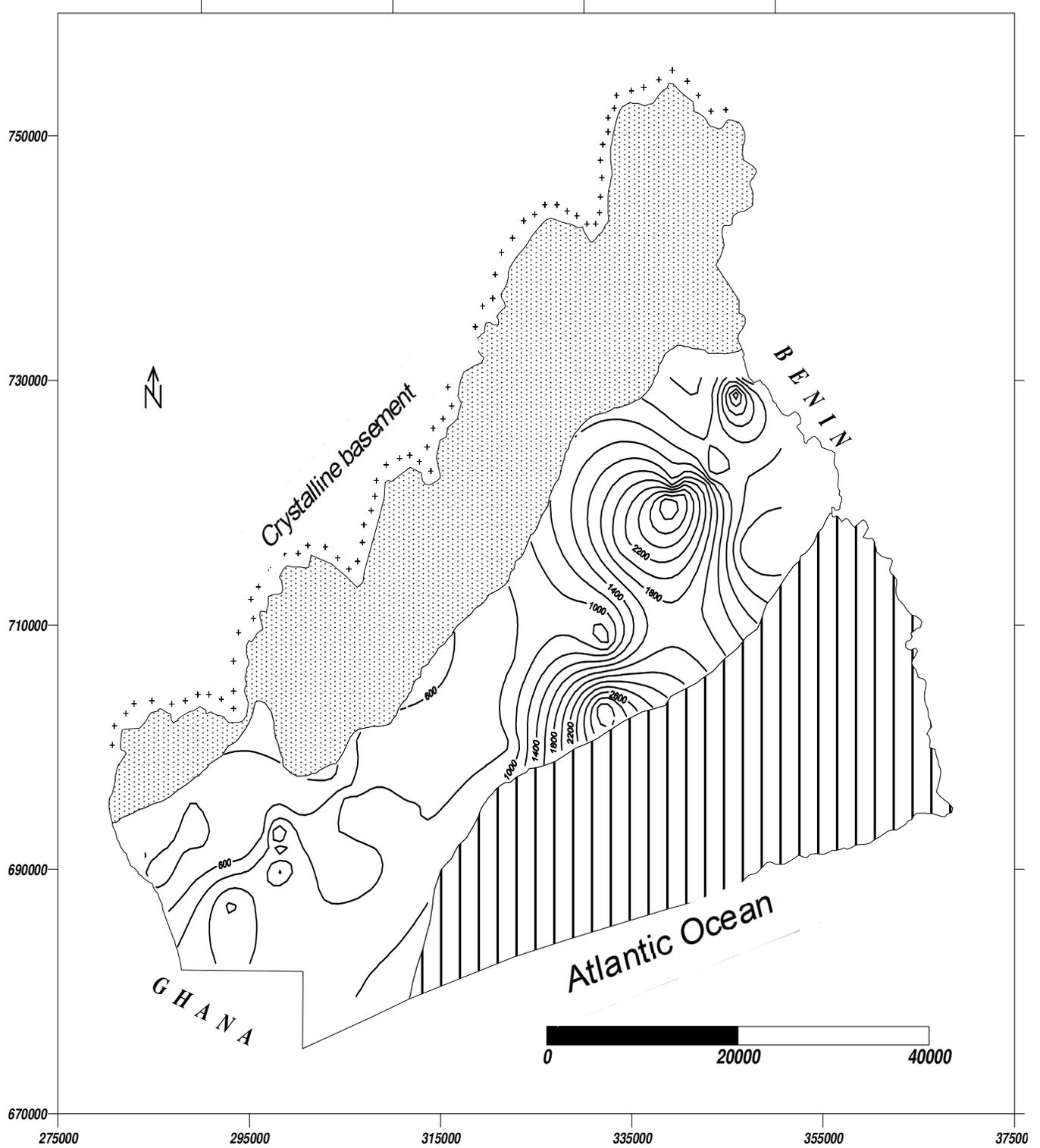


Figure 5. Spatial distribution of conductivity.

(i) The calcic and magnesian bicarbonated facies that evolved toward the sodic and potassic bicarbonated

facies in the South-West.

(ii) The calcic and magnesian sulphated facies. This

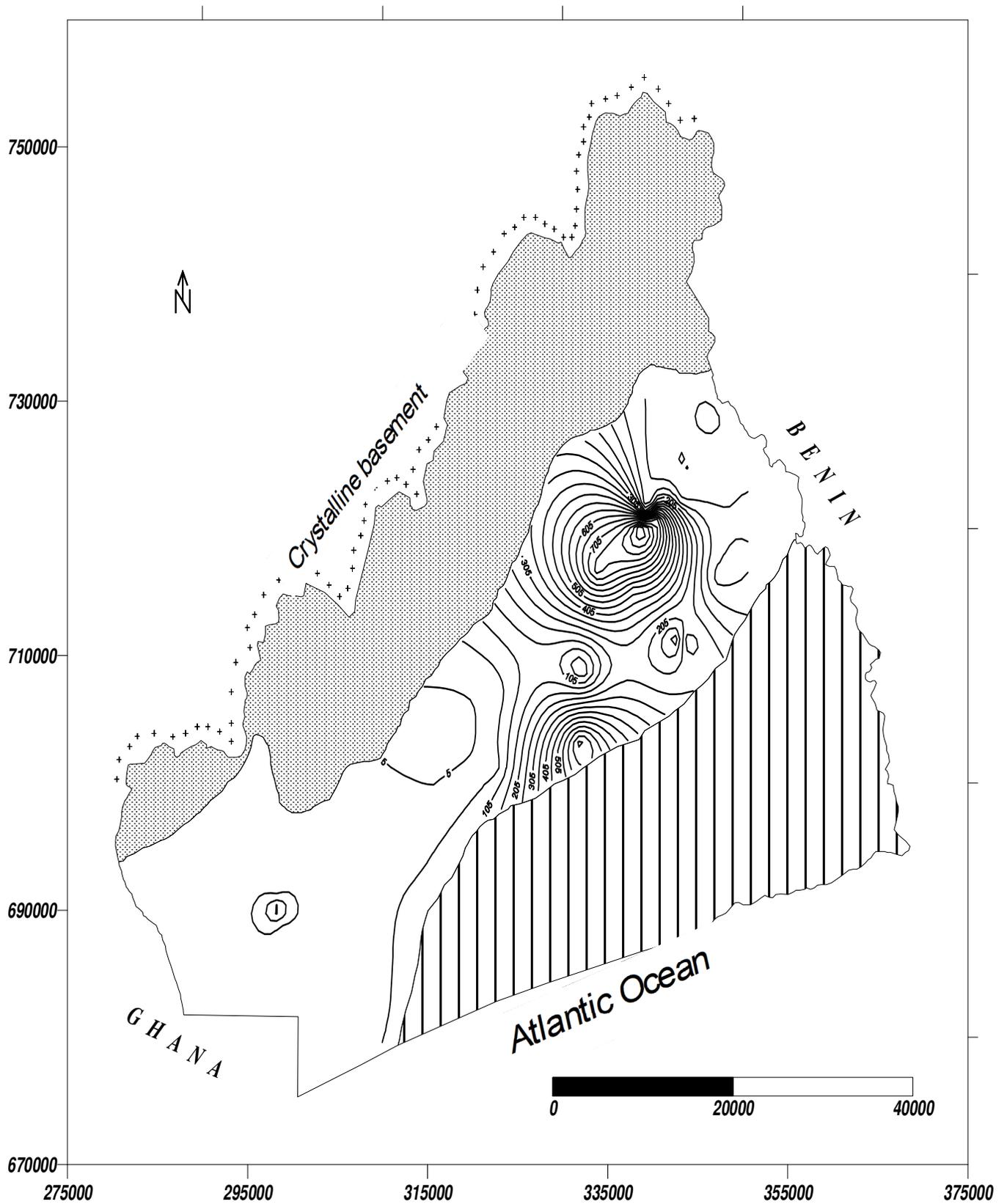


Figure 6. Spatial distribution of sulphate.

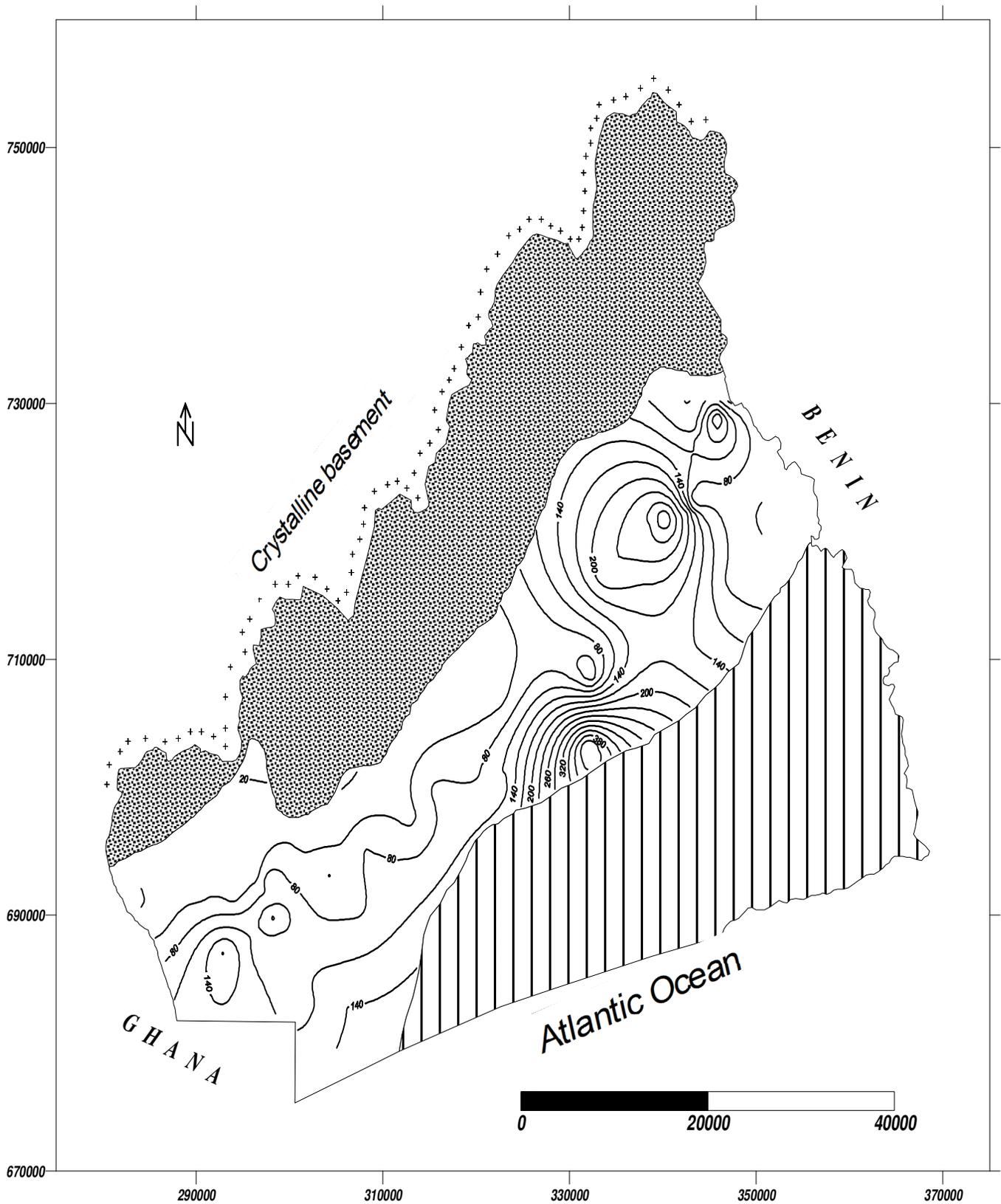


Figure 7. Spatial distribution of chloride.

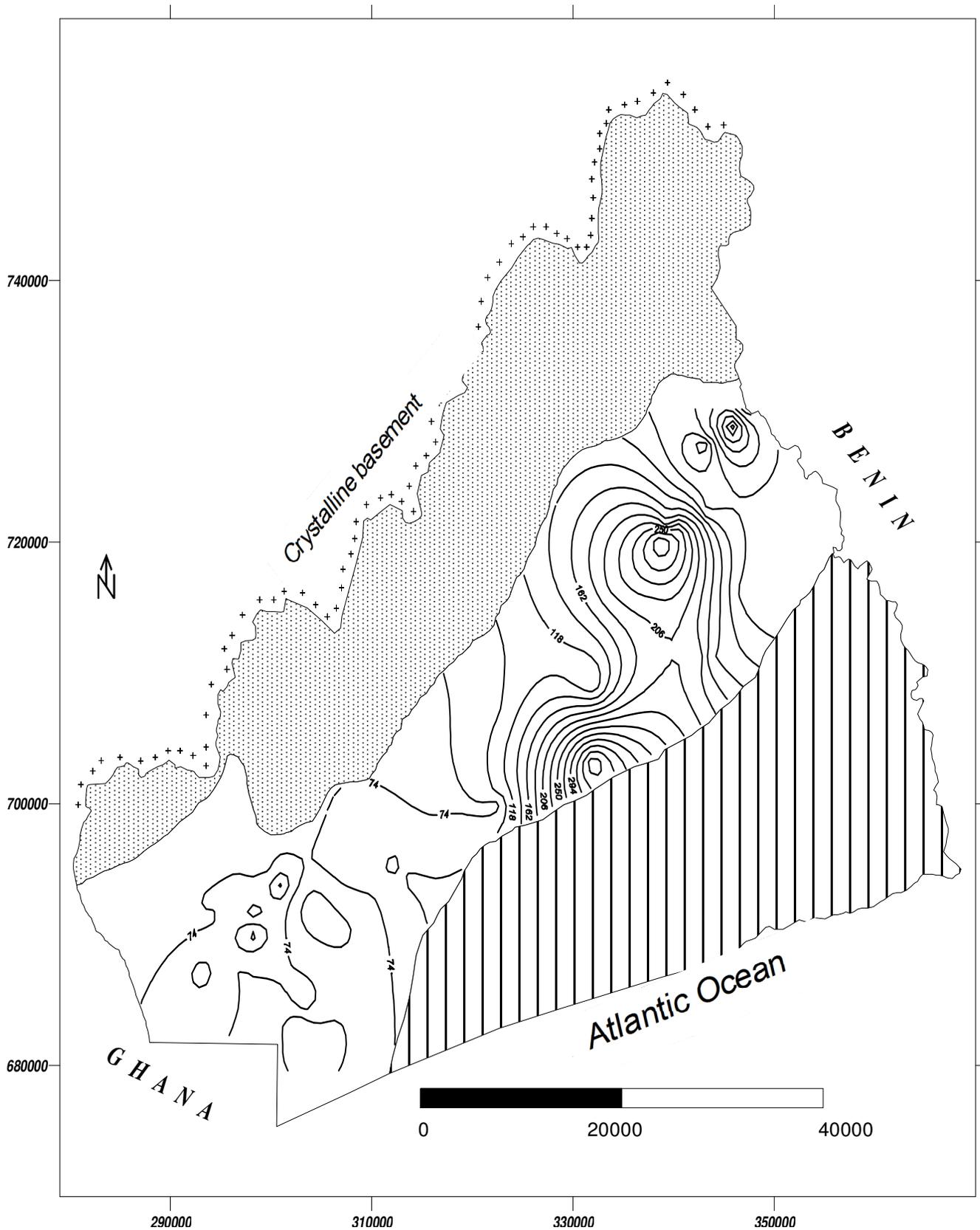


Figure 8. Spatial distribution of calcium.

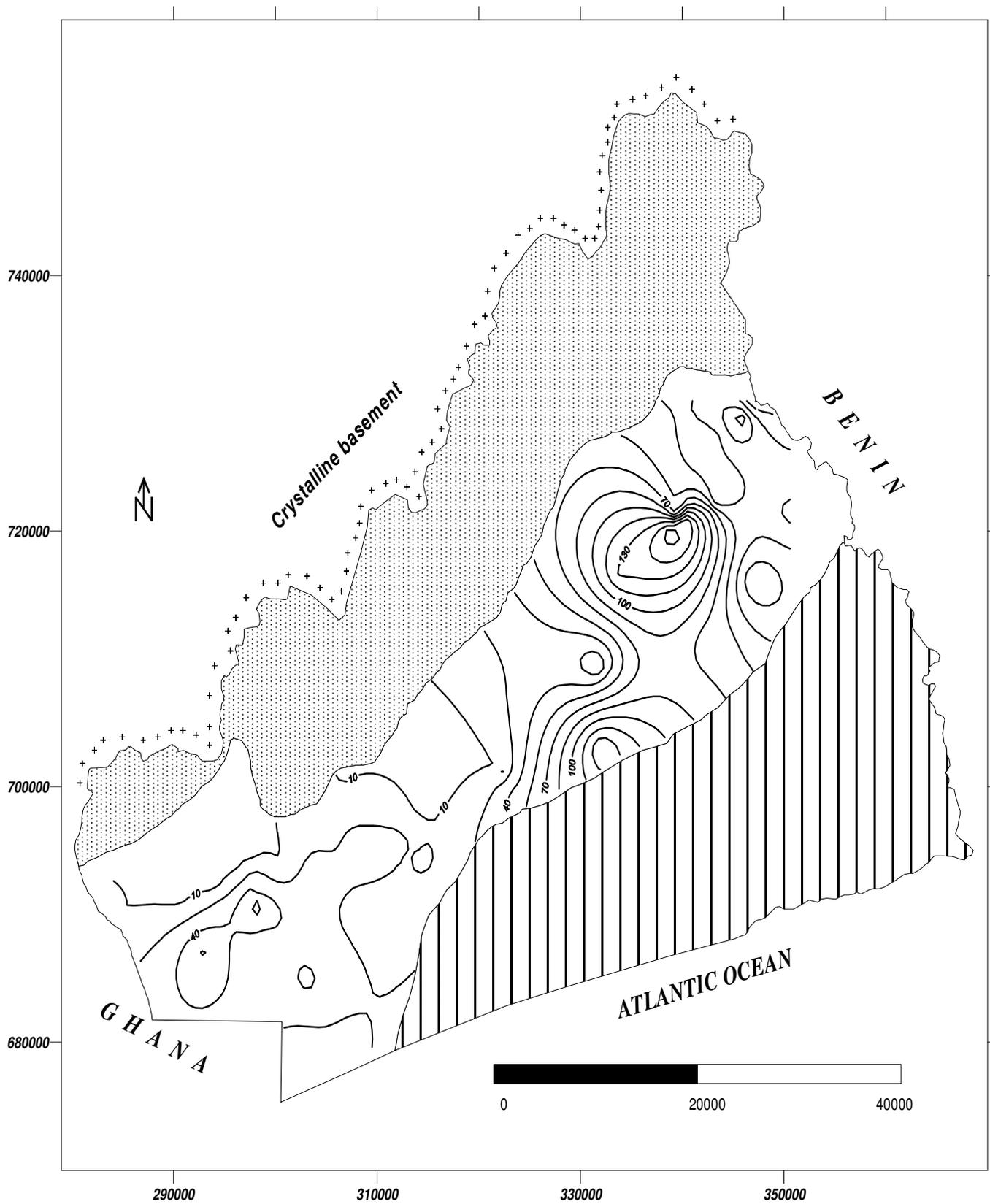


Figure 9. Spatial distribution of magnesium.

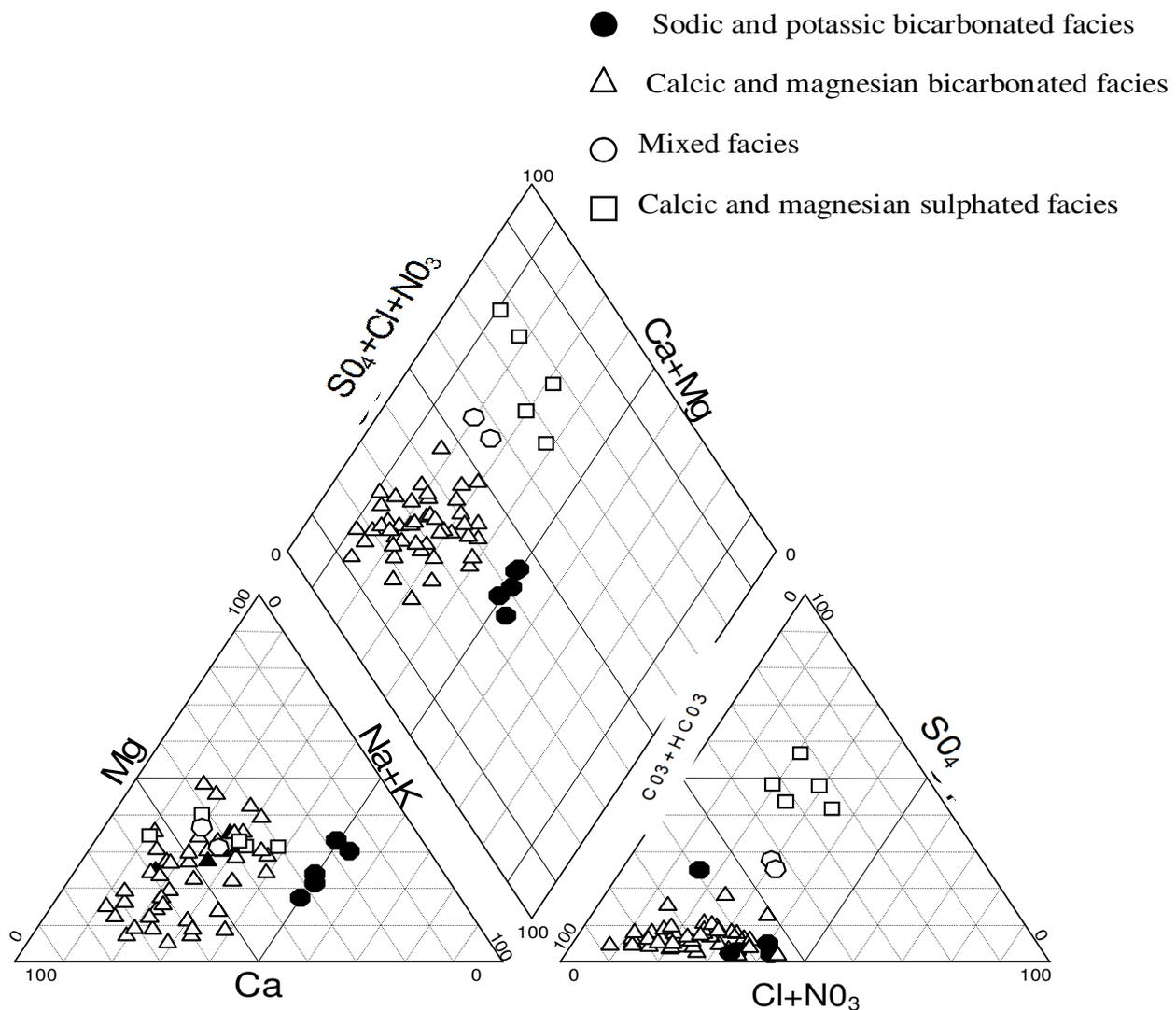


Figure 10. Piper's diagram: representation of hydrochemical pattern of Paleocene groundwater aquifer.

facies is found exclusively in the East of the study area (Figure 11).

(iii) The mixed anionic and cationic facies with the exception of a single point oriented toward the calcic pole. Projection of these points in the lozenge shows that these are calcic and magnesian and chloride-sulphated waters.

To explain the presence of sodic and potassic bicarbonated facies in the South-West of the study area, correlations between the major cations such as Ca^{2+} , Mg^{2+} , Na^+ , and K^+ and well depth were analyzed. These indicated that calcium concentrations decreased with aquifer depth. Similarly magnesium concentrations decreased with aquifer depth but to a lesser extent (Figure 12).

Conversely, sodium and potassium concentrations tended to increase with depth (Figure 12). Long periods of residence and the associated water-rock interactions in the Paleocene reservoir could contribute to cationic substitution reactions. This is a typical exchange phenomenon that takes place at the contact with clay minerals (illite, smectite) present in the aquifer (Drever, 1997). Decreasing Ca^{2+} concentrations associated with increasing Na^+ and K^+ is observed by Edmunds et al. (1987) and Edmunds and Smedley (2000) in some British aquifers. For the Paleocene aquifer, this phenomenon can be considered a qualitative indicator of the age of the waters. These results are in agreement with those obtained by Akiti (1980), and AKouvi (2000) which show, using isotopic techniques, the aging from North to South of the Paleocene water.

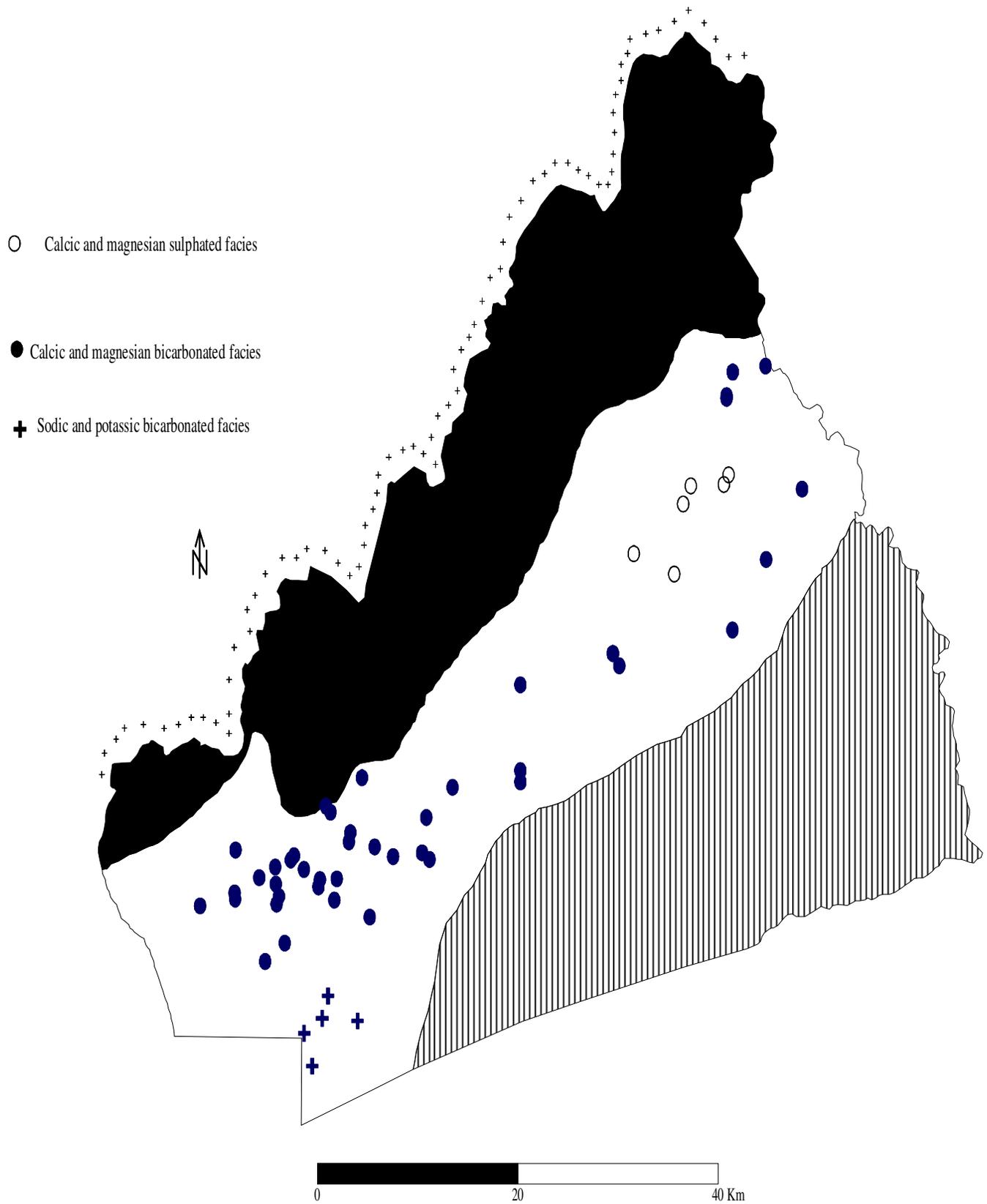


Figure 11. Spatial distribution of hydrochemical facies.

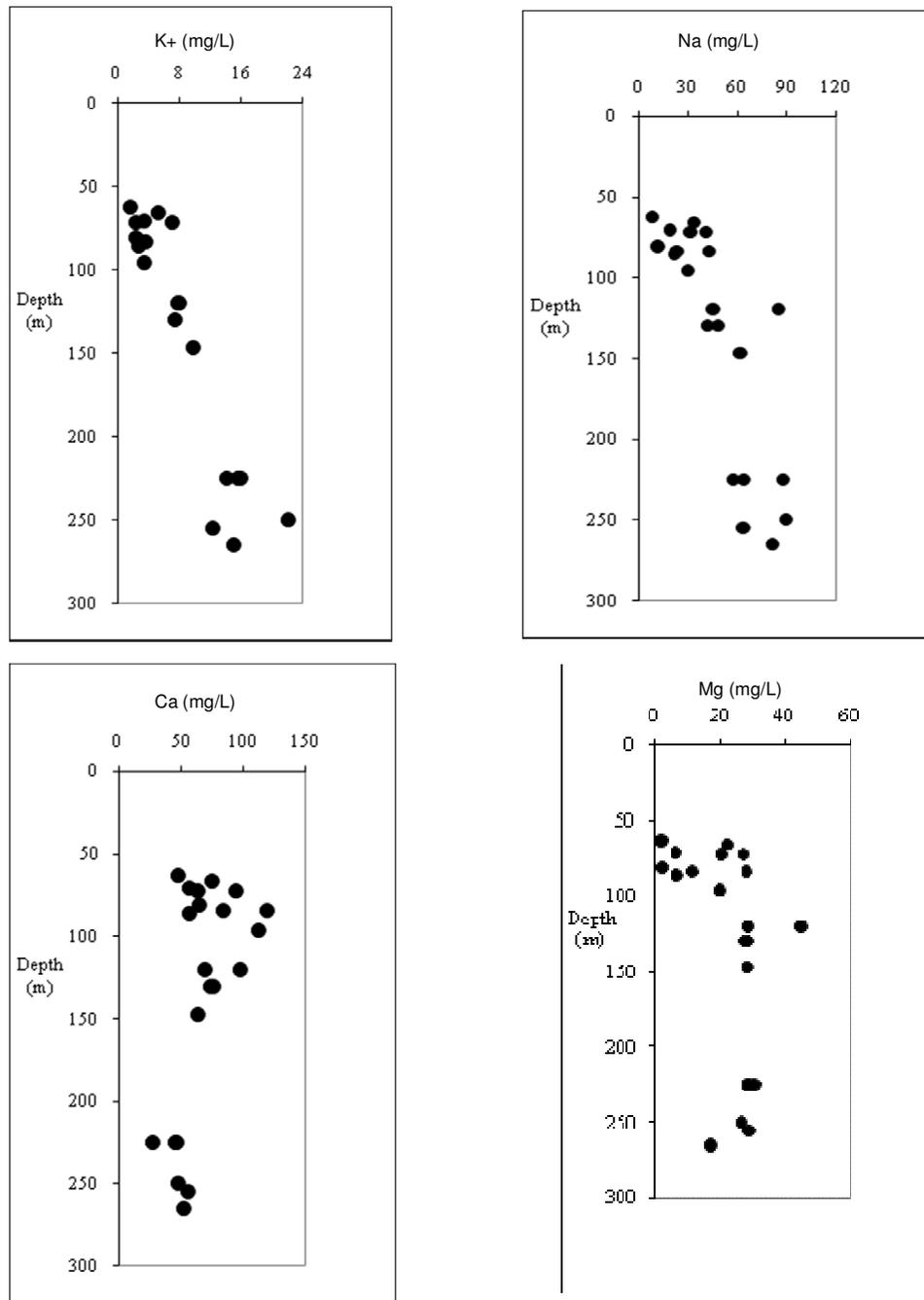


Figure 12. Distribution of cation (K^+ , Na^+ , Ca^{2+} , and Mg^{2+}) concentrations with depth in the Western part of the aquifer.

It should also be added that for Akiti (1980), the presence of high contents of chloride, sodium, calcium and magnesium in the water suggests a mixing of Paleocene water and that contained in the gneissic substratum. This is not the case in the Togolese part of the aquifer where the substratum is clayey.

Principal component data analysis

Principal Component Analysis (PCA) is a mathematical technique that allows the reduction of a complex system of correlations to a smaller number of dimensions. This study employed this multidimensional analysis because

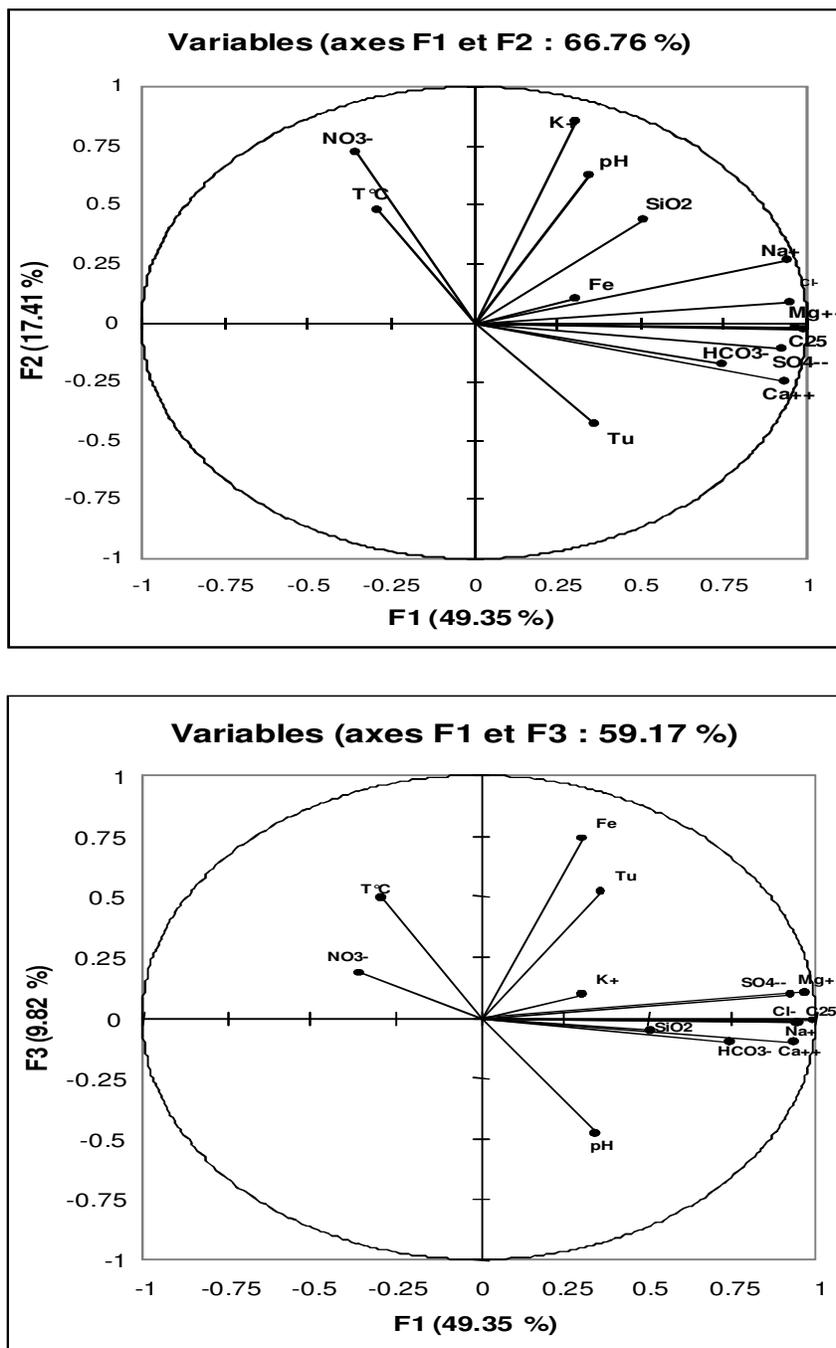


Figure 13. Diagram of variables: plans I-II and I-III (14 parameters).

of the great number of samples and the many chemical parameters considered. PCA considers all the variables and their relationships simultaneously, revealing relationships that are not always evident in the usual graphical representations or simple correlations (Lefebvre, 1980). The program used for data analyses was Xlstat (Fahmy, 2006). The variables considered in this study are

temperature, pH, electrical conductivity, turbidity, major and minor ions; that is a total of fourteen parameters. Variability percentage (67%) for the first two factors (F1 and F2) was not high enough. To avoid a misinterpretation of the graphs we posted the F1 and F3 axes (Figure 13).

Axis F1 (49% of the variance) is characterized by

Table 4. Correlation coefficients of chemical parameters (in bold type the significant correlation coefficients).

| Variables | T°C | pH | C25° | HCO ₃ ⁻ | Cl ⁻ | SO ₄ ⁻ | Ca ⁺⁺ | Mg ⁺⁺ | Na ⁺ | K ⁺ | SiO ₂ | NO ₃ ⁻ |
|-------------------------------|-------|------|-------|-------------------------------|-----------------|------------------------------|------------------|------------------|-----------------|----------------|------------------|------------------------------|
| T°C | 1 | | | | | | | | | | | |
| pH | -0.01 | 1 | | | | | | | | | | |
| C25° | -0.28 | 0.32 | 1 | | | | | | | | | |
| HCO ₃ ⁻ | -0.17 | 0.13 | 0.732 | 1 | | | | | | | | |
| Cl ⁻ | -0.19 | 0.35 | 0.94 | 0.73 | 1 | | | | | | | |
| SO ₄ ⁻ | -0.31 | 0.24 | 0.94 | 0.56 | 0.81 | 1 | | | | | | |
| Ca ⁺⁺ | -0.46 | 0.22 | 0.95 | 0.73 | 0.87 | 0.92 | 1 | | | | | |
| Mg ⁺⁺ | -0.19 | 0.27 | 0.97 | 0.71 | 0.89 | 0.94 | 0.89 | 1 | | | | |
| Na ⁺ | -0.15 | 0.47 | 0.93 | 0.61 | 0.95 | 0.85 | 0.83 | 0.88 | 1 | | | |
| K ⁺ | 0.28 | 0.56 | 0.29 | -0.04 | 0.34 | 0.25 | 0.06 | 0.31 | 0.54 | 1 | | |
| SiO ₂ | -0.08 | 0.36 | 0.43 | 0.38 | 0.56 | 0.30 | 0.31 | 0.41 | 0.55 | 0.42 | 1 | |
| NO ₃ ⁻ | 0.33 | 0.12 | 0.35 | -0.45 | 0.30 | 0.33 | 0.48 | 0.35 | 0.13 | 0.52 | 0.13 | 1 |

conductivity, chloride, sulphate, calcium, sodium, bicarbonate. This axis showed a mineralization that is mainly lithological in origin. The elements correlated with this axis are indicators of carbonated and evaporitic environments. This axis therefore indicates the water time residence in the aquifer.

Axis F2 (17% of the variance) is characterized by nitrates, potassium, pH, turbidity and to a lesser extent silica. This axis is defined by pollution elements.

Finally, axis F3 (10% of the variance) is defined by temperature, iron, turbidity and to a lesser extent nitrate. Axis F3 showed that sample turbidity was due to iron concentration. As with axis F2, this axis is characteristic of pollution elements.

Table 4 shows the significant correlation coefficients for 59 samples. One notes that water mineralization represented by electrical conductivity, is determined mainly by major ions ($r > 0.7$). The contribution of nitrates and potassium is low ($r < 0.3$).

Calcium and magnesium were well correlated with bicarbonates. This indicated the calcareo-dolomitic nature of the matrix. A spot test performed by Monciardini et al. (1986) on organogenic limestones that constitute the matrix shows that they are composed of 81% calcite and 9% dolomite. Silica was also correlated with potassium and sodium ($r = 0.55$ and 0.41 respectively) indicating the presence of clay minerals in the carbonate matrix.

Conclusion

The results of this study have allowed bringing out the main chemical characteristics of the Paleocene aquifer. Chemical parameters and Principal Component Analysis indicate that groundwater composition of the Paleocene aquifer is related to the geological nature of the formations traversed.

The confinement of the deep groundwater in the Paleocene aquifer, sometimes in contact with distinctive rocks (notably gypseous) confers on them in many places specific hydrochemical characteristics

Cation distribution with depth showed calcium and magnesium depletion of the waters to the detriment of sodium and potassium ions as depth increases. This evolution can be considered an indicator of residence time of water in the reservoir.

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