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Influence of Climate and Tectonics on the Crystallization of Carnallite and Related Salts in the Congolese Atlantic Basin during the Lower Cretaceous, Republic of Congo

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Abstract

Lithological, petrographic, and morphoscopic studies were conducted on cuttings and cores from three boreholes drilled in the Loemé salt, Kanga site, Republic of the Congo, to determine 1) the preferential conditions for crystallization of carnallite and associated salts and 2) to reconstruct paleoenvironmental and paleoclimatic conditions at the time of sedimentation. Sequential analysis of logs, sedimentary structures, carnallitite facies and associated salts concluded to the existence of a potassic carnallitite lagoon basin with low water cover, on a very wide and extensive plateau, affected by coastal waves and swells resulting from successive collapses. This basin evolved in two phases: confined and then open. The regular stratifications of halite, the rhythmicity of the halite-carnallitite elementary sequences are characteristic of salts that precipitated in relatively stable brines. These salts are therefore tectonosedimentary. The brecciated facies of the carnallitites sometimes associated with tachyhydrite result from the evolution of these deposits into salt crusts reworked by the surges into subaquatic allochemical gravelly cords under water. These crusts mark stages of partial and complete drying of the basin in a very hot and arid climate. Prolonged exposure of halite brines as well as their homogenization by surges accelerated evaporation and their abrupt evolution into carnallite brines obstructing the fossilization of sylvite. The precipitation of tachyhydrite marks the final stage of the successive complete drying of the basin.

Keywords

Potassium Lagoon, Surges, Stable Brines, Rhythmicity, Elementary

Sequences, Salt Crusts, Arid Climate, Republic of the Congo

1. Introduction

Salt deposits in sedimentary basins are the result of evaporation of marine waters in hot and arid climates. These climatic conditions have been identified in the central segment of the South Atlantic during the period from the Aptian to the Albian [1] [2]. Previous work in this central segment highlights salts consisting essentially of halite (NaCl) according to [3]. On the other hand, in the Congolese and Gabonese part, the salt series is constituted by a succession of elementary rhythmic sequences in which the layers of halite are surmounted by layers of potash salts (sylvinite and carnallite) [3] [4].

In Congo, sylvite was described by Dorling and al. (2011, 2012) [5] [6], at the end of cycle VII in the Sintoukola site located northwest of the Kanga site (**Figure 1**). For these authors, it is the carnallite present in this cycle which, by diagenesis, gave sylvite following the hydrothermal waters which migrated through the normal faults and which came to alter these carnallite horizons. This hypothesis was also mentioned by [7], in the same basin. On the other hand, for [8] [9], the sylvinite at Holle, located east of the Kanga site (**Figure 1**), was interpreted as being localized by a diagenetic conversion of carnallite, along the flanks of the anticlines whose tops were truncated by erosion preceding the transgression and the deposition of anhydrite.

One could ask the question of how this carnallite was set up in the saliferous basin of the Loemé at Kanga, as well as the origin of the formation of the sylvinite? It is to answer this question that the present work with the theme "influence of climate and tectonics on the crystallization of carnallite and related salts in the Congolese Atlantic basin in the Lower Cretaceous" has been proposed. Its main objective is to reconstruct the evaporitic sedimentation preferentially potassic to carnallitite, in relation to the climatic, paleoenvironmental and post-rift tectonic evolutions that prevailed during the functioning of this basin.

From this main objective flow the following specific objectives:

- determine the nature of the basin;
- reconstruct the hydrodynamic and sedimentological conditions of the basin;
- determine the nature of the climate that influenced the evolution of brines and the tectonosedimentary character.

2. Geological Context of the Coastal Basin

The Congolese coastal basin presents a geodynamic evolution divided into three tectonosedimentary phases: the pre-salt, salt and post-salt phase.

The pre-salt phase of Jurassic to Barremian age is 1600 to 4200 m thick [11] [12]. It contains two cycles which correspond to the two phases of collapse. The first is that of the opening of the continental rift during which the coarse

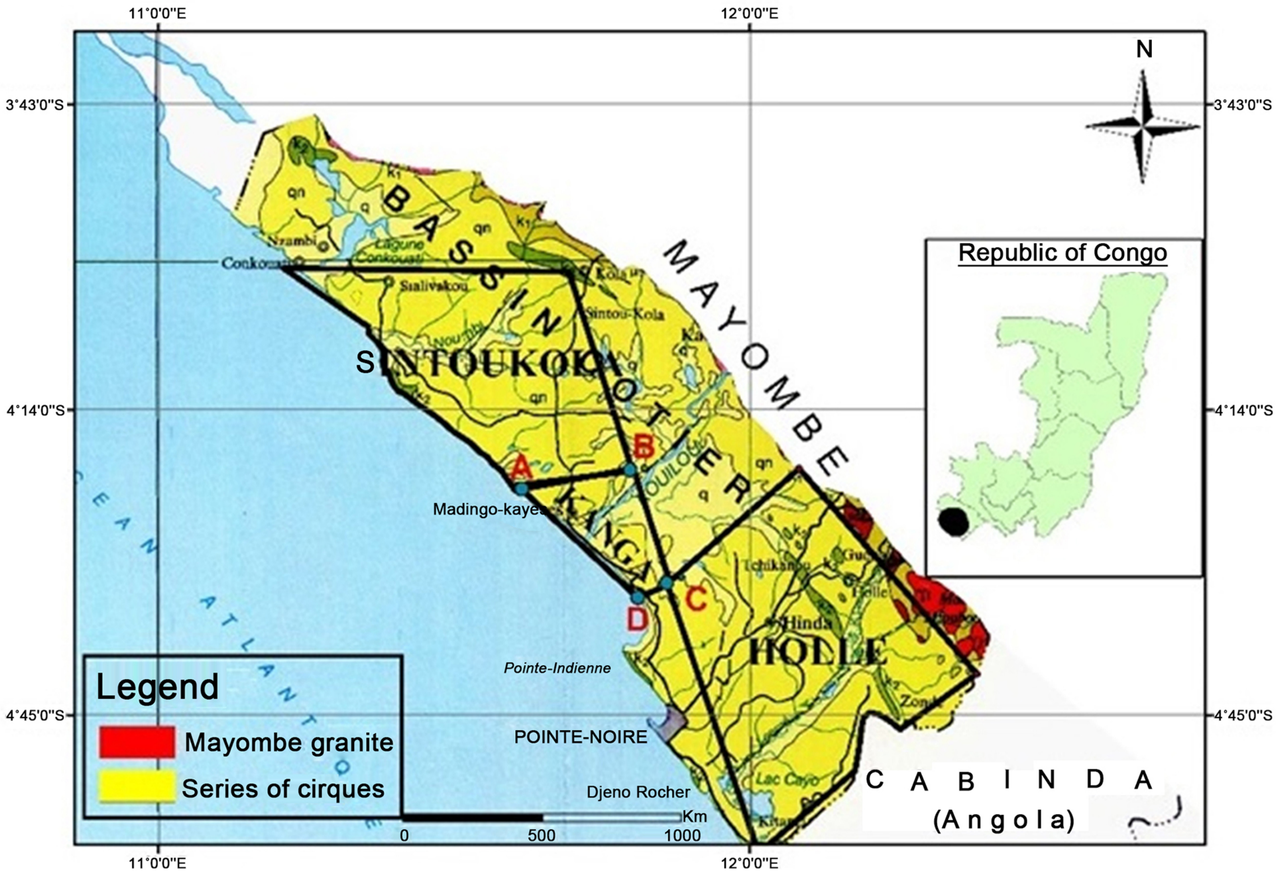

Figure 1. Location of the study area (Kanga site), extract from the geological map of the Congo at 1/1000,000 according to [10].

sandstones of Vandji are deposited (**Figure 2**), discordant on the bedrock of Mayombe, followed by the marls of Sialivakou. The second favored the sedimentation of the sands and sandstones of Djéno, the marls of Pointe-Noire and the clays of Pointe-Indienne (**Figure 2**).

The upper Aptian saliferous phase, 800 m thick, presents evaporites which rest in angular unconformity on Chela sandstones of Lower Aptian age, deposited in a fluvio-lacustrine environment [12] (**Figure 2**). These evaporites are the consequence of a lagoonal phase fed by the sea following several successive collapses, each of which corresponds to an evaporitic cycle of the clay, halite, carnallite type. Some cycles can end in bischofite or tachyhydrite [5] [6]. We also note in some cycles the presence of sylvite [5] [6] [13] [14]. These evaporites are covered homogeneously by a thick layer of anhydrite at the end of the Upper Aptian where the sea begins to flood the lagoon.

Finally, the post-salt phase of Albian to Current age, presents in its lower part the dolomites and limestones of Sendji of Albian age, the bioclastic limestones of Likouala of Cenomanian age, the marls of lower Madingo which have as lateral equivalent the Loango carbonates of Turonian age, the Emerald silts of lower Senonian age, the phosphate series of Holle and Kola of Maastrichtian age (**Figure 2**). The upper part is made up of Upper Madingo marls of Paleocene to Eocene age, followed by the sandy clays of Paloukou which lie in unconformity by

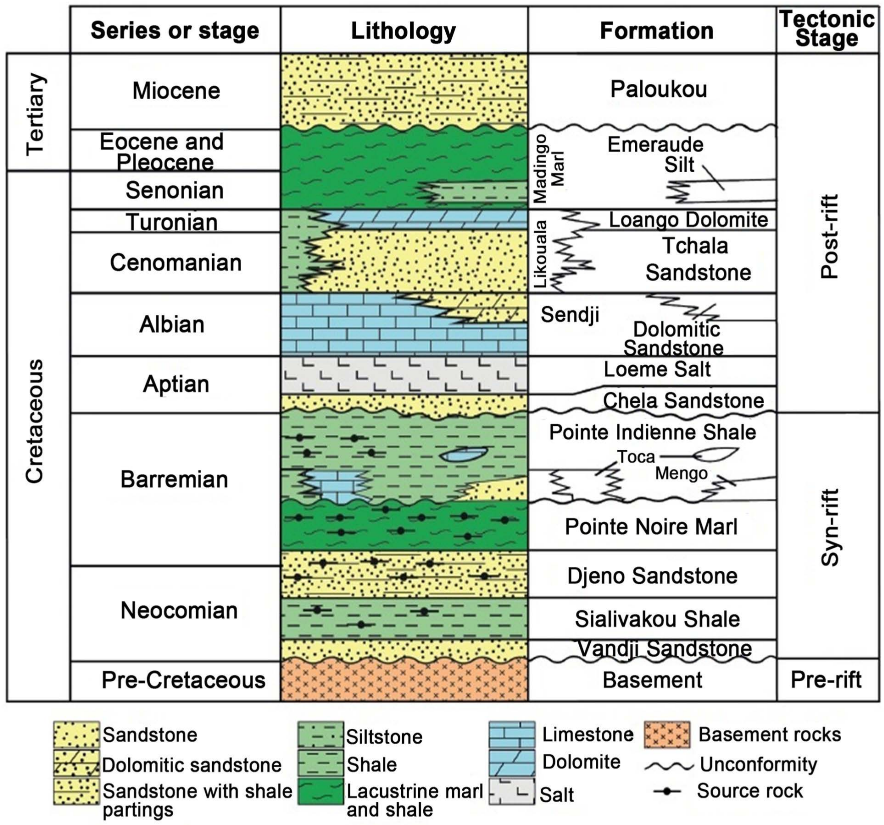

Figure 2. Lower Congo Basin generalized chronostratigraphic column, modified after [15].

stratigraphic gap of Upper Eocene to Lower Miocene. The Paloukou formation has as a lateral equivalent the series of cirques of Miocene age (**Figure 2**).

3. Materials and Methods

3.1. Sampling

The samples submitted for this study were taken from drill cuttings and rock cores from three boreholes (KEW-1, KEW-2 and KEW-3). The samples were taken taking into account the specific characteristics of each layer and type of salt. The drill cuttings were taken from the vibrating screen on the drilling site. They are placed in insulated plastic bags, which are numbered according to the techniques used by the company, then stored in the sample boxes and kept in the core shack.

During the coring phase, each core taken from 9 m in length is placed in half of the PVC, listed taking into account the depth from which it was taken. The carrot is cut in slices of one meter each, always respecting the quotation. Each slice is kept in an isothermal plastic bag, then placed in the carrot boxes.

3.2. Lithological and Petro-Sedimentary Description

This description was carried out in the field and refined at the petrography, mineralogy and sedimentometry laboratory of the Geological and Mining Research

Center in Brazzaville (Republic of Congo). It related to all the cuttings and cores in the field during the monitoring of the drilling, then to one hundred samples of cuttings and carrots selected for further studies in the laboratory.

- Description of cuttings

In the field, cleaning with a clean cloth is carried out. The description consists of determining the color, taste and resistance to the cutter. Carnallitite is brick red, with a bitter taste and stings the tongue. It squeaks with the cutter because it is hard. Halite is milky white and translucent, its taste is salty but not stinging. It is hard but does not squeak. Tachyhydrite is honey or yellowish in color and warm to the touch. It dissolves easily or exhibits strong dissolution in contact with air. Anhydrite is white, gray to yellow and has a creamy appearance. The cutter penetrates easily and does not squeak.

In the laboratory, the selected cuttings were made with a binocular and trinocular loupe. It resulted in the nature and shape of the crystals, the mode of arrangement, but also on the specificity of the color of each crystal of salt (inclusions).

- Description of carrots

In the field, the determination of the salts obeyed the same criteria described during the study of the cuttings. In this study, we defined the vertical organization of the deposits (sequences) at the core scale. Attention has been paid to the identification of each layer of salt, emphasizing the sedimentary figures (the stratifications) and the petrography of each layer of salt (the structure and nature of the cement), based on the nomenclature of Folk and Dunham [16].

The definition of the carnallitite potassium evaporitic megasequences was made at the scale of each well. Each megasequence has been transformed into an evaporitic cycle which itself is a consequence of tectonics, based on the work of [5] [6] [12] [13] [14].

In the laboratory, the same studies were refined on photographs of the carrots selected on an HP computer.

4. Results

4.1. Lithologically and Petrographically

The lithological and petrographic studies of the different layers of salts from the three wells have shown the characteristics of each salt but also of the vertical organization of the deposits of these salts which are organized into megasequences of potassium evaporitic with carnallitite. Each megasequence is marked by a basal layer of milky white halite-bedded clay overlain by a finely bedded halite layer that contains millimeter-scale rhythmic elemental sequences and is terminated by layers of macrobrecciated carnallitite. Some megasequences are overlain by layers of microbrecciated carnallitite with beds or layers of tachyhydritite. These megasequences characterize the confined lagoon. In the case of the open lagoon, the finely stratified character of halite is replaced by the massive and bedded character, while the carnallitite remains massive. This study defined two sedimentary assembly:

- a lower assembly with an average thickness of 350 m subdivided into two units: the lower unit consists of megasequences which present at the base, a layer of black clay sometimes rich in bitumen, with continuous or discontinuous passages or halite beds. These megasequences are terminated by a succession of finely stratified and rhythmic halite-like elementary sequences, overlain by a layer of macrobrecciated carnallitite. Macrobrecciated carnallitite layers consist of irregular polygonal carnallitite phenoclasts (intraclasts) with macrocrystalline carnallitite matrix and macrocrystalline halite cement (**Figure 3**). Their structures are wackestone, close to packestone.

The layers of halite are finely layered and rhythmic. This stratification is marked by an elementary two-bed sequence: a milky white halite bed at the base, surmounted by a translucent halite bed, 1 mm to 3 cm thick. It is delimited by two stratification surfaces (basal and summit) of anhydrite and/or clay of variable color, yellow, gray or black, of the same orientation as the stratifications, 1 mm to 3 mm thick. These regular stratifications are either tabular (**Figure 4(A)**), subtabular to oblique (**Figure 4(B)**) or concentric (**Figure 4(C)**).

In some megasequences, these finely stratified halite layers alternate with macrobrecciated halite layers with polygonal halite-matrix intraclasts and clay and/or anhydrite cement (**Figure 5(A)** and **Figure 5(B)**).

The upper unit consists of the same megasequences described in the lower unit, except that they end in a succession of rhythmic elementary sequences of the type layer of red microbrecciated carnallitite at the base, surmounted by a layer or bed of colored tachyhydritite honey or pale yellow (**Figures 6(A)-(C)**). The thickness of each megasequence can reach 65 m. Some microbrecciated carnallitite layers and tachyhydritite layers or beds exhibit dissolution zones (**Figure 6**).

- An upper assembly with an average thickness of 390 m, which is organized into a lower unit and an upper unit. The lower unit presents the same lithological and petrographic characters of the megasequences of the lower unit of the lower assembly. The upper unit is marked by a succession of megasequences, each of which begins with a layer of clay with beds of milky white halite rich in organic matter. This clay is surmounted by a succession of elementary rhythmic sequences of the bedded massive halite layer type (**Figure 7(A)**), surmounted by a massive carnallitite layer (**Figure 7(B)**). The layers of halite thicken more and more towards the top of this unit to the detriment of the layers of carnallitite whose thickness gradually decreases to end in beds or crystals towards the top. Each bedded massive halite layer also presents a succession of elementary rhythmic sequences of the massive layer type of milky white halite at the base, surmounted by a layer of translucent halite (**Figure 7(A)**). In well 2, the megasequences have a condensed character. The uppermost megasequence has a layer of microbrecciated carnallitite with tachyhydritite beds, containing dissolution zones. Each megasequence can reach a thickness of 105 m.

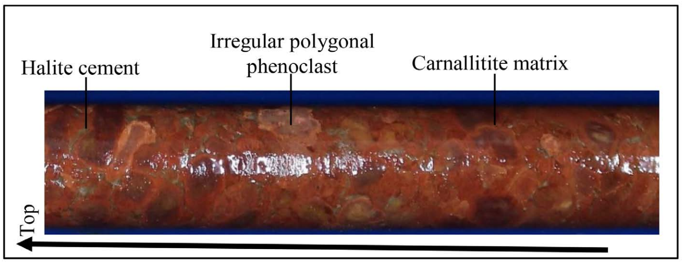

Figure 3. Macrobrecciated carnallitite facies with polygonal intraclasts, macrocrystalline carnallitite matrix and macrocrystalline halite cement.

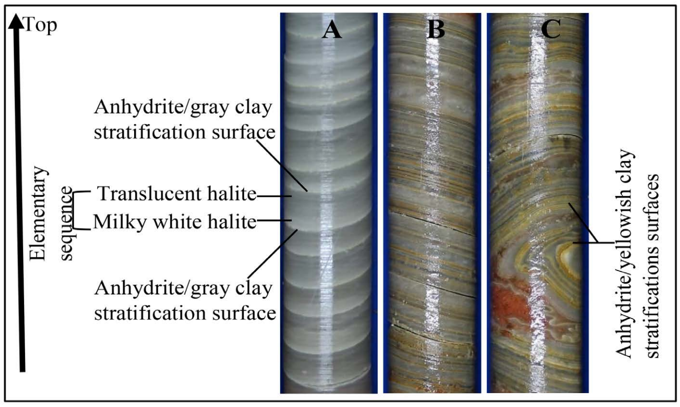

Figure 4. rhythmic halite facies. (A): With tabular stratifications; (B): with subtabular to oblique stratifications; (C): with concentric stratifications or contournites.

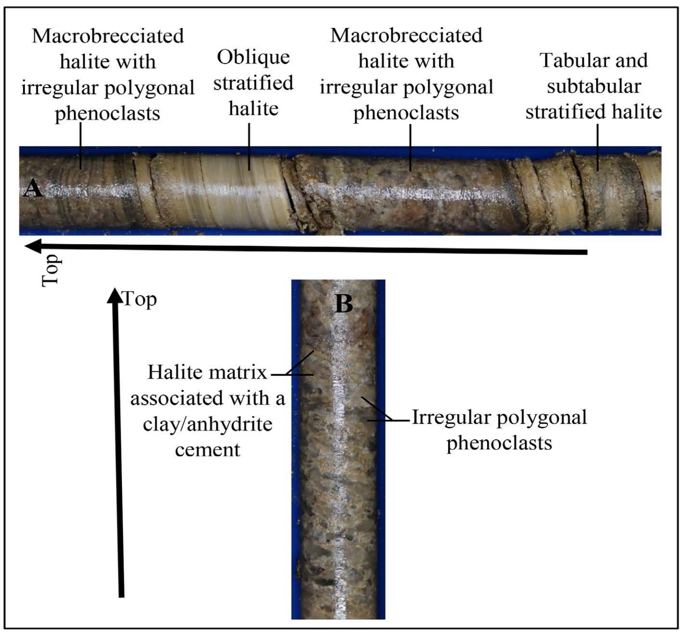

Figure 5. Macrobrecciated halite facies. (A): Alternation between stratified halite layers, with macrobrecciated halite layers; (B): macrobrecciated halite with polygonal intraclasts, halite matrix and clay and/or anhydrite cement.

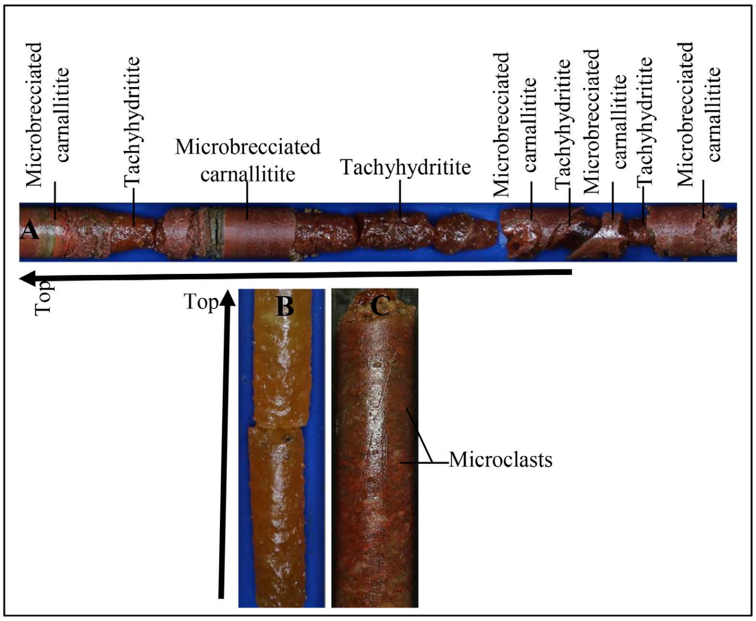

Figure 6. Microbrecciated carnallitite facies with tachyhydritite beds. (A): Elementary rhythmic sequences of the layer type of microbrecciated carnallitite at the base, surmounted by a layer or bed of honey-colored tachyhydritite; (B): a layer of pale yellow tachyhydritite; (C): a layer of red, matrix microbrecciated carnallitite.

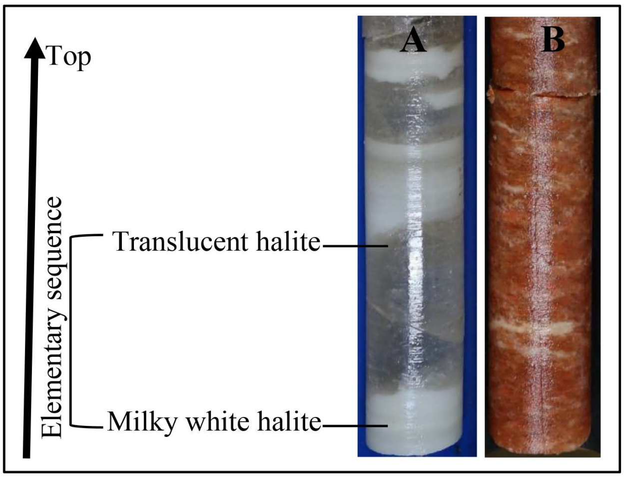

Figure 7. Massive halite and carnallitite facies. (A): Bedded halite, made up of a succession of elementary rhythmic sequences of the type: layer of milky white halite, surmounted by a layer of translucent halite; (B): red carnallitite.

This vertical organization of the deposits of these salts from three Kanga wells is summarized in Figure 8 below.

4.2. Morphoscopically

Morphoscopically, the massive or brecciated layers of carnallitite are essentially made up of pseudo-hexagonal crystals. The bipyramidal crystals are the most

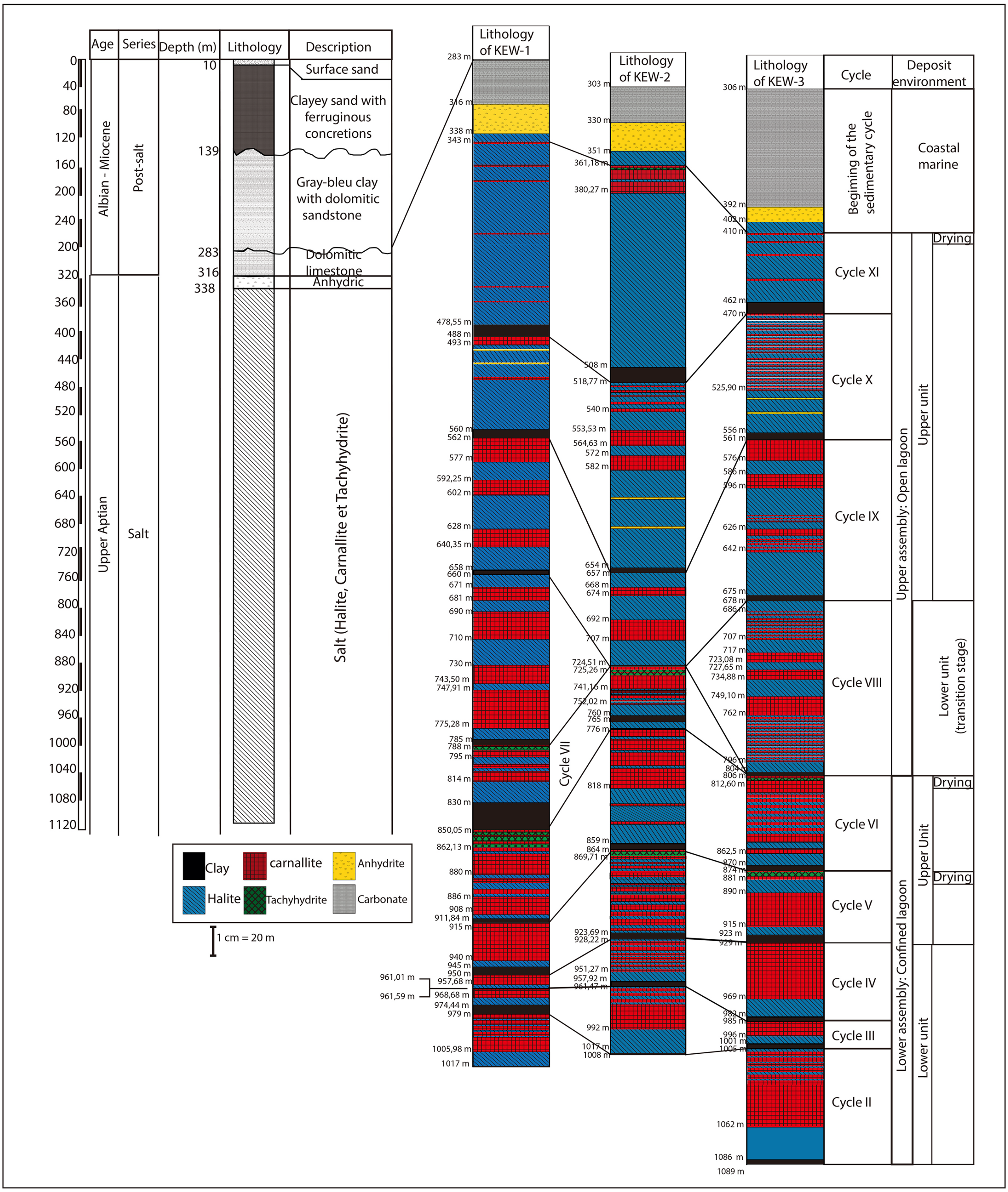

Figure 8. Lithostratigraphic logs and potassium evaporitic megasequences from the three Kanga drill holes (KEW-1, KEW-2 and KEW-3).

abundant and are glued and parallel two by two. Their mode of arrangement is on their rectangular faces (**Figure 9(A)**). Their growth is by aggradation. Orthogonal crystalseach consist of a pyramid crystal which grows on the rectangular faces of the bipyramid crystals (Figure 9(B) and Figure 9(C)). The sizes of these crystals are millimeters to centimeters. The presence of isolated bipyramid crystals is also noted (Figure 9(D) and Figure 9(E)).

All the crystals are translucent, the red appearance of carnallite in most cases is linked to the presence of a ferri-humic cortex which envelops the centimetric crystals. The millimetric crystals remain translucent.

Halite crystals are also translucent. They turn milky white when they contain clay impurities. Their mode of growth is marked by a basal carpet made up of barely visible crystals, thus giving the milky white character to the halite. It is on this carpet that we observe a succession of more and more visible crystals, more and more translucent but also less and less milky white. It is on the latter that the centimetric crystals grow (Figure 10(A) and Figure 10(B)).

In some samples of cores (Figure 11(A)) and cuttings (Figure 11(B) and Figure 11(C)) crystals soaked in bitumen were observed.

4.3. Results Analysis

The vertical organization of the Loemé salt formation in the Kanga sector presents a succession of megasequences, each of which begins with a basal layer of clay with beds of halite surmounted by a layer of finely stratified halite (Figure 4) which in some cases in its upper part is marked by a layer of macro-brecciated halite (Figure 5). This layer of halite is overlain by a layer of macro-brecciated carnallitite (Figure 3). The same megasequence shows in its upper part

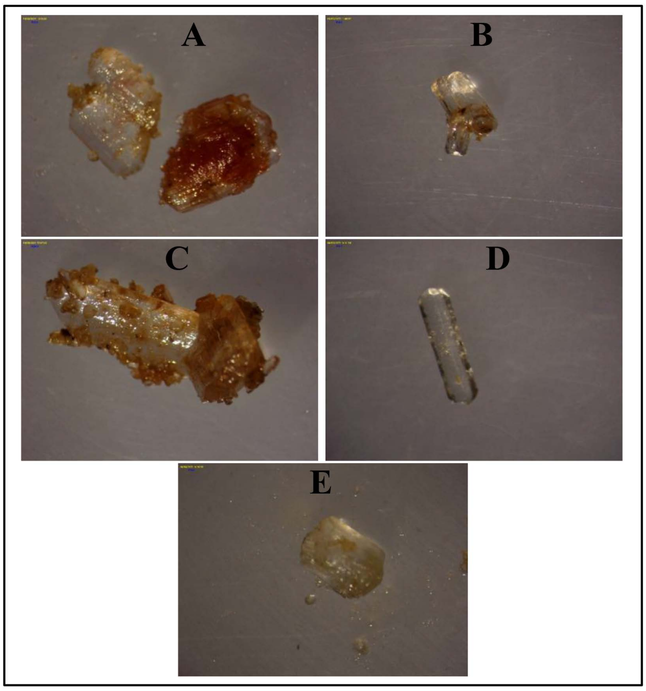

Figure 9. Translucent pseudo-hexagonal carnallite crystals, sometimes partly coated by red humic iron. (A): Two-by-two parallel bipyramids; (B) and (C): orthogonal; (D): bipyramidal crystal; (E): bipyramid and stocky crystal.

Figure 10. Halite fragments. (A): Halite fragment containing a large translucent cubic crystal; (B): massive halite fragment with visible cubic crystals, with the presence of bitumen.

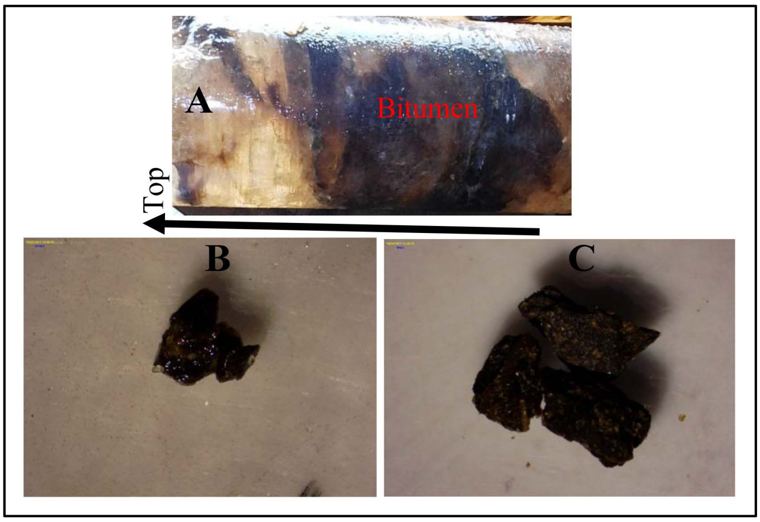

Figure 11. Salts impregnated with bitumen. (A): Translucent halite core; (B): carnallite crystals; (C): fragments of halite.

a succession of elementary rhythmic sequences of the type layer of halite on layer of carnallitite. The analysis of these megasequences allowed them to be transformed into evaporitic potassium cycles with carnallitite. This definition took into account our methodology which retained each layer of clay as the base of the evaporitic cycle and which ends with the uppermost layer of carnallitite.

The definition of these cycles led to the definition of the potassic carnallitite lagoon. The finely stratified structure of halite shows that the brine in which these salts precipitated is relatively stable. The macrobrecciated character of certain upper layers of halite and layers of carnallitite shows that these deposits evolved into beds and crusts of salts affected by a network of shrinkage cracks. This evolution in salt crusts showed the presence of a basin with low water recovery which experienced episodes of drying out following its exposure to sunshine in a hot and arid climate. The presence of microbrecciated carnallitite layers with beds or tachyhydrite layers at the tops of certain megasequences marks stages in the complete drying of this lagoon. These breccias reflect a reworking of these crusts by the waves linked to the coastal winds in the breaking zone where the polygonal fragments have been accumulated in the form of underwater cords.

These hydrodynamic conditions reflect a basin with low water recovery, the base of which is a very wide and extensive plateau, an area where the water depth is less than 10 m. The rhythmic character of the finely stratified halite layers which are organized in elementary sequences of the type bed or layer of milky white halite surmounted by a bed or layer of translucent halite as well as the rhythmicity of the elementary sequences of the type layer of halite on carnallitite layer that characterize these megasequences reflect tectonosedimentary deposits. They are the consequence of the collapse, based on the work of [5] [6] [12] [13] and [14].

The great thickness of these salt deposits, around 800 m, reflects the subsiding nature of the basin. There are 11 successive megasequences which correspond to 11 carnallitite potassium evaporitic cycles which justify the particular conditions of the formation of carnallite throughout the functioning of the lagoon in our study area (**Figure 8**).

The first cycle enabled the establishment of a halitic basin in which the deposit consists of a basal layer of clay with beds of halite, surmounted by a successionelementary rhythmic sequence of the milky white halite bed type, surmounted by a translucent halite bed. Each elementary sequence is delimited by an anhydrite lamina (**Figure 4**). The succession of these halitic sequences is the result of the arrival of turbid water in the basin following the first collapse followed by its aftershocks. The milky white halite results from the precipitation of cloudy halitic brine rich in less dense clay in suspension on the other hand. The translucent halite precipitates as soon as this brine becomes more and more limpid. It is in this context that we will explain the great regularity of these stratifications throughout the halite deposit, which justifies the relative stability of the brine.

Three basic halitic sequences were set up, of the clay layer type at the base, surmounted by a layer of stratified halite and which are the consequence of two collapses. The sudden change from the upper layer of halite to a layer of carnallitite marks the instantaneous evolution of this halitic basin into a carnallitite basin. This abrupt evolution is the prolonged exposure of the last slice of clear halitic water (residual halitic brine) to the sunshine favoring its evaporation. The intensification of its evaporation will be accelerated by its homogenization following the action of the waves linked to the winds. This strong evaporation is accompanied by its sudden saturation in potassium and magnesium to evolve into carnallitite brine favorable to the precipitation of carnallite crystals ($KClMgCl_2{\cdot}6H_2O$) thus obstructing the fossilization of sylvite (KCl). This sylvite acted as a catalyst to facilitate the precipitation of carnallite. This carnallitite deposit will evolve into beds, then into salt crusts affected by a network of shrinkage cracks, which mark a momentary drying up of the basin. These shrinkage slots will be reworked and accumulated in the form of subaquatic allochemical gravelly cords by the successive breaking of the waves in the depths of less than 2 m.

The appearance of these ridges at the same depth of the different wells of Kanga clearly demonstrates that this basin evolved on a very wide plateau, affected by several successive surges whose depth is less than 10 m. The existence of the rhythmic elementary sequences of finely stratified rhythmic macrobrecciated halite-carnallitite which succeed each other after the emplacement of the first layer of carnallitite marks the desalination of each carnallitic brine into halitic brine after each aftershock of the collapse. The presence of milky white halite beds of millimeter to centimeter thickness shows that the settling rate of the clays in suspension in this turbid halitic brine is slow. It is in this context that we have integrated each layer of halite-bedded clay, as part of the onset of turbid halitic sedimentation that marks the beginning of the carnallitite evaporitic cycle. Four evaporitic cycles with macrobrecciated carnallitite have been counted (cycles I to IV), each of which marks a renewal of water in the basin following the collapse. They constitute the lower unit of the confined lagoon (**Figure 8**). The presence of oblique and tabular stratifications in the finely stratified, rhythmic halite layers (**Figure 4**) demonstrates that these halite salts evolved by progradation and aggradation.

From cycle V to VII, the last deposit of carnallitite is structured by a succession of elementary rhythmic sequences of the microbrecciated carnallitite type surmounted by a layer or bed of tachyhydritite (**Figure 6(A)**). This rhythmic character of this deposit can result momentarily in a saturation of the residual carnallitic brine with calcium to quickly evolve into tachyhydrite brine which ends up precipitating. The residual tachyhydrite brine after precipitation of the tachyhydrite will become depleted in calcium and then in turn will rapidly evolve into carnallitic brine.

It is not a question of a successive desalination of the carnallitic and tachyhydritic brines but rather of a desaturation with each episode of the precipitation of tachyhydrite which uses the maximum of calcium present in its brine. This is what creates each time a deficit of calcium in the residual brine post-precipitation of the tachyhydrite and this reaction is reversible. The microbrecciated character of this carnallitite deposit is a consequence of the crumbling of the shrinkage cracks. This crumbling is a marker of the exposure of the salt crusts to sunshine for a very long time in a climate that is becoming increasingly hot and arid. The existence of tachyhydrite layers in the microbrecciated carnallitite deposits marks the filling and complete drying of the confined lagoon basin. Two successive dryings have been recorded which mark the end of the functioning of this confined lagoon. These cycles constitute the upper unit of this lagoon (**Figure 8**). The structure of brecciated carnallitite and brecciated halite is wackestone close to packestone. Halitic breccias consist of a matrix of halite associated with clay. This consolidation was done by cementation, that is to say the subaquatic halitic gravelly cord will be cemented by interstitial turbid halitic brine which is rich in clay, hence the notion of matrix. On the other hand, the cementation of the bead of the carnallitite was done in two phases. A primary phase where the interstitial carnallitite brine to precipitate into the pores to form the carnallitite matrix. The second phase consists of the new cloudy halitic brine which invades the basin and fills the interstitial spaces not cemented by carnallite. These interstitial spaces which are cemented by clay and halite constitute the secondary phase of this cementation. Consequently, the wackestone structure close to packestone shows that the subsiding character of the basin had no impact on the diagenesis of these salts.

Cycle VIII marks the beginning of the opening of the potassic carnallitite lagoon to the sea. It is a transitional episode, as it is made up of a megasequence which recalls those of the lower unit of the confined lagoon. The basin gradually opens by the successive installation of carnallitite potassium evaporitic megasequences in which the halite and carnallitite layers are all massive and bedded for the halite layers during cycles IX to XI (**Figure 7(A)** and **Figure 7(B)**). The evolution of these deposits is marked by a progressive thickening of the layers of halite to the detriment of those of carnallitite towards the end of the operation of the lagoon. In the uppermost part of these deposits, the layers of carnallitite gradually thin out into beds and crystals (**Figure 8**).

This situation was observed in all three wells. It therefore translates the installation of an increasingly stable halitic brine which is increasingly long in time, which is the consequence of the periodic arrivals of sea water through the channels by the waves resulting from the tide but also coastal waves linked to the winds. Each arrival of water triggers a desalination of the carnallitic brine which will rapidly evolve into halite brine. This phenomenon will gradually intensify towards the end of the operation of the open lagoon. This intensification results in a gradual decrease in the thickness of the layers of carnallitite in favor of those of halite. The shallow nature of this basin indicates that despite its large size, its progressive opening to the sea which results in an increasingly massive arrival of water but which will spread and dissipate over the entire basin. The persistence of this basin with low water recovery and which continues to evolve in a hot and arid climate still retains the lagoon character and is favorable to the precipitation of carnallite. The presence of a top layer of microbrecciated carnallitite with tachyhydrite beds at the level of well 2 marks the drying up of this basin in the upper zones and therefore the end of the functioning of this potassic carnallitite lagoon (**Figure 8**). This lagoon will then evolve into a coastal sea favorable to the precipitation of anhydrite and reef carbonates.

Morphoscopically, the detailed description of the halite fragments (**Figure 10(A)** and **Figure 10(B)**) showed the evolution of the crystallization of halite salts in several successive stages. This begins first with the crystallization of small cubic crystals on a millimeter scale while the halitic brine undergoes the settling of the clay. The turbidity of the halitic brine is an unfavorable factor for the growth of these crystals, because the cubic phenocrysts are translucent and have crystallized while the halitic brine becomes clear. The halite crystals are organized in a carpet of successive crystals. The first massive milky white halite carpet is made up of small crystals that are difficult to identify with the binocular and the trinocular. They were put in place when the decantation started, which is an environment that is not favorable to the development of these crystals. All halite crystals, whatever their size, are all cubic and superimposed on each other, thus forming a succession of mats which correspond to a succession of generations of crystals ranging in size from millimeters to centimeters. This vertical organization at the scale of the crystals, which is marked by the aggradation of these, marks the elementary sequence of the layer of finely stratified halite in the deposits of the basin during the confined phase and even of the massive and bedded character in halite layers during the open phase. This elementary sequence observed at the crystal scale confirms the mode of sedimentation of the halitic brine in this shallow basin set up by the aftershocks of each collapse.

Carnallite crystals of millimeter to centimeter size are also organized vertically in mats as described for halite. This organization is the result of long exposure of the clear carnallitic brine to sunlight. The basal carpet of millimetric carnallite crystals but already identifiable with a binocular magnifying glass rests on the top carpet of centimetric halite crystals. The crystals that form in this brine are pseudo-hexagonal bipyramidal parallel two by two and their arrangements are made on the rectangular faces (110). Their mode of fixing on each support is done by one of the pyramid bases. Their mode of growth makes them unstable to the action of the waves, which easily overturns them. This new lying position allows the new generation of crystals to have as their base the rectangular surface or surfaces of the two reworked crystals. It is under these conditions that orthogonal crystals are formed. The presence of these crystals in the layers of carnallitite confirms that this lagoon basin was affected by the waves, particular conditions very favorable to the precipitation of carnallite. The red coloration of these crystals is linked to the presence of the ferri-humic cortex which precipitates on these crystals. This complex confirms the oxidizing nature of our basin which is affected by the waves. The hydrodynamic conditions of this basin are favorable to sedimentation by precipitation of these salts which are primary.

5. Discussion

The sequential analysis as well as the geodynamic and sedimentation reconstruction of the Kanga salt deposits showed a lagoon basin that evolved in two phases: the confined phase and the open phase. In this basin, the carnallitite potassium evaporitic megasequences have developed. They consist of a layer of clay rich in organic matter at the base, surmounted by several rhythmic elementary sequences of the type layer of finely stratified halite in the confined lagoon basin or of massive and bedded halite in the open lagoon basin. This halite is surmounted by a layer of macrobrecciated or microbrecciated carnallitite in the confined lagoon basin, on the other hand it is massive in the open lagoon basin. These macrobrecciated and microbrecciated carnallitite facies reflect the evolution of carnallitite into beds and crusts of salts on a shallow, wide plateau with an irregular bottom, subject to very significant evaporation and where the winds have gathered the fragments of these crusts of salts in subaquatic allochemical gravelly beads.

These facies described in these megasequences in the area have not been described by [5] [6] in the Sintoukola deposit which is bordering to the north of this study area. The shallow nature of these facies as well as the great thickness of these salt deposits, sometimes reaching 800 m in certain wells, confirms the subsiding nature of this basin. [2] [13] [17] [18] [19] [20] [21] confirm the subsiding nature of this basin, but the mode of emplacement and its evolution in a geodynamic and sedimentation context has not been addressed by these authors. [22] [23] [24], dismiss this subsiding character of the Congo and Gabon basins, because for them, the sedimentation rate which is 5 mm/year in these basins is much higher than that of rifting which is 1 mm/year and defines a deep basin.

The bischofite layers that overlie carnallite in cycle V and sylvinite in cycle VII described by [5] [6], in the Sintoukola permit, have also been described by [8] [13] [14] [21] [25] [26] [27] [28], in certain cycles of the mine of Holle, were not identified along the sequences of our wells either in the confined lagoon basin or in the unconfined one.

The evaporitic cycles described in our zone are potassic to carnallitite, and always begin with a layer of clay surmounted by a succession of elementary rhythmic halite-carnallitite sequences, and each cycle is the consequence of a collapse. We noted 11 successive potassic to carnallitite evaporitic cycles during the entire operation of the lagoon. [5] [6] who worked on the Sintoukola permit counted seven potassium evaporitic cycles without characterizing them by grouping certain cycles. [8] [13] showed 11 potassium evaporitic cycles without also characterizing them in the Holle mine. This number of cycles does not call into question the normal organization of the deposits which characterizes the lagoon, because certain cycles that we have identified in the Kanga zone have been grouped together in the Sintoukola permit. In our study, the contact between the carnallitite layer and the clay layer with milky white halite beds marks the end of the carnallitite potassic evaporitic cycle and therefore the beginning of the new cycle whatever the thickness of this layer clay.

The structure of the finely stratified halite layers in the confined lagoon basin and in that of the open lagoon basin, present the same lithological characters as those studied by [29] [30] [31], in the Kwanza basin in the south from Angola. On the other hand, these authors did not describe the macrobrecciated character of halite in certain places in the lagoon basin. These structures showed us the nature of the basin with low water recovery characterized by relatively stable halitic and carnallitic brines whatever the importance of the quantity of water which feeds this basin. The facies that we have described of these salts have shown the particular geodynamic and sedimentation conditions as well as the impact of the climate which prevailed during the functioning of this basin but also to justify the preferential crystallization of carnallite. Several levels of salt crusts were temporarily or for a long time dried up during their emersion phases. Three episodes of complete drying of the lagoon basin have been highlighted, which indicates that this basin evolved under a hot and arid climate. This hot and arid character of the climate was also described by [1] [2], who confirmed that the climate was hot and arid in the central segment of the South Atlantic throughout the period from the Aptian to the Albian by modeling.

In our study area, the existence of a sudden saturation of the residual halitic brine into carnallitic brine linked to the geodynamic conditions and sedimentation highlighted in this lagoon basin, did not allow the development of sylvinite brines and bischofite and their fossilization. This hypothesis justifies their absence in this lagoon basin and therefore all the salts described in our sequences are primary. Sylvinite in the Sintoukola mine was described by [5] [6] at the end of cycle VII which is the equivalent of cycle XI in our study area. According to these authors, it is the carnallite present in this cycle, which by diagenesis gave sylvite following the hydrothermal waters which migrated through the normal faults and which came to alter these carnallite horizons. This hypothesis had also been put forward by [7] in theCongo Basin. In our study area, the drillings of the three wells crossed fault zones marked by layers of halite and carnallitite soaked in bitumen oil (**Figure 11**). These faults were rather zones of migration of hydrocarbons towards the post-salt littoral carbonates which were transformed into structural traps [8],

The facies of certain layers of carnallitite bearing signs of dissolution, especially in the beds or layers of tachyhydrite in the levels where the carnallitite has been completely dried up in the confined lagoon basin and in the open lagoon basin, clearly shows that this dissolution is only accidental following the use of poor quality drilling mud. On the other hand, if this dissolution was linked to hydrothermalism, we should have encountered levels of sylvinite by correlation with these dissolved salts both in the confined lagoon and in the open one. For [8], the sylvinite in the evaporitic basin of the Congo is of secondary origin, it would come from the weathering of carnallite by water. [9], confirm this hypothesis. For these authors, the sylvinite at Holle, which was located along the flanks of the anticlines, the summits of which were truncated by the erosion preceding the transgression and the deposit of anhydrite, justifies the diagenetic character of this salt. In our study area, we did not observe the existence of the truncated summit carnallitite of the condensed facies of well 2. On the other hand, we note the presence of a summit layer of microbrecciated carnallitite with tachyhydrite which marks the end of cycle XI which is the lateral equivalent of cycle VII in the Sintoukola site. This carnallitite marks the drying up of the basin in these high zones and therefore the absence of an alteration phase that affected this layer. This completely dry area was flooded by halitic brine from the beginning of the littoral sea. This transgressive deposit confirms the coastal, very shallow character of a still relatively stable halitic brine which is the consequence of the spreading of these marine waters over a wide and extensive plateau.

The morphoscopic analysis of the carnallite crystals taken from several levels of the carnallitite layers in the two phases of the lagoon basin, are all translucent, pseudo-hexagonal and bipyramidal. Some are glued two by two along the rectangular faces (parallel to each other) and the others are orthogonal. The quadratic and monoclinic crystals described by [32] [33], obtained by crystallization of a carnallitic brine in the laboratory, have not been identified in our carnallitite facies.

6. Conclusions

The lithological and petrographic studies carried out on the logs obtained from the three Kanga permit wells located northwest of Pointe-Noire in the Republic of Congo show a succession of salt layers which are organized into 11 carnallitite potassium evaporitic megasequences. Each sequence begins with a layer of clay with continuous or discontinuous beds or laminae of halite, surmounted by elementary rhythmic sequences of the finely stratified halite layer type, sometimes macrobrecciated in its upper part, surmounted by a layer of macrobrecciated carnallitite. It constitutes the lower unit of the confined lagoon. In its upper unit, the megasequences are terminated by layers of microbrecciated carnallitite with tachyhydrite interlayers.

The open lagoon megasequences show the same organization except that the halite and carnallitite layers are massive and bedded for the halite. There is a progressive decrease in the layers of massive carnallitite which end in beds or carnallite crystals at the end of the operation of the lagoon in favor of the layers of halite. The fine and regular stratifications of the layers of halite show that this halite crystallized in a relatively stable brine. The abrupt transition from layers of halite to layers of carnallitite throughout the basin shows an abrupt evolution from clear halitic brine to carnallite brine.

This abrupt evolution is the prolonged exposure of the halitic residual brine to sunshine in a hot and arid climate favoring its strong evaporation. This strong evaporation is accompanied by its sudden saturation in potassium and magnesium to evolve into carnallitite brine favorable to the precipitation of carnallite crystals ($KClMgCl_2 \cdot 6H_2O$) thus preventing the fossilization of sylvite (KCl). The brecciated facies of the layers of halite and carnallitite present in the confined lagoon determine episodes where these deposits evolved into beds and then into salt crusts. These benches reflect a basin with low water recovery. These facies also show the reworking of these salt crusts by the breaking of the waves linked to the coastal winds which affect the lagoon to form underwater cords. These surges will also cause the homogenization of these two brines to accelerate its evaporation and thus promote the precipitation of carnallite. These surges also reflect that this lagoon evolved on a plateau where the depth of the brine is less than 2 m. the evolution of the salt crust beds affected by a network of shrinkage cracks shows stages of partial drying up of the confined lagoon.

The presence of layers of carnallitite with tachyhydrite which crown the deposits of the confined and open lagoon confirms the stages of complete drying up of the basin and also the end of the functioning of these lagoons in a climate becoming increasingly hot and arid.

The wackestone character close to packestone of these brecciated facies shows that these salts underwent diagenesis by cementation. The rhythmic and shallow character of these deposits as well as the great thickness sometimes reaching 800 m in our study area confirm the tectonosedimentary character of these deposits which evolved in a subsiding basin with low water recovery whose seat is a wide and extended platform.

The morphoscopic study of carnallitite cuttings shows pseudo-hexagonal bipyramid crystals, arranged two by two along rectangular planes and orthogonal crystals, each pyramid crystal of which has rectangular planes of bipyramid crystals as its base. The orthogonal crystals reflect a new generation of crystals after the reworking of bipyramid crystals following the passage of large waves. The red color of these crystals is marked by a ferruginous cortex reflecting the oxygenation of the carnallite brine following the breaking of the waves accentuating its evaporation and therefore the precipitation of the carnallite.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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