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3D Multi-Layer Geological Modeling of the Allou Kagne Attapulgite Deposit (Senegal, West Africa)

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Abstract

The Allou Kagne attapulgite deposit (Senegal) has a complex geological structure characterized by significant lateral and vertical heterogeneity. Conventional two-dimensional approaches cannot accurately represent this variability, hence the need for 3D modeling incorporating the available data. This study therefore aims to construct a reliable geological model to characterize the internal architecture of the deposit. The modeling is based on the integration of field and survey data into GDM Standard software and its Multilayer extension, which specializes in sedimentary sequence modeling. A 3D model was generated from a defined stratigraphic stack, ranging from Paleocene limestone to recent lateritic overburden. The results show the spatial distribution of the four attapulgite facies (ochre, low carbonate, medium carbonate, and high carbonate), revealing significant variations in thickness and erosion phenomena. This model is a valuable decision-making tool for optimizing exploration and rational resource exploitation.

Keywords

Attapulgite, 3D Modeling, MSGBC Basin, Stratigraphic Pile, Optimization

1. Introduction

The study of the geological context of our sector in the Thiès region is part of the geodynamic framework of the MSGBC (Mauritania-Senegal-Gambia-Bissau-Conakry) Atlantic margin basin. The Thiès region is located entirely within the Senegalese Mesozoic-Cenozoic sedimentary basin, covering an area of 6601 km^2. This part of the basin has significant mining and energy potential that could help improve the country's economic situation and the well-being of its people (Thiam, 2016). In the specific context of this study, we will focus on the exploitation of attapulgite.

Attapulgites (or palygorskites) and sepiolites are clays generally composed of fibers ranging from 1 to 3 microns in length. The terms "attapulgite" (from Attapulgus, Georgia, USA) and "palygorskite" (from Palygorsk, Perm Province, USSR) refer to the same type of clay [1].

Attapulgite, a fibrous phyllosilicate with exceptional absorbent and colloidal properties, is a strategic mineral resource for many industries, including pharmaceuticals, cosmetics, agriculture, and petroleum. Senegal, with identified deposits on its territory, has significant potential for exploiting this mineral. Among these, the Allou Kagne deposit, located west of the city of Thiès (**Figure 1**), stands out for its economic importance. However, rational and sustainable exploitation of this deposit is hampered by its intrinsic geological complexity, marked by significant lateral and vertical heterogeneity of the clay facies.

Conventional exploration approaches, based on two-dimensional (2D) geological maps and spot drilling, struggle to reproduce the actual three-dimensional (3D) architecture of the subsurface. These methods provide a fragmented and often insufficient view of layer continuity, thickness variations, beveling, and the spatial distribution of different mineralogical facies. This shortcoming can lead to underestimation of resources, suboptimal mining planning, and uncertainties during exploitation.

In light of these challenges, 3D geological modeling is an indispensable tool. By coherently integrating all field and drilling data, this approach makes it possible to construct an accurate digital representation of the deposit's geometry. 3D geological modeling is based on the explicit definition of the geometry, topology, topography, and physical properties of geological objects, in accordance with the principles established by [2].

It allows for unprecedented visualization and analysis of the spatial organization of geological bodies, transforming the static understanding of the deposit into a dynamic, searchable model. The main objective of this study is to develop a reliable and detailed 3D geological model of the Allou Kagne attapulgite deposit.

The specific objectives were: 1) to integrate and harmonize all available geological and cartographic data; 2) to define a coherent stratigraphic stack reflecting the geological history of the site; 3) to construct a volumetric 3D model characterizing the geometry, distribution, and thickness of the main attapulgite facies (ochre, low, medium, and high carbonate); 4) to provide a decision-making tool for planning and optimizing mining operations.

To achieve these objectives, it is important to have a better understanding of the local geology. The stratigraphy of the area can be summarized as Paleocene to Quaternary outcrops [3]:

- The Paleocene (Ndayane Formation and Poponguine Formation) marked by zoogenic and sometimes karstic carbonate deposits.

- The Lower Eocene (Thiès Formation), subdivided into five members, rests unconformably on the Paleocene [4]. From bottom to top, we note the Yène, Tiémassas, Pointe Sarène, Ravin des Voleurs, and Ngazobil members.
- The overburden consists of Pliocene Quaternary deposits composed of laterite and sand.

This work thus aims to fill a knowledge gap by providing an integrated and quantitative view of the structure of the deposit, forming a solid basis for its economic development.

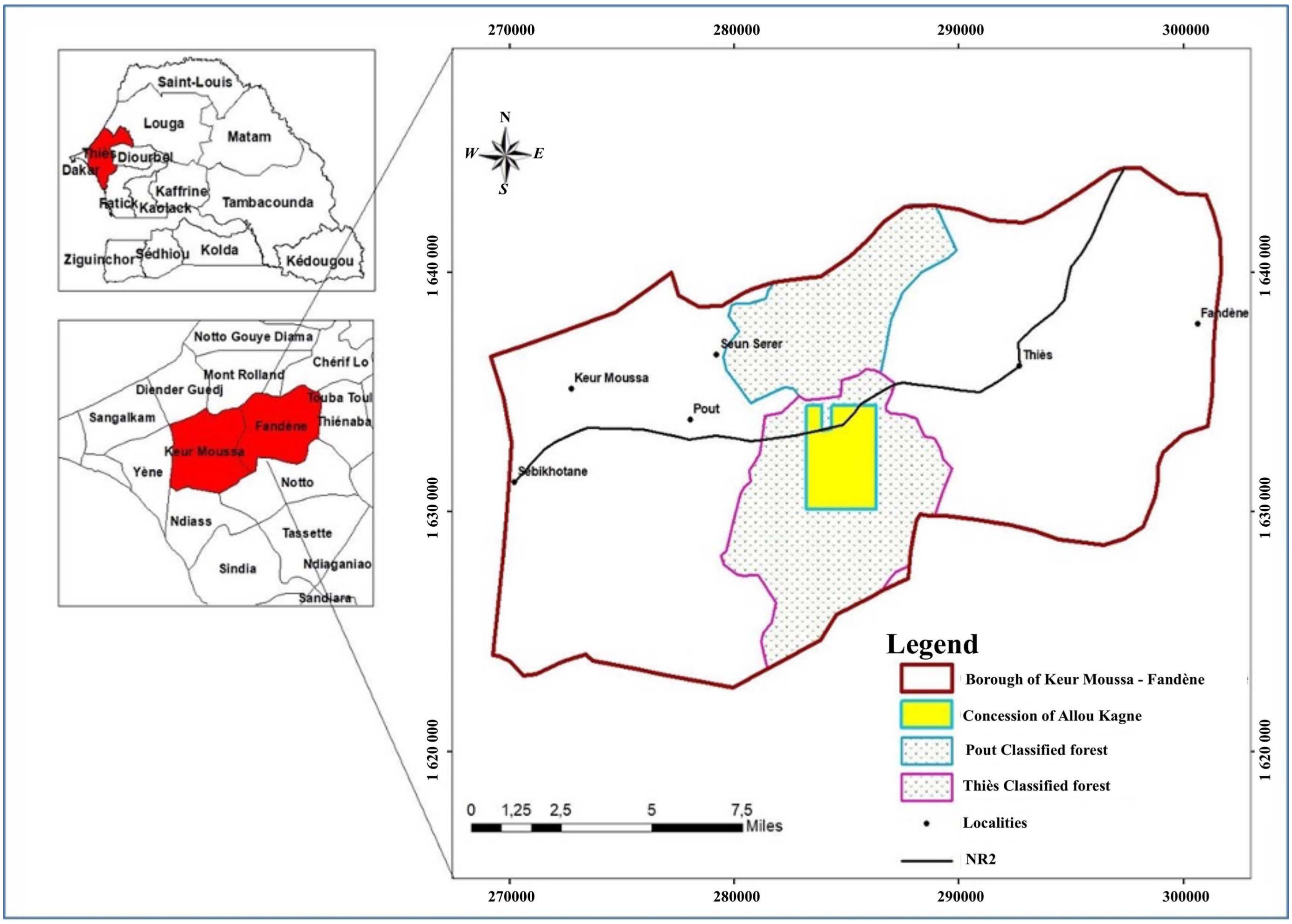


Figure 1. Map showing the location of the study area [5].

2. Materials and Methods

This study adopted a multi-layer modeling approach, particularly suited to sedimentary formations where each geological unit appears only once along a given vertical. This work was carried out using BRGM's GDM (Geological Database Model) software suite, comprising: GDM Standard for the integration and validation of geological data, and GDM Multilayer for the automated construction of multilayer models.

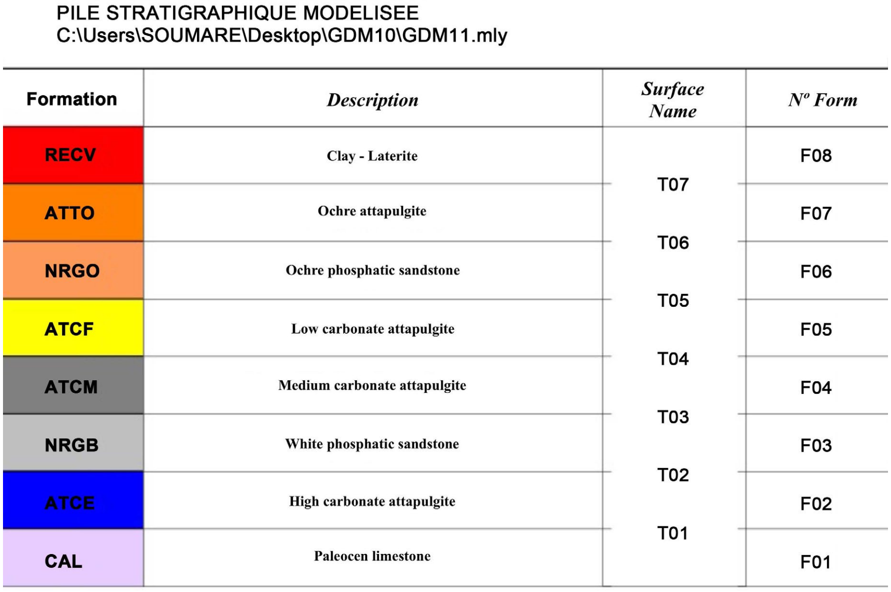
This approach allows sedimentary stacks to be modeled effectively, but has the limitation of not taking into account complex tectonic structures (reverse faults, recumbent folds, thrust faults) that would introduce a reversal in the chronological order of the formations.

2.1. Modeling Methodology

The model was constructed based on two fundamental principles of GDM Multilayer:

2.1.1. Stratigraphic Stack

This concept is fundamental for interpreting the data. The stratigraphic stack describes the chronological order of the succession of formations, specifying the depositional logic and any erosional relationships between two successive formations. The order has been defined from the oldest formation (the Paleocene limestone (CAL)) to the most recent (the cover (RECV)), specifying the erosion surfaces. This organizational logic of the formations allows the software to automatically combine interpolations to construct a topologically correct 3D model. Once the stratigraphic stack of the geological formations to be modeled is defined, model-building analysis tools are retained and can be reused (**Figure 2**). The model can be easily used through the automatic generation of maps, cross-sections, 3D views, and export to various formats.



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Formation	*Description*	*Surface Name*	*N° Form*
RECV	Clay - Laterite	T07	F08
ATTO	Ochre attapulgite	T06	F07
NRGO	Ochre phosphatic sandstone	T05	F06
ATCF	Low carbonate attapulgite	T04	F05
ATCM	Medium carbonate attapulgite	T03	F04
NRGB	White phosphatic sandstone	T02	F03
ATCE	High carbonate attapulgite	T01	F02
CAL	Paleocen limestone		F01

Figure 2. Stratigraphic stack of modeled formations.

2.1.2. Interpolation and Combination of Surfaces

The modeling process consisted of interpolating the various stratigraphic surfaces based on control points obtained from surveys and field observations. These surfaces were then combined according to a predefined stratigraphic logic in order to ensure the continuity and geological consistency of the model. A data coding stage enabled the interfaces to be modeled (layer boundaries, discontinuities, erosive contacts, etc.) to be identified and characterized. Finally, a rough model grid was generated and then refined to produce a final model grid, incorporating the surfaces and thicknesses corrected after cutting and stratigraphic adjustement.

3. Results

Figure 3 shows the position of the geological sections created in the model at the Allou Kagne study area. The 3D model generated confirms the heterogeneity and stratigraphic complexity of the Allou Kagne deposit.

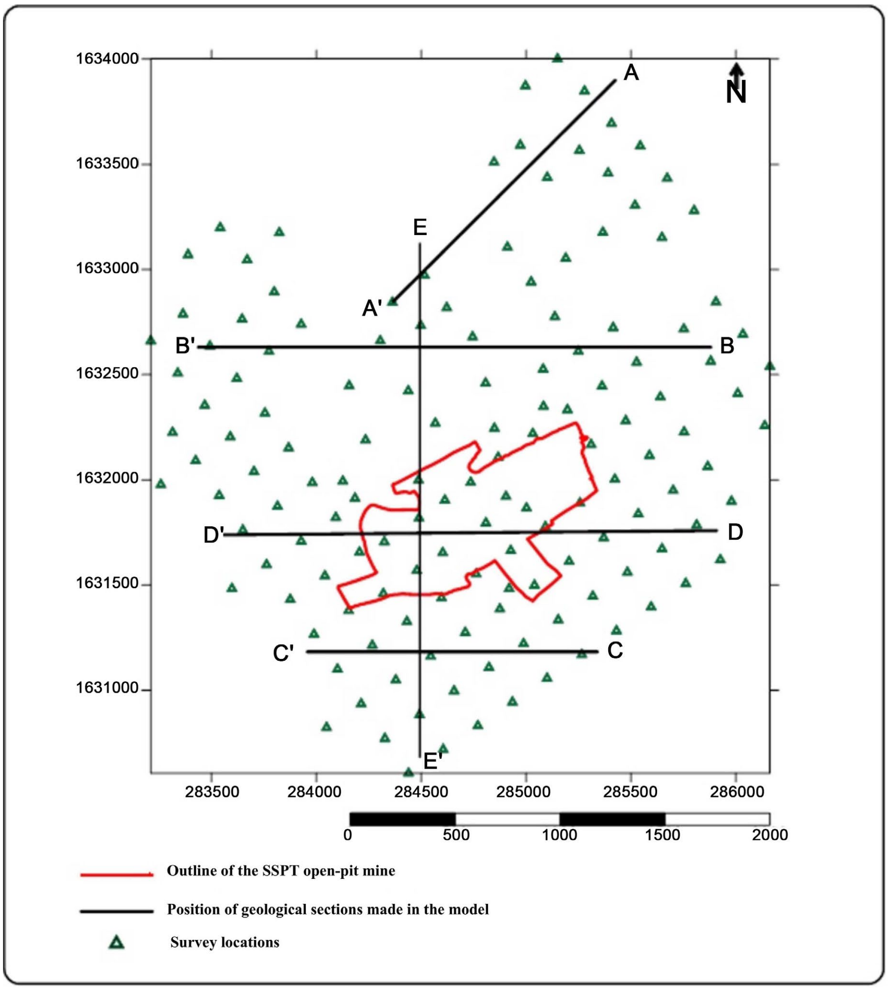

Figure 3. Map showing the locations of geological sections in the study area.

3.1. Analysis of Vertical Sections

- **Vertical section AA'**

Vertical section AA' was made to the north of the Allou Kagne mining concession and runs NE-SW. Above the limestone at the base of the section, the ochre-colored attapulgites are more than 20 m thick, with this thickness decreasing towards the southwest. Low-carbonate attapulgites are found in the center of the section. We noted a greater thickness of medium-carbonate attapulgites in the SW. This section shows the heterogeneity of the Allou Kagne attapulgite deposit and the frequency of bevelling.

- **Vertical section BB'**

Vertical section BB' was made south of section AA'. It is located north of the SSPT open pit mine and runs east-west. This vertical section shows a thick layer of attapulgite to the east. The attapulgite ore is therefore more than 35 m thick in this area. The thickness of ochre attapulgite, high-carbonate attapulgite, and medium-carbonate attapulgite decreases laterally from east to west (Figure 4). To the west of the study area, there is a thick overburden layer (clay, laterite, and sand).

- **Vertical section CC'**

Vertical section CC' was made south of the SSPT open pit mine. The SW is characterized by a thick layer of carbonate attapulgite (medium carbonate attapulgite and high carbonate attapulgite). In some places in this section, the carbonate ore can reach a thickness of 30 m. To the west, low-carbonate attapulgites still predominate, with a thick layer of lateritic sandy-clay overburden.

- **The DD' vertical section**

The DD' vertical section crosses the SSPT mine and also runs east-west. This section confirms the presence of ochre attapulgites, medium carbonate attapulgites, and high carbonate attapulgites to the east of the study area. Their thickness decreases towards the west, and these attapulgites eventually give way to low-carbonate attapulgites (Figure 5). At the westernmost end of the study area, all boreholes are negative. This disappearance of attapulgites can be explained by total erosion of the ore, leaving laterite in its place.

- **Vertical section EE'**

The last section created in the model runs north-south, crossing the western part of the SSPT open pit mine (Figure 6). Like the other vertical sections created in the model, this section shows the heterogeneity of the Allou Kagne attapulgite deposit, with the presence of several types of attapulgite.

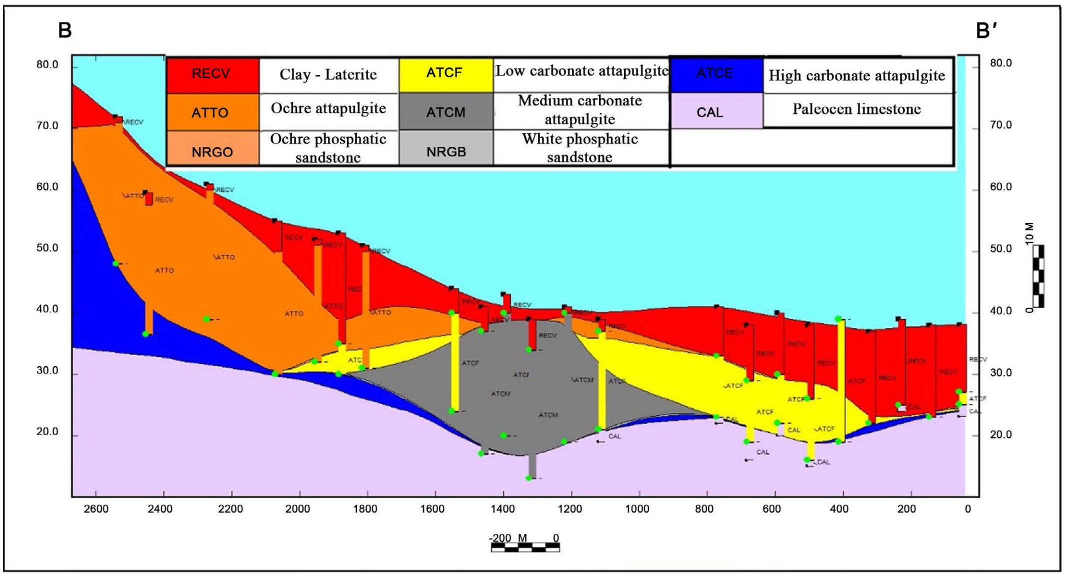

Figure 4. Vertical section BB' in the model.

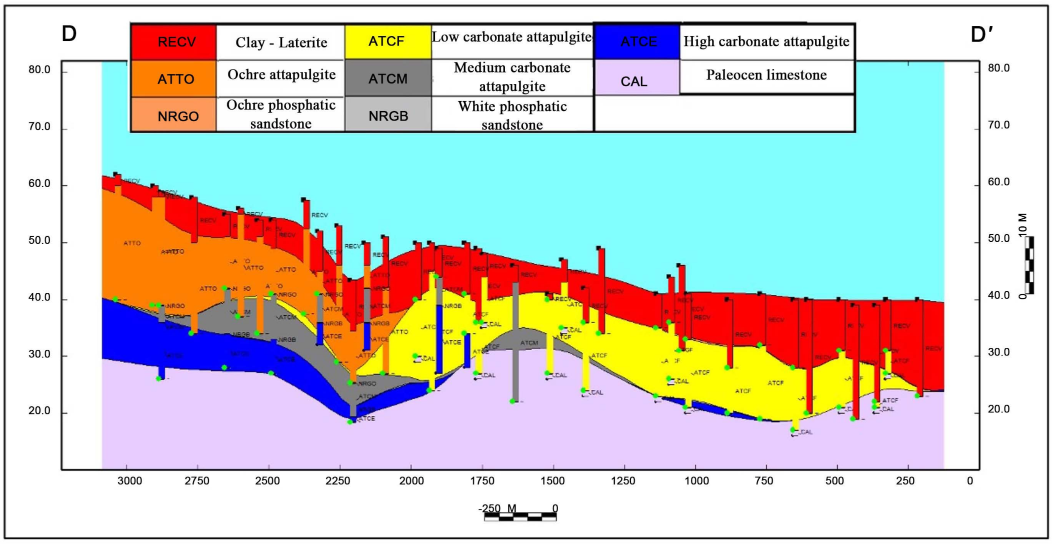

Figure 5. Vertical section DD' in the model.

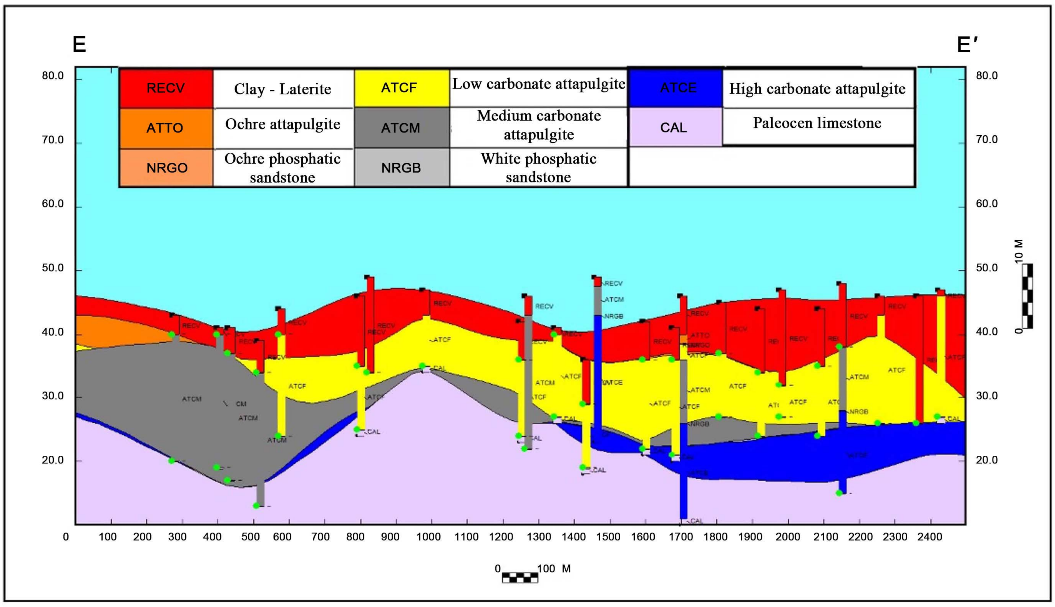

Figure 6. Vertical section EE' in the model.

3.2. 3D Visualization and Spatial Distribution

The 3D visualization of the model allows the spatial distribution of facies to be synthesized: To generate an initial model, the data must first be coded, which involves interpreting the stratigraphic stack to determine the interfaces to be modeled and their nature. Once the coding is complete, the result is added to the MultiLayer tree ("Data coding"), and a new log document is created ("Data coding log").

Next, a raw model grid must be created to store the results of the raw interpolations before the surfaces are cut, and a final model grid must be created to store the final surfaces and thicknesses after the surfaces have been cut. Finally, the various modeled surfaces can be represented in a 3D document in Multiyer.

The eastern part of the Allou Kagne area, located at the foot of the Thiès cliff, is characterized by the presence of a thick layer of high-carbonate attapulgite, and the center of this eastern part of the study area is occupied by ochre-colored attapulgites. There is an absence of low-carbonate attapulgites (**Figure 7**).

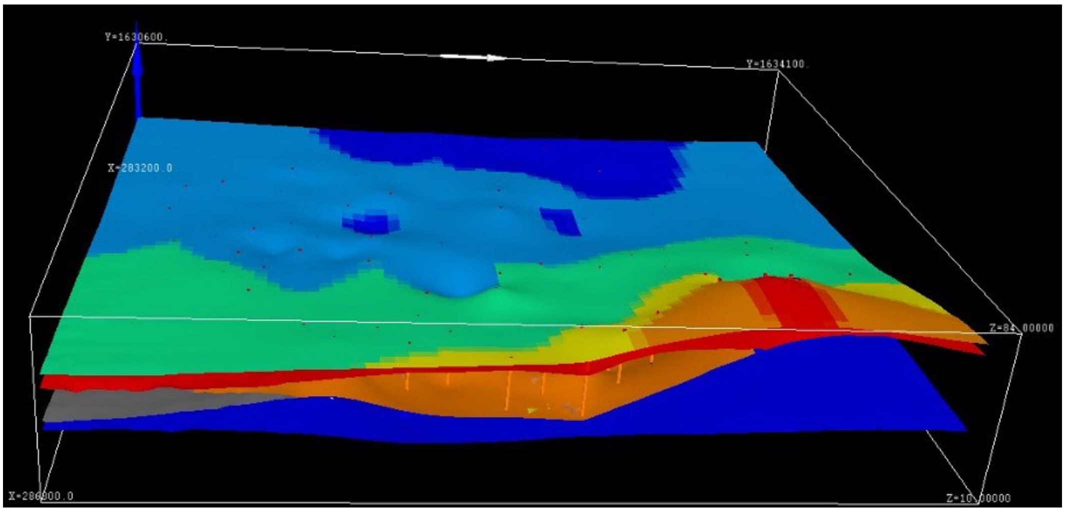

Figure 7. 3D visualization in the model (east side).

On the north side of the model, the deposit shows two parts: to the east of this north side, ochre-colored attapulgites and high-carbonate attapulgites are more dominant, whereas to the west of this north side, the thickness of the attapulgite ore is very low (**Figure 8**).

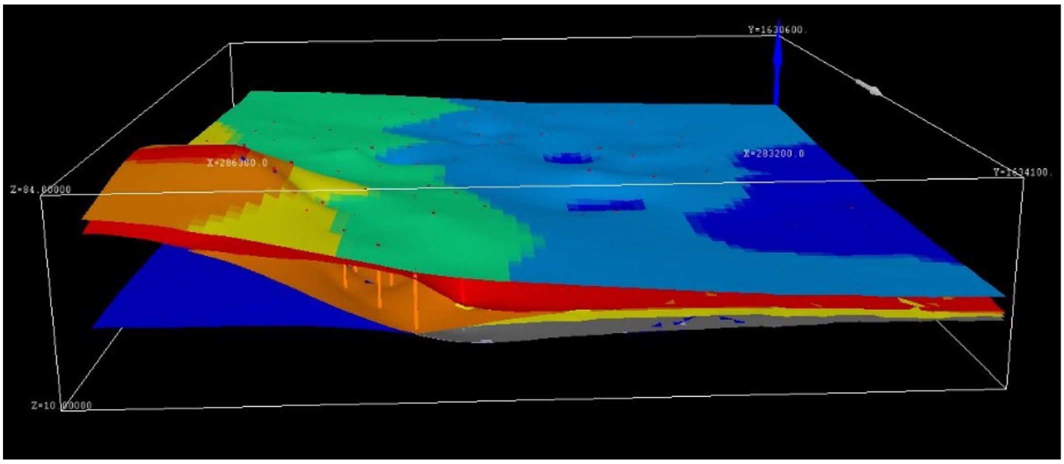

Figure 8. 3D visualization in the model (NORTH face).

The West Allou Kagne sector is characterized by the presence of a thick layer of laterite. It is in this sector that we find low-carbonate attapulgites (**Figure 9**).

The southern area shows the predominance of carbonate attapulgites and the absence of ochre-colored attapulgites, as shown in **Figure 10**.

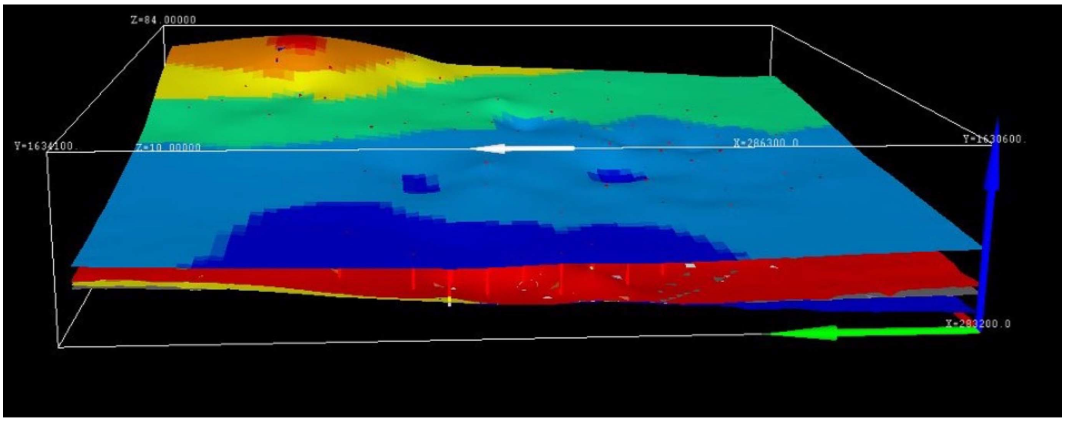

Figure 9. 3D visualization in the model (WEST side).

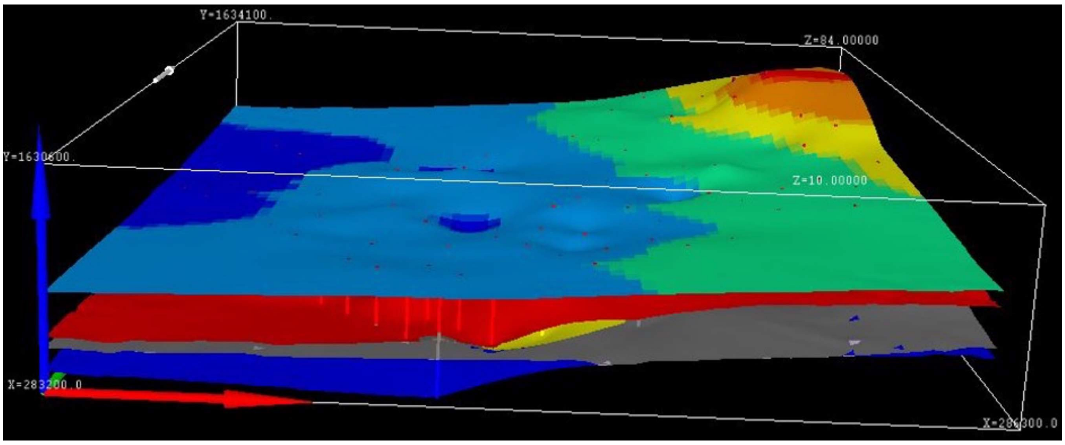

Figure 10. 3D visualization in the model (SOUTH side).

4. Discussions

The 3D geological modeling performed with GDM Multilayer overcame the limitations of 2D approaches by providing a dynamic view of the layer geometry. The stratigraphic stack proved to be a fundamental concept for ensuring the topological consistency of the model, particularly in light of the lateral variations observed.

The heterogeneity of the Allou Kagne attapulgites, notably the coexistence of four mineralogical facies of attapulgite, has major implications for exploitation:

- **Mining planning:**

Accurate knowledge of high-grade zones (over 35 m) and eroded or beveled zones is important for optimizing extraction sequences and estimating reserves. The discovery of total ore erosion in the west and its replacement by a thick layer of lateritic sandy-clay material makes it possible to streamline future drilling programs and avoid unprofitable areas. It also allows for the management of overburden material at the mining permit level.

The study is subject to methodological limitations inherent in the Multilayer model used. The latter, based on a surface modeling approach, focuses exclusively on the geometry of geological interfaces. This feature makes it particularly effective for representing structures composed of subhorizontal sedimentary layers, in accordance with the principles established by [6]. Consequently, its application is optimal in geological contexts characterized by relative tectonic stability, such as the sedimentary formations of the Thiès cliff. However, the model's inability to integrate and simulate major tectonic phenomena (folds, significant faults) is a significant limitation in terms of generalizing its results to more structurally complex environments.

- **Quality control:**

The spatial distribution of the different attapulgite facies is essential for quality control of the ore throughout the production chain. In the western part of the study area, the low-calcium carbonate attapulgites appear monotonously, interspersed with flints that occur as lenticular beds or nodules. The attapulgites are finely bedded and strongly jointed, giving the appearance of crushed rock. These attapulgites occur as a single horizon with a low $CaCO_3$ content, between 0 and 5%.

The $CaCO_3$ content also allows for the distinction of an upper horizon, with $CaCO_3$ levels between 5% and 35%, represented by the medium-calcium carbonate attapulgites, and a lower, highly carbonated horizon, with $CaCO_3$ levels between 35% and 45%, representing the high-calcium carbonate attapulgites [7].

5. Conclusions

This study successfully constructed a robust and topologically consistent 3D geological model of the Allou Kagne attapulgite deposit using GDM Multilayer. The model confirms a complex stratigraphy and high spatial variability in the thickness and facies of the attapulgite ore. The results provide valuable information on:

- The location of areas with high attapulgite thickness;
- The distribution of carbonate attapulgite facies;
- The identification of eroded areas in the west, now occupied by laterite.

This model is an essential mining engineering tool for estimating resources, reducing mining risks, and effectively planning the exploitation of attapulgite in Senegal.

Conflicts of Interest

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

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