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BASIC HYDROGEOCHEMICAL PROCESSES OF GROUNDWATER FROM GNEISSO-MIGMATITIC FORMATIONS IN SOUTHWEST TOGO

OSNOVNI HIDROGEOHEMIJSKI PROCESI PODZEMNIH VODA IZ GNAJSO-MIGMATITSKIH FORMACIJA U JUGOZAPADNOM DELU TOGOA

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Abstract: The gneisso-migmatitic formations are part of the internal units of the Panafrican Dahomeyides Belt in southwest Togo. They are mainly composed of various gneisses and migmatites, which constitute groundwater reservoirs defined as fracture and laterite aquifers. In this study, diagrams (Gibbs, Piper and bivariate Plots) were elaborated using chemical data to highlight water facies and processes that control groundwater mineralization. The four water types identified in the area are Ca+Mg - HCO₃, Ca+Mg - Cl+SO₄, Na+K - Cl and Na+K - HCO₃. The analysis reveal that the gneisso-migmatitic formations groundwater chemical elements are controlled by water-rock interaction i.e. weathering through dissolution or hydrolysis of silicate minerals and leaching by infiltrating/percolating and also by ion exchange. These results confirm the importance of determining the mineralogy of aquifers in understanding groundwater chemistry.

Key words: Hydrogeochemistry, Basement aquifer, Groundwater-rocks reaction, Gneisso-migmatitic formation, Southwest Togo.

Apstrakt: Gnajso - migmatitska formacija je deo unutrašnje jedinice Panafričkog pojasa Dahomejida na jugozapadu Togo. Ova formacija se uglavnom sastoji od različitih tipova gnajsa i migmatita, u kojima se podzemni vodni resursi nalaze u pukotinama i izmenjenim delovima stena. U ovom istraživanju, dijagrami: po Gibsu, Pajperu i bivarijantni dijagrami, su izrađeni prema hemijskim analizama kako bi se istakli hidrogeološki tipovi voda i glavni procesi koji kontrolišu mineralizaciju podzemnih voda. Četiri glavna tipa voda identifikovani su u ovom području: Ca+Mg - HCO₃, Ca+Mg - Cl+SO₄, Na+K - Cl and Na+K - HCO₃. Rezultati analiza otkrili su da su hemijski elementi u podzemnim vodama gnajso-migmatitske formacije kontrolisani interakcijom vode i stene, odnosno razlaganjem silikatnih minerala putem rastvaranja ili hidrolize silikatnih minerala, ispiranjem/infiltriranjem u podzemnim vodama, kao i jonskom izmenom. Ovo potvrđuje značaj određivanja mineralogije akvifera za razumevanje hemije podzemnih voda.

Ključne reči: hidrogeohemija, izdan, reakcija stena-podzemna voda, gnajso-migmatična formacija, JZ Togo

INTRODUCTION

In southwest Togo, the gneisso-migmatitic formations represent the main groundwater reservoirs. Those formations are made up of crystalline or hard rocks and contain tectonic structures that give them the properties of basement aquifers. Then, the groundwater is located in the fractures and exploited through boreholes installed by Togolese government as part of village water supply programs.

Face the many challenges of quality those groundwater needs minimal or no treatment before consuming, unlike surface water.

The quality and chemical composition of groundwater from basement aquifers are shaped by fundamental processes known as hydrogeochemical processes. These processes take place at the interface of water and geological materials (rocks). It involves complex chemical reactions, affects the distribution of elements and chemical composition of water in these aquifers.

When water encounters rocks, it is charged with various elements that determine its chemical composition. These elements are provided during weathering process, mineral dissolution and ion exchange.

In basement rocks such as gneisses and migmatites, hydrogeochemical processes can be influenced by many factors such as mineralogy, groundwater recharge, runoff conditions and human activities.

The purpose of this study is to identify the basic hydrogeochemical processes that take place in gneisso-migmatitic formations and understand the mechanism controlling groundwater chemistry in the associated aquifers.

GEOLOGY AND HYDROGEOLOGY

The study area is located in the south-west of Togo between longitudes 00°37' and 01°15' East and latitudes 6°20' and 06°50' North. It corresponds to a little frontal part of the Dahomeyides Belt internal zone mainly composed of gneissic and migmatitic formations outcropping NNE-SSW (Figure 1a). According to Sylvain et al. (1986), these formations include various gneiss suites (2-mica gneiss, amphibole biotite gneiss, amphibole, biotite and/or garnet metagranites) and migmatites (Figure 1b). These lithological components, containing many centimetric to metric amphibolite enclaves, outcrop sporadically in flattened domes or inselberg relics. Structurally, the Dahomeyides Belt internal units bear imprints of five Pan-African deformation phases (Chala et al., 2015; Sylvain et al., 1986). In fact, the deformation markers in the gneisso-migmatitic formations retrace thrusting, folding and later fracturing to which is related an important lineament or fracture network.

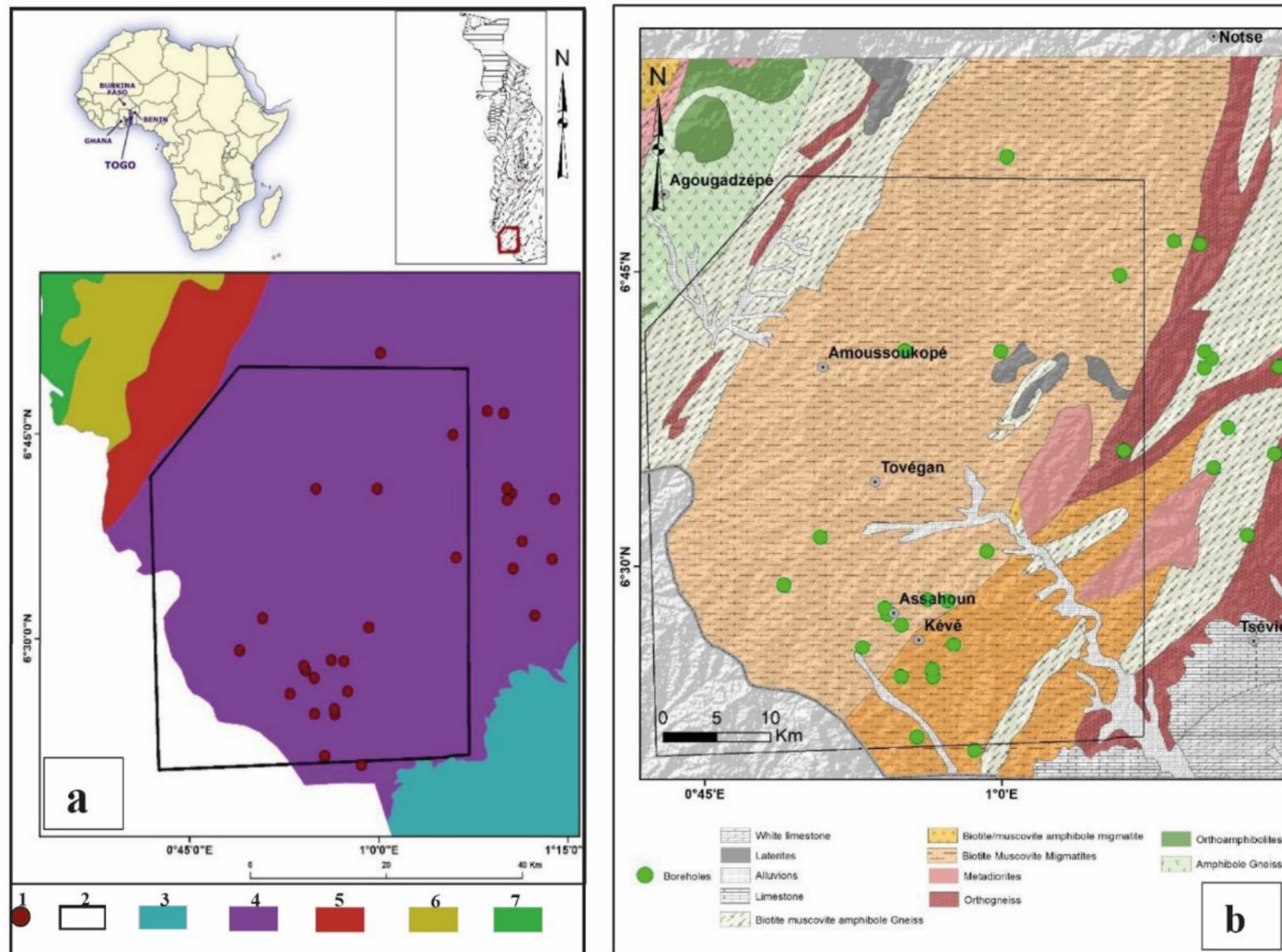


Figure 1. a) Geological map of the area according to Sylvain et al. (1986) showing: 1- Samples location; 2- study area; 3- Coastal sedimentary basin: Sand, limestone, clay and phosphate; 4- Intern zone: Various Gneiss and Migmatites; 5- Suture zone: basic to ultrabasic massifs, 6- Extern zone: Kpalimé-Amlamé anatectic complex; 7- Extern zone: Quartzitica structural unit of Atacora; **b)** Detail of geological map of the area

Hydrogeologically, the gneisso-migmatitic peneplain in the southwest of Togo contains two types of aquifers: weathered rock aquifers and fracture aquifers (Gnazou et al., 2016). The first type corresponds to a generally clayey sand supergene weathered rock cover often tapped by big diameter wells. The average thickness of this pedological cover is generally only a few meters, but it can be much greater in depressions (Levêque, 1979).

Aquifers related to alteration or weathering typically have porosities of 2-5%, with hydraulic conductivity on the order of 10^{-3} m/d. The second i.e. fracture aquifers are represented by reservoirs in more or less fractured gneiss and migmatite (Akakpo, 2017; Chala, et al., 2015; Tairou et al., 2012). The storage capacity of these rocks is defined by a secondary porosity (fracture porosity) stemming from the late episodes of panafrikan brittle tectonics. These discontinuous reservoirs are those solicited by rural water drilling projects. Fractured basement aquifers have lower porosity (1%) and may produce yields of up to 120 m³/day.

It's important to note the presence, on some outcrops in the area, of natural reservoirs resulting from rainwater accumulation in alteration and erosion pockets of big amphibolitic enclaves. These structures, generally of varied shapes, are sometimes quite deep, and are exploited throughout the year by the people for their different needs including for domestic uses.

In this area, no spring has been identified. The only way of accessing water is by boreholes and a few rare wells. The depths of the boreholes range from 35 to 118m with average around 66 m. The depths of the underground water in its boreholes vary from 2 to 44 m and the average flow is around 4.4 m³/s (Zondokpo et al., 2022).

METHOD

This study involved analysis of chemical sheets of 44 boreholes collected at the Ministry in charge of water. On each analysis sheet, physical parameters such as temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity and chemical parameters like Ca, Mg, Na, K, HCO₃, Cl, SO₄, NO₃, NO₂, FeT, PO₄, Mn, NH₄, KMnO₄ are provided. The methodological approach of this study is based on the use of Piper (1944) diagrams for the hydrochemical classification of water, Gibbs (1970) and bivariate Plots to determine the main hydrogeochemical factors and processes involved in water mineralization. The Gibbs (1970) and Piper (1944) diagrams are established by Diagrammes 5.1 software (<http://www.lha.univ-avignon.fr/>). The Bivariate plots were produced by MS Excel 2016.

RESULTS AND DISCUSSION

Hydrochemical facies

To find the Hydrogeochemical facies of groundwater of the gneiss-migmatite formation, the trilinear diagram of Piper 1944 is used by plotting the concentration of major cations and anions (Fig. 2).

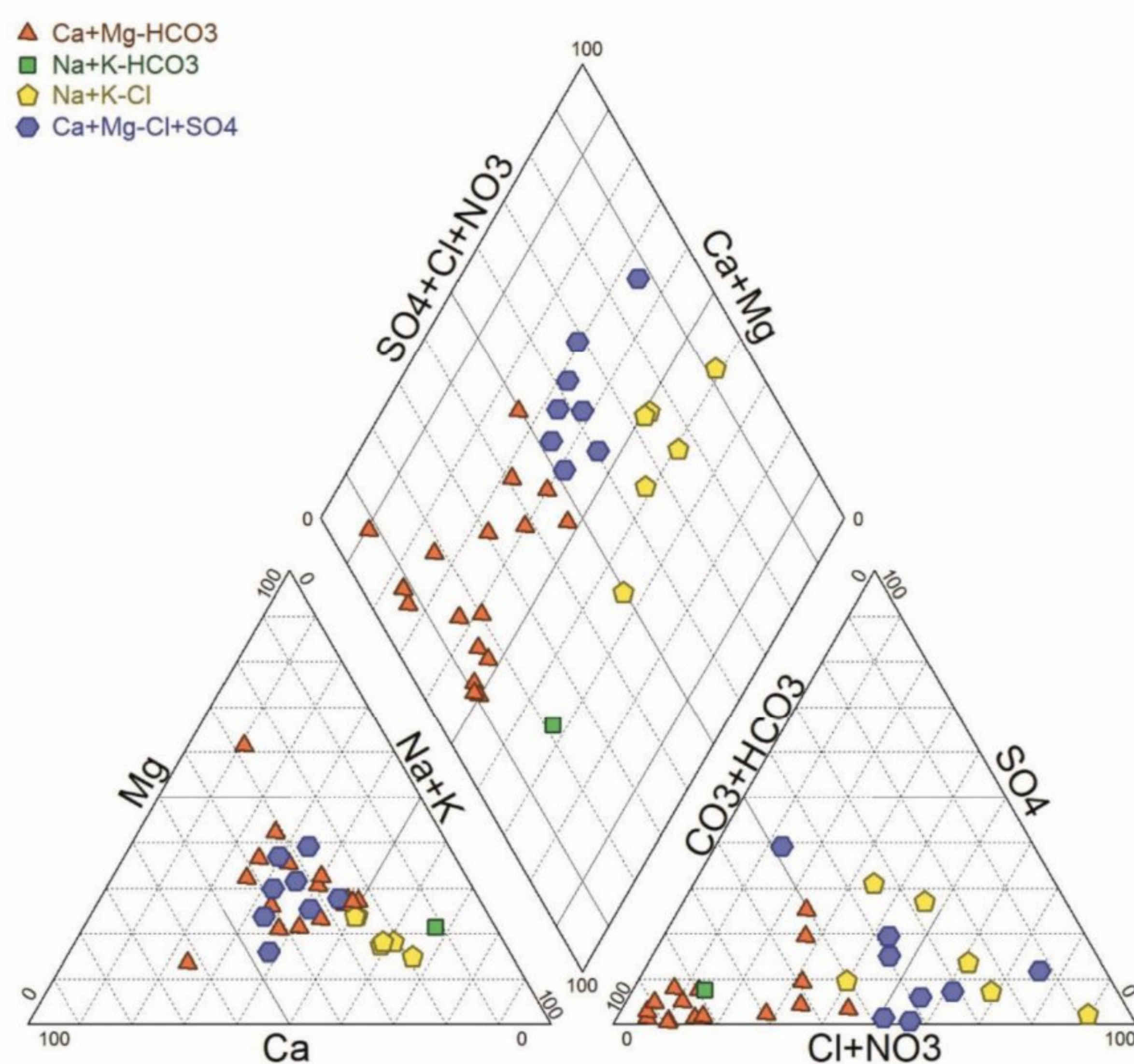


Figure 2. Piper diagram showing hydrogeochemical facies

Four water types can be identified according to the order of dominance: Ca+Mg - HCO₃, Ca+Mg-Cl+SO₄, Na+K-Cl and Na+K-HCO₃.

Figure 2 shows that for all these waters, 2 main hydrofacies can be distinguished. These are the chloride, sulphate, calcium and magnesium facies and the carbonate, calcium and magnesium facies.

Hydrogeochemical Processes Diagrams of Gibbs (1970)

The diagrams of Gibbs (1970) are used to highlight the main mechanisms affecting the mineralization of water. They show variations in TDS values as a function of the ratios $(Na + K)/(Na + K + Ca)$ and $Cl/(Cl + HCO_3)$. Gibbs distinguishes three main water mineralization mechanisms by considering the chemical composition of water on a global scale : (i) rainwater chemistry, this first mechanism is the influence of atmospheric precipitation, (ii) water-rock interactions, in this second mechanism, the minerals in the rocks are weathered and ions are released into the water that flows through the aquifer system, enriching it with dissolved constituents as it flows, and (iii) evaporation and mineral precipitation processes, this third mechanism highlighted by Gibbs is the influence of the residence time and the flow system by the evaporation and minerals precipitation.

Analysis of the Gibbs diagrams (Fig.3) shows that the variations in TDS values as a function of the ratios $(Na + K)/(Na + K + Ca)$ and $Cl/(Cl + HCO_3)$ of all boreholes are close to the field of rocks weathering dominance and are tending towards Evaporation dominance field. Thus, the mineralization of groundwater in the area is mainly due to "water-rock" interaction and evaporation that also help to increase concentrations and cause the water to move rapidly towards mineral saturation.

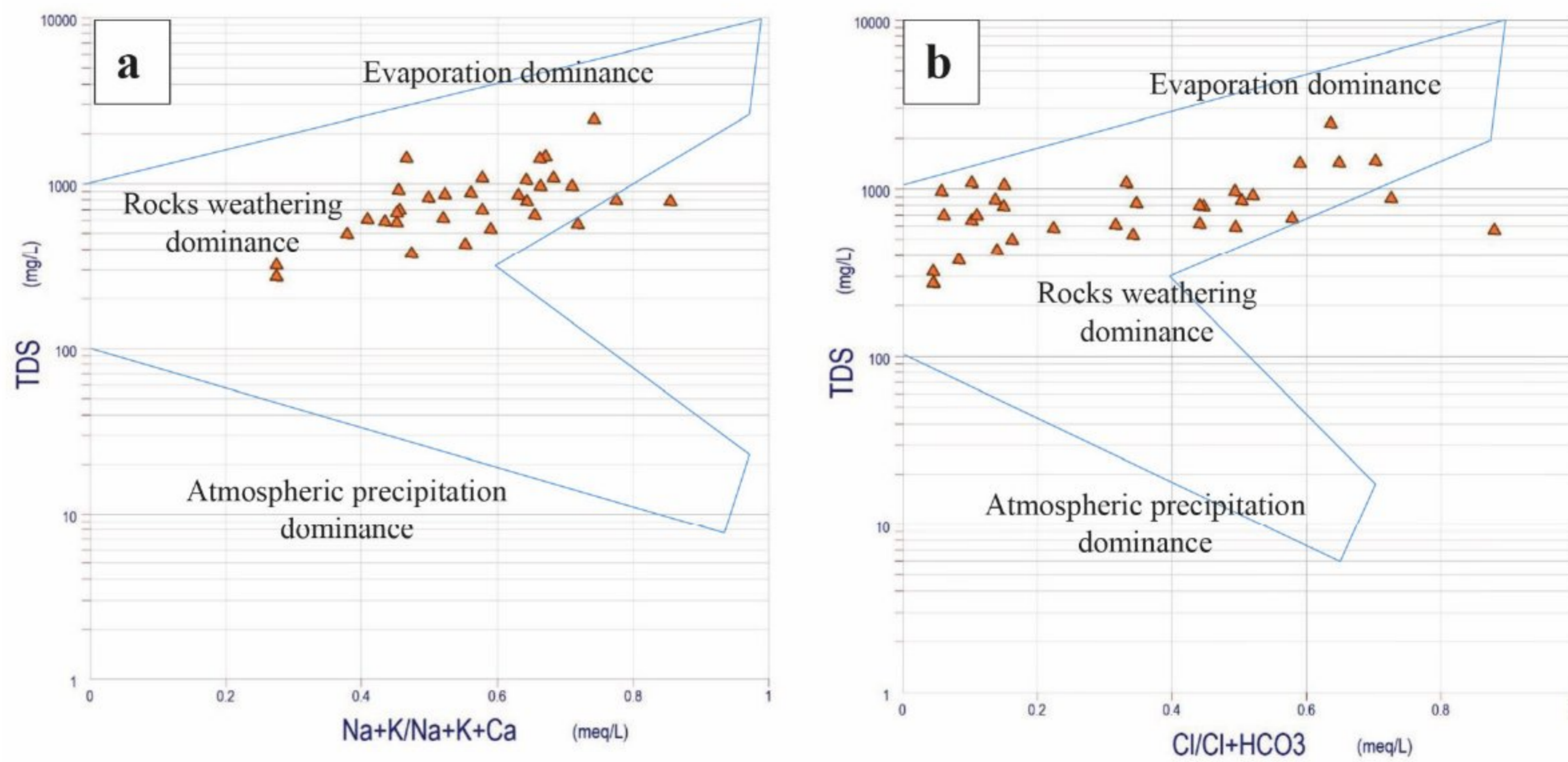


Figure 3. Diagrams of Gibbs. **a)** $(Na + K)/(Na + K + Ca)$ vs TDS ; **b)** $Cl/(Cl + HCO_3)$ vs TDS

Ion exchange

The ability of solid substances to exchange cations or anions with cations or anions in aqueous solution is called ion exchange capacity. In natural systems, anions are exchanged very rarely, in contrast to cations, which exchange more readily (Merkel and Planer-Friedrich, 2008).

Cation exchange is a crucial process in the mineralization of groundwater, particularly when clay minerals are relatively abundant in the aquifer system, as was the case in the basement zone.

The phenomenon of cation exchange has a significant impact on the mineralization of groundwater. The diagrams $[(Ca^{2+} + Mg^{2+}) - (HCO_3^- + SO_4^{2-})]$ vs. $[(Na^+ + K^+) - Cl^-]$ (Mc Lean et al., 2000; Garcia et al., 2001) highlight the basic exchange processes between the Ca^{2+} in the water and the Na^+ ions coming from the aquifer. During this process, Ca^{2+} and Mg^{2+} existing in the groundwater were exchanged by Na^+ previously adsorbed to the surface of the clay minerals.

The diagrams show that the clouds of points tend to align themselves almost on the slope line -1 (Fig. 4), clearly showing that base exchange exists. This is explained by the fact that the Ca^{2+} present in the water is thus replaced by Na^+ initially fixed on the adsorption sites of the geological materials that constitute the underground. This phenomenon generally takes place in contact with clays or contact with aquifers containing sodium (Na).

Cation exchange occurs according to the following global mass balance equation (Guo and Wang, 2005; Ben Moussa et al., 2010): $Na\text{-clays} + Ca^{2+} \rightleftharpoons Ca\text{-clays} + 2 Na^+$.

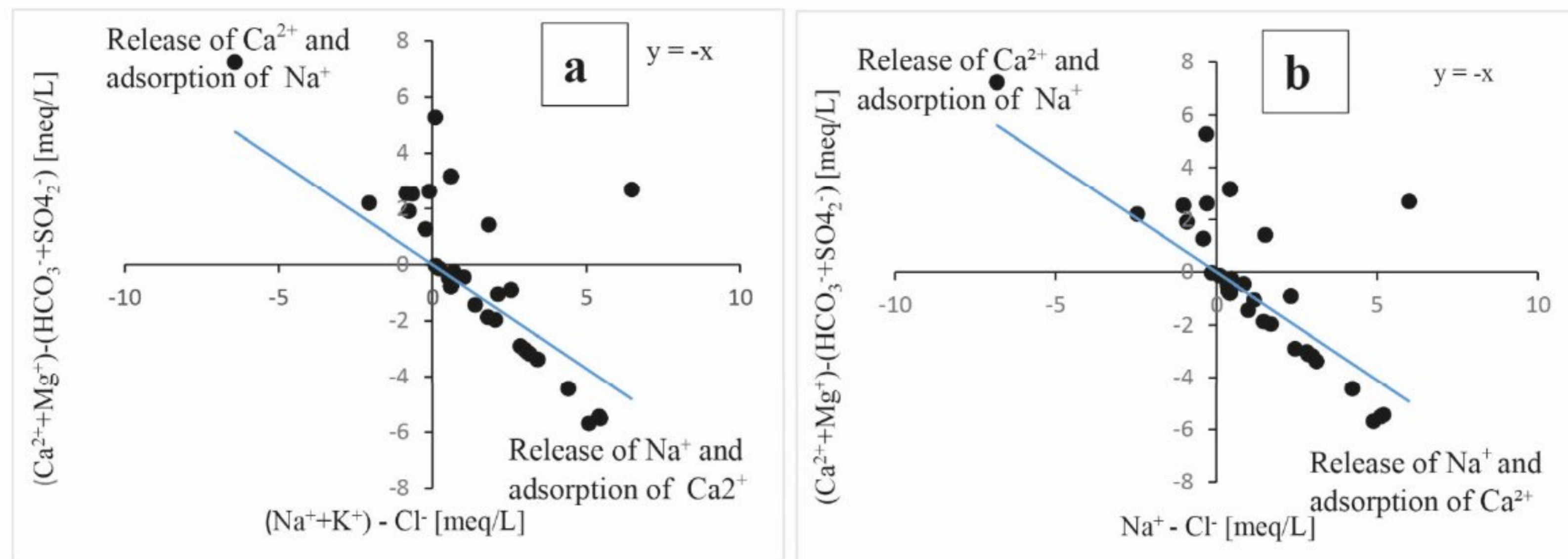


Figure 4. Cation exchange diagram: **a)** $(Ca+Mg)-(HCO_3+SO_4)$ vs $(Na+K)-Cl$; **b)** $(Ca+Mg-HCO_3-SO_4)$ vs $(Na-Cl)$

Evidence of Silicate Weathering

Inference from Gibbs diagrams shows that groundwater chemical composition has been affected largely by the rock–water interaction and partially by the evaporation.

To identify the sources of the major ion in the groundwater, bivariate Plots (Gaillardet et al. 1999) Ca/Na vs Mg/Na and HCO_3/Na were used (Fig. 5). These diagrams show that all points fall inside the silicate weathering field. This implies therefore that silicate weathering is the main source of the cations. Probably, because of the presence of basement rocks. Identical results have been obtained in similar aquifers (Kana et al., 2022).

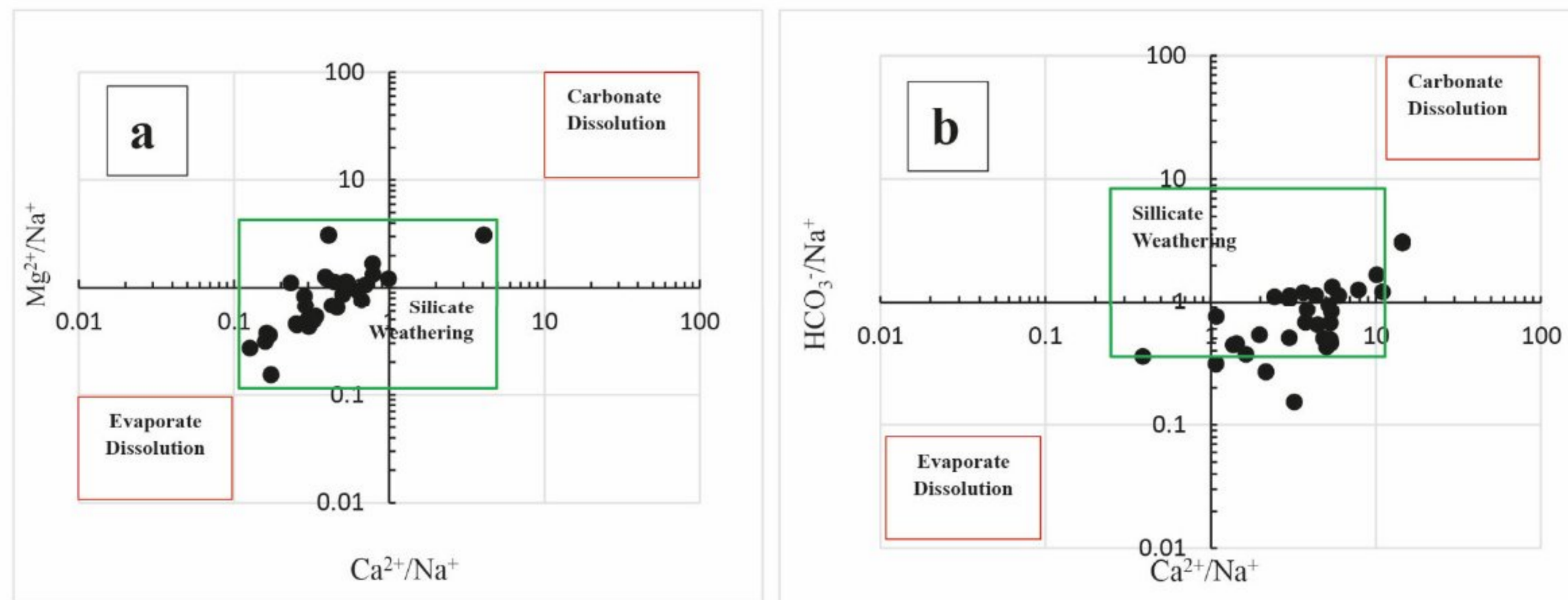


Figure 5. Bivariate plots of the ratios: **a)** Ca/Na vs Mg/Na and **b)** HCO_3/Na

CONCLUSIONS

Hydrogeochemical processes have a significant impact on the chemical composition of water in basement aquifers. Thus, through the processing and hydrochemical analysis of preliminary data from these basement aquifers, we have attempted to identify all hydrogeochemical processes of groundwater from a basement unit using major ion concentrations.

Major rock types in the area are various gneiss and migmatite. These rocks showed predominantly Quartz, Feldspars, Plagioclase, Biotite, Muscovite and Hornblende.

According to hydrochemical analysis, groundwater mineralization is mainly controlled by intense water-rock interaction, ion exchange reactions, and human activities. The hydrofacies approach shows the existence of four facies largely dominated by the facies $Ca+Mg-HCO_3$, $Ca+Mg-Cl+SO_4$, and $Na+K-Cl$.

Ion exchange is due to the silicates weathering and the existence of a large fraction of clay especially in depressions where the thickness of weathering is high confirming a significant proportion of plagioclase weathering. This silicate weathering has been highlighted by the bivariate Plots. Then, according to geological framework, we could say that the silicate weathering is the main process in this area.

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