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Microfacies Characterization of Calcareous Crusts and Pleistocene Moghrebian Strata in the Coastal Basin of Tarfaya (Morocco): Paleoclimatic and Paleoenvironmental Implications

Fatima Jira* , Abdallah Lakhouili

Hassan First University of Settat, Faculty of Sciences and Techniques Settat, B.P. 577, Settat Morocco

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Abstract

Outcrops of detrital sediments dating from the Moghrebian are found in the coastal basin of Tarfaya in southwestern Morocco. These sediments are still little studied and spectacularly extended and surmounted by a hard crust. Our study will focus on three objectives (1) to characterize the microfacies of Moghrebian sediments and to identify their diagenetic evolution, (2) to reconstruct the modalities of development of superficial crusts, and (3) to elucidate the origin of calcium carbonate in these sediments. The results show that the Moghrebian strata have alternating conglomerate beds, lumachel, sandstone, calcarenite, and a well-developed calcareous crust on the surface. The diagenetic evolution of these facies is very early and is characterized by corrosion and isovolumetric epigenesis of quartz by calcite, particularly in the superficial crust. Clay minerals of detrital origin characterize the fine fraction of these sediments. The oversaturation of the environment with calcium carbonate prompted the development of a crust where fibrous clays are newly formed, which reflects the development of climatic conditions with alternating dry and wet seasons in the basin during the post-Moghrebian period.

Keywords: Moghrebian, newly formed, Tarfaya, epigenesis, Pleistocene

1. Introduction

The reconstruction of ancient environments can be revealed by analysing limestone crust deposits and their clay mineral content. For this, there is growing interested in crusts due to their significance as a referential for the reconstruction of the ecosystems and environments of the ancient environment, as well as the tectonic, weather patterns and the sedimentary conditions in which they were formed [1] [2] [3]. Crusts also carry significant information on the ancient climate's physical, biological, and chemical activities. On the other hand, the clay mineralogy of sedimentary successions provides important insights about continental weathering conditions and climate control. The use of clay minerals as a paleoclimatic indicator is somewhat limited, most likely due to the limited preservation of ancient sedimentary successions little affected by changes during diagenesis and metamorphism [5] [6] [7]. Within the less-weathered rock record, however, Clay mineral assemblages can provide valuable indicators of changing continental weathering regimes to determine the source of the sediments [8] [9]. Biodetritic series of marine and continental origin comprising conglomerate, sandstone, lumachel, and calcarenite beds and a well-developed calcareous crust on the surface [10] characterized the Moghrebian strata in the Tarfaya coastal basin. These sub-horizontal series are unconformably underlain at most sites by extensive

*Email: fatima.jira@uhp.ac.ma

Cretaceous marl, except in a few places in the southwestern part of the basin where the Moghrebian series overlies the Pliocene sandstones. Based on lithological and paleontological comparative data [10] and palynological determinations [11]. This series was assumed to be lower Pleistocene in age. The development of a calcareous crust at the top of the biodetritic series gives it the name Moghrebian slab [12].

Moreover, in previous studies, the Tarfaya Basin has been the focus for the reconstruction of biostratigraphy, oxic/anoxic events, and organic geochemical characterization [13] [14] [15] [16] and its references]. Nevertheless, the origin of the high contents of calcium carbonates within the basin and the development of the calcareous crust in the Moghrebian formations have not been addressed by any of these studies.

The present work presents new information on calcium carbonate and clay mineral content, lithology, and microfacies of the Moghrebian strata. These data were analyzed to (1) define the microfacies of the Moghrebian sediments, (2) clarify the evolution of their lithification, and (3) stress the origin of the calcium carbonate and the modalities of calcification of the superficial part of these sediments. As a result, it was possible to reconstruct the climatic and environmental conditions that prevailed in the Tarfaya coastal basin during the post-Moghrebian period.

2. Geographical and geological contexts

The Tarfaya coastal basin is located in southwestern Morocco on the western edge of the Saharan platform between 27° and 29° North latitude and 11° and 13° West longitude. The Atlantic Ocean borders the basin to the northwest and west, the southern Atlas Mountains to the east and southeast, and the Sebkha Et-Tah to the south (Figure 1).

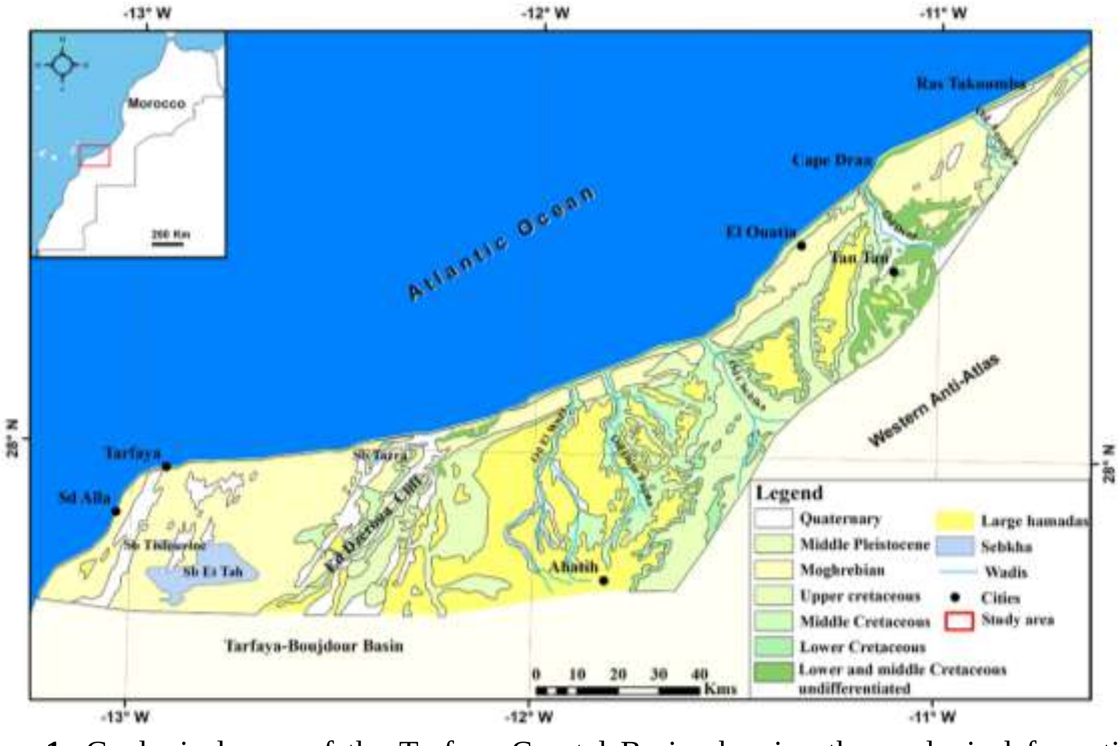


Figure1: Geological map of the Tarfaya Coastal Basin showing the geological formations from Cretaceous to Quaternary (modified after [10]) and the location of lithostratigraphic sections: A: Bou Issafen; B: Aoreora; C: Draa; D: Chebeika North; E: Chebeika South; F: El Waar; G: Sidi Akhfennir; H: Sebkha Tazra; I: Carriere Shell; J: Sidi Aila; K: Sebkha Tisfourine.

The main feature of the region is a dry climate with ‘’Alizes’’ winds, whose characteristic feature is air moistening, causing flora development close to the coast. The temperatures in the study area are relatively low, with an average of 20°C per year. This is attributed to the so-called Canary Current, a cool current that follows the Moroccan Atlantic coast and fluctuated during the Quaternary period. The area is subject to significant variations in the wind regime [12]. Precipitation is random, violent and stormy. The average rainfall for the last ten years is about 60 mm.

From a geologic point of view, in the Tarfaya coastal basin, lithostratigraphic data show a Precambrian basement covered by strata ranging from Paleozoic to Quaternary [17]. The majority of outcrops are monoclinal cretaceous strata [18]. The tabular shape of the Tarfaya coastal basin is primarily due to (1) westward sedimentary progradation and (2) positive vertical movements during the Alpine tectonic phase of the Late Cretaceous [19]. The coastal basin of Tarfaya is a poor area at Plio-Pleistocene levels. It is characterized by the extension of the quasi-tabular Moghrebian platform and was the center of a Pleistocene neotectonic. On a larger scale, lower Pleistocene Moghrebian strata have been defined in the Rabat region [20] [21], composed of detrital deposits unconformably over Pliocene strata.

In the Tarfaya coastal basin, deep secondary and tertiary series have been stacked and shaped into step-like plateau [22]. Three geomorphological features are considered: the hamadas, the coastal platform and the sebkhas (Figure 1).

1. Hamadas are plateaus of about 200 m altitude and surrounded by steep cliffs [10].
2. A coastal platform extends between hamadas and the coast, corresponding to a marine abrasion surface covered by Moghrebian deposits. The latter runs along the coast, throughout the basin, with a variable width and an altitude that increases from SW to NE [22].
3. Sebkhas correspond to troughs that can reach an altitude of -55 m (sebkha Et-Tah) and are located in the southwestern part of the basin. The depressions of different sizes, having flat bottoms and steep edges, have an endoreic character except for the sebkha Tazra which communicates with the sea through the lagoon of Puerto-Cansado. [22] [10].

3. Materials and Methods

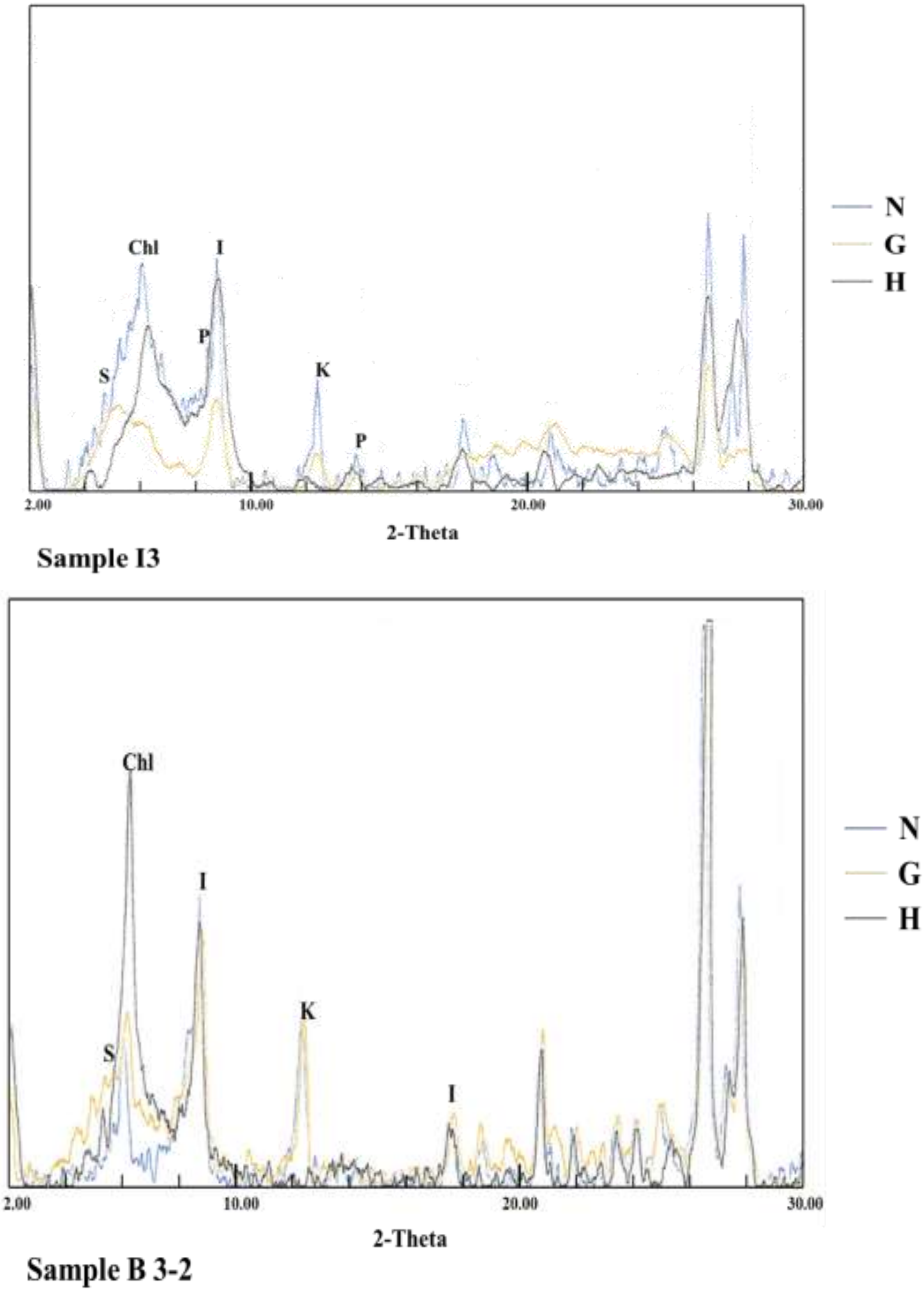
Field stratigraphic surveys were conducted along the wadis and coastal cliffs (Figure 1). Additional investigations were conducted on the edges of the sebkhas. Moghrebian facies have shown significant horizontal facies variability, and lithostratigraphic data were produced to represent the area (Figure 3).

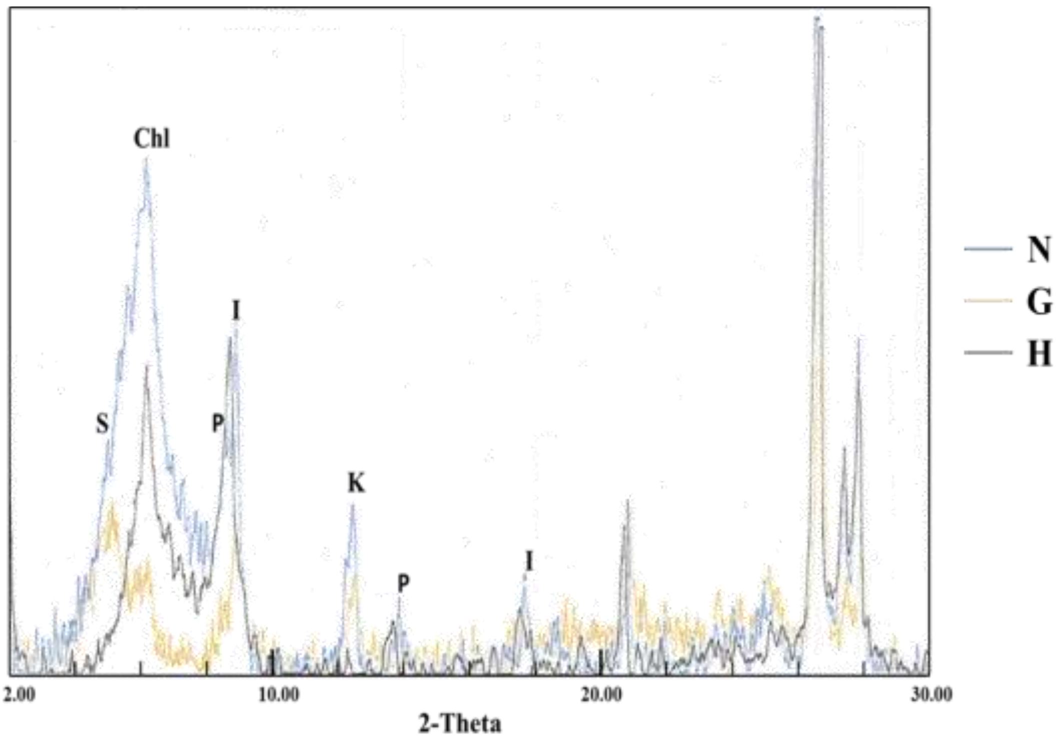
Three types of analysis were conducted to identify different Moghrebian facies in the Tarfaya coastal basin and to define the crust development modalities: microfacies study, calcimetry and X-ray diffractometry (XRD) of the fine fraction [23].

The 47 samples of lumachel, sandstone, calcarenite and superficial crust from the sections (Figures 1 and 3) were selected for analysis using the Bernard calcimeter to measure the percentage of $CaCO_3$. After an operation of decarbonatation and elimination of organic matter with 30% H2O2, the samples were leached for 12 hours to study their clay minerals content. Once the clay fraction (<2 µm) was separated from the resulting stable suspension, it was spread on oriented sections that were analysed using an X-ray diffractometer. The purpose of this analysis was to record the following three patterns for each sample after their preparation.

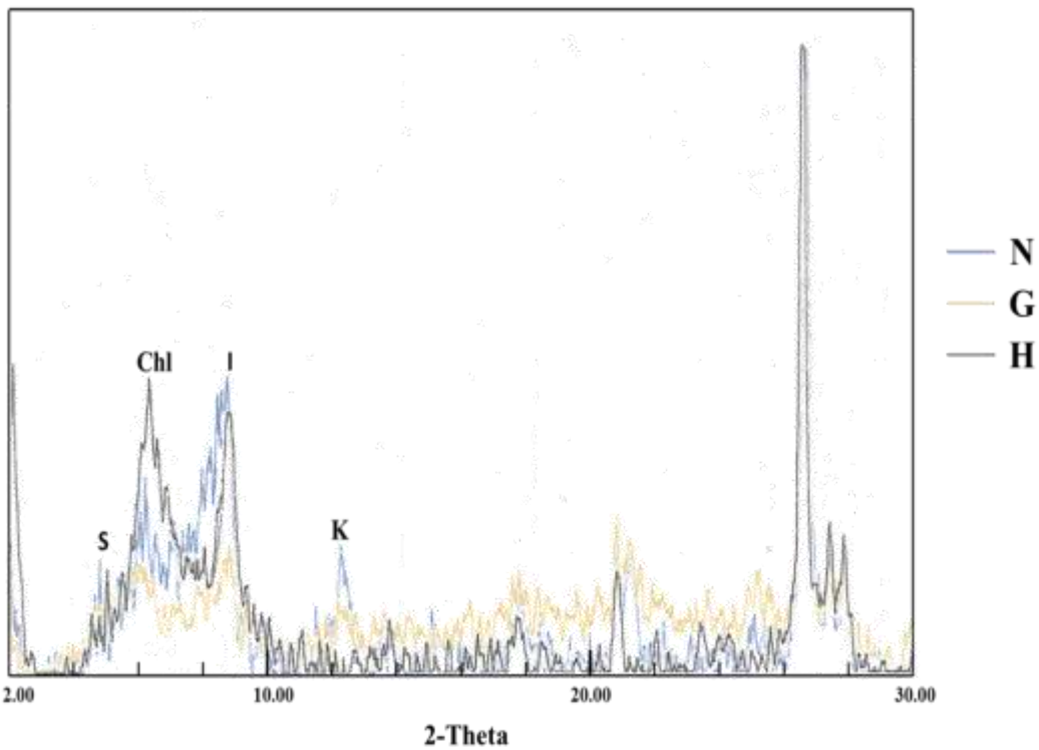
- A "normal" pattern (Air-dried without treatment);
- A "heating" diagram made by heating the sample for 4 hours at 490°C;
- An "Ethylene-Glycol" diagram was performed by placing the slides under a vacuum overnight in the presence of ethylene glycol.

The analyses were carried out at the Laboratory of the Ministry of Energy and Mines (Morocco)
The relative content of each clay mineral was estimated semi-quantitatively using the information provided by [24] and [25]. The diffractograms identified smectite and illite at 17 Å and 10 Å, respectively. Kaolinite and chlorite, respectively, at 7.2 Å and 14 Å. Peaks of 6.46 Å and 12 Å were found corresponding to palygorskite and sepiolite, respectively (Figure 2). Interbedded clays were identified between 14.5 Å and 15 Å.





Sample I1



Sample D3

Figure 2: X-ray diffraction pattern of sandstone, lumachelle and calcarenite from various sections showing the presence of smectite (S), illite (I), chlorite (Chl), kaolinite (K), palygorskite (P), Air-dried N, glycol G and heated to 490°C.

For the study of microfacies, thin sections were made for lumachel, calcarenites, sandstones and superficial crusts. These slides were studied under polarized transmitted and reflected lights microscopes at the Department of Applied Geology, Faculty of Sciences and Technology, University of Hassan First (Settat, Morocco).

4. Results

The Moghrebian strata are found in a coastal strip 350 km length between Râs Takoumba and Tarfaya (Figure 1). The lithostratigraphic data indicate that the thickness of the Moghrebian strata ranges from 5 to 30 m, and they are formed of beds of conglomerate, lumachel, sandstone and calcarenite (Figure 3). A calcareous encrusting with continental gastropods covers the overall pattern.

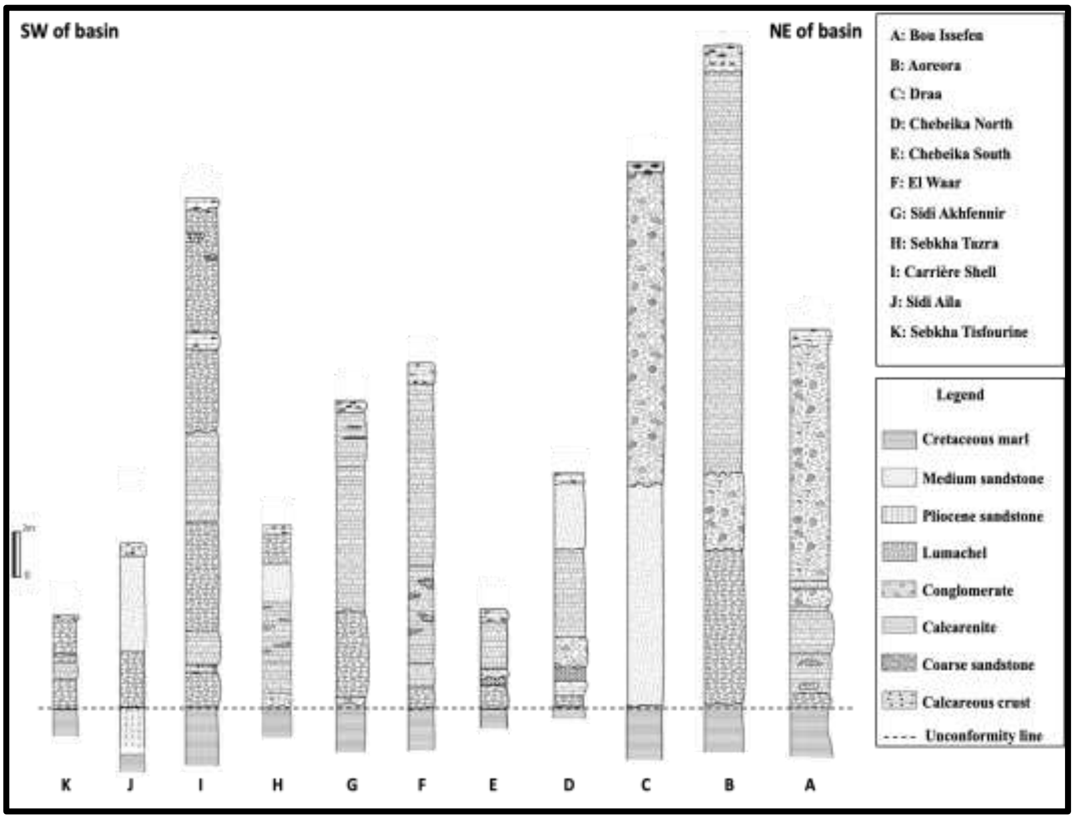


Figure 3: Lithostratigraphic sections of Pleistocene Moghrebian strata in the coastal basin of Tarfaya.

The conglomerates of sections A, B and C consist of clasts size (0.05mm) to 1m diameter. Features of very different petrographic compositions (quartzite, limestone, green shale) are probably the result of the erosion of the Western Anti-Atlas formations. A calcareous matrix binds these components. Conglomerates that represent section D on the first level are formed of pebbles of yellow Cretaceous marl that represent the substratum of the Moghrebian and flint that is formed by the concentration of dissolved silica. These elements are bound by a calcareous matrix. Macroscopic analysis of the lumachel revealed that these facies are composed of lamellibranchs (Pectinidae) in sections D and F, Cirripeds and Echinides in section H and Ostreidae in section K. Microscopic observation of these facies shows that these levels are characterized by high porosity and by the existence of bioclasts surrounded by a micritic envelope. The diagenetic evolution of lumachel is marked by the micritization of bioclastic debris as well as their dissolution, which is responsible for secondary porosity and by the beginning of recrystallization of a micritic matrix into microsparite. (Figure 4B).

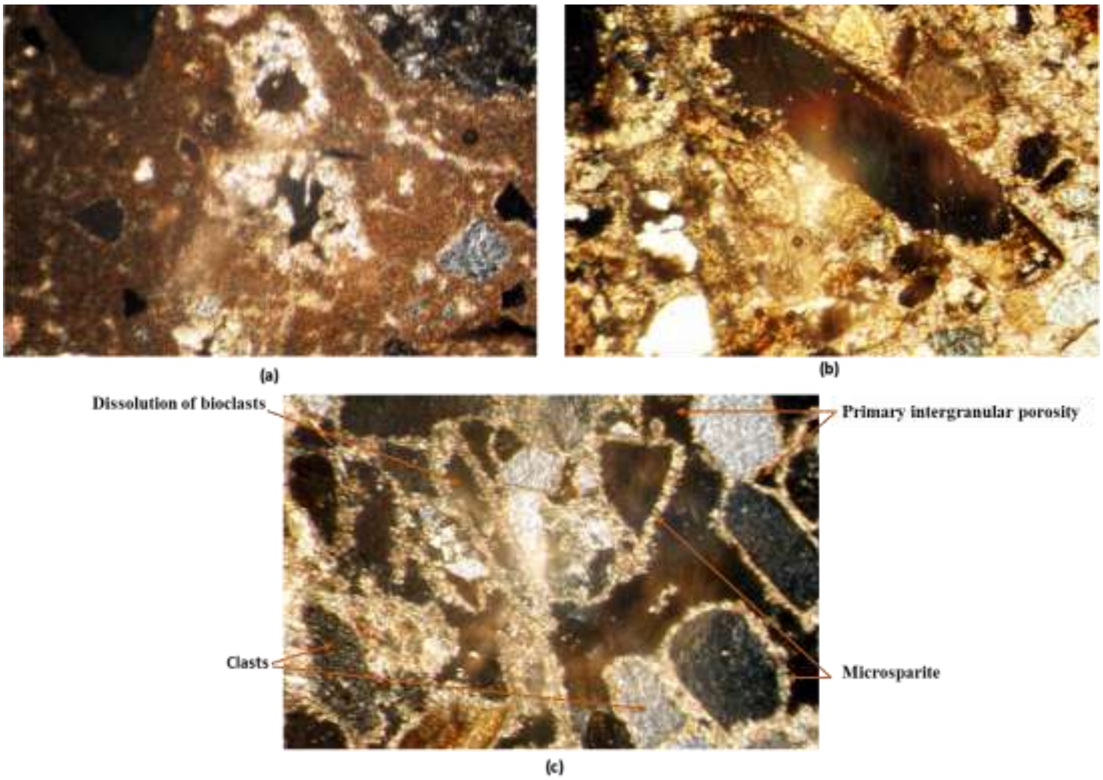


Figure 4: Microphotographs of the Moghrebian facies with polarized light analyzed.
(a) : Recrystallization of micritic matrix into microsparite and Filling of pores with calcite in drusy cement (sandstone level 3 of section D).
(b) : Micritization of bioclastic debris as well as their dissolution and crystallization of microsparite in lumachel level (sections H, K and H).
(c) : Dissolution of bioclasts, corrosion of quartz and precipitation of microsparite around the clasts (calcarenite, level 2, section A).

On the calcarenites side, the petrographic investigation of thin sections revealed a diagenitic evolution summarized in four stages: (figure 4C)

- **Stage I:** The setting up of calcareous sand with significant primary intergranular porosity.
- **Stage II:** During this stage, a dissolution of bioclasts is responsible for the creation of dissolution pores [26]
- **Stage III:** The supersaturation of the interstitial solutions in calcium carbonate led to the corrosion of the quartz grains and the precipitation of calcite in the erosion golfs. And also the crystallization of microsparite around the clasts (Figure 4C).
- **Stage IV:** Filling of primary and diagenetic pores with calcite in drusy cement [26]

The sandstones representing level 3 of section D correspond to a calcirudite with rare bioclasts consolidated by a calcareous cement. In the thin section, the diagenetic evolution of these sandstones is marked by the crystallization of the matrix into microsparite and the development of a drusy cement in the intergranular spaces (Figure 4A).
The microfacies of the calcareous encrusting are characterized by extensive corrosion of detrital elements, especially quartz grains. This corrosion is achieved either by the development of corrosion gulfs on the surface of the grain until its total replacement by calcite (Figure 5B and 5D) or by the bursting of the grain before its dissolution and its isovolumetric replacement by calcite (figure 5A and 5B). The matrix is displayed as glaebules of different sizes (Figure 5C), and it is recrystallized in microsparite in the intergranular spaces.

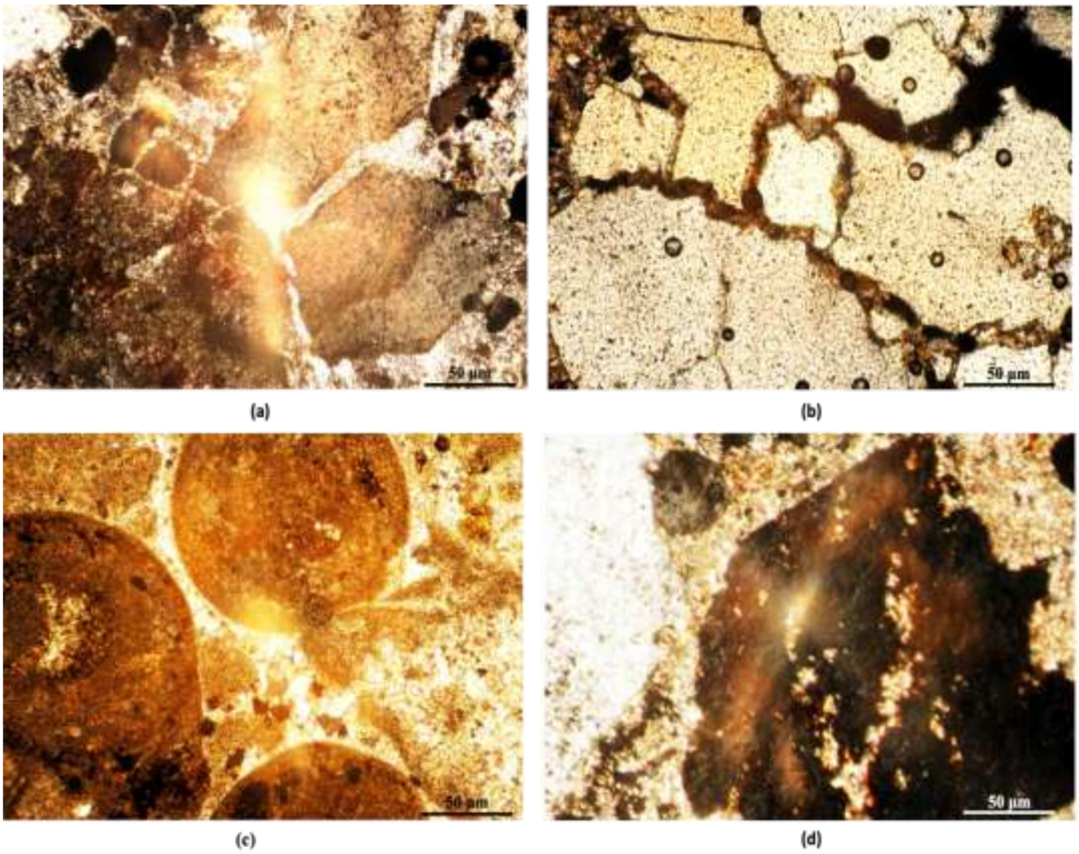


Figure 5: Thin section photographs of calcareous crusts that form the uppermost bed of the Moghrebian strata in the coastal basin of Tarfaya with polarized light analysed.
(a) : Quartz bursting and microsparite crystallization in cracks.
(b) and (d): Corrosion of quartz and crystallization of microsparite in corrosion golfs.
(c): Matrix in the form of glaebules and filling intergranular spaces with drusy cement.

Calcimetry results showed that calcium carbonate is relatively abundant in the facies identified in the sections studied (Table 1). Indeed, its content in the superficial crusts varies between 65% and 90%; for the calcarenites, it is between 34% and 83%. The calcium carbonate content in the lumachel ranges from 58% to 77%. Even the conglomerates have high contents (51% to 77%), and the sandstones have a percentage of calcium carbonate varying between 22% and 70%.

For the clay mineralogy, the diffractograms of the fine fraction of the sediments in the different facies of the lithostratigraphic sections reveal the following clay assemblage of clay minerals: chlorite, kaolinite, illite, smectite, interbedded clay (chlorite-smectites, chlorite-vermiculite, vermiculite-smectite) and fibrous clay (sepiolite and palygorskite). The latter is most abundant in the surface crust. The percentage of the different clay minerals is listed in Table 1, and their weighted average is plotted in Figure 6.

Table 1: Clay mineral data for the Moghrebian facies samples of the Tarfaya basin. Chl : Chlorite ; Verm : Vermiculite ; Smec : Smectite ; Il : Illite ; K : Kaolinite

Lithostratigraphic section	*ID Sample*	*Facies name*	*CaCO3*	*Kaolinite*	*Illite*	*Chlorite*	*Smectite*	*Palygorskite*	*Sepiolite*	*Chl/ Verm*	*Smec / Verm*	*Chl/ Smec*	*Illite +Chlorite*	*K/I+ CL*
Bou Issafen	A4	Crust	90%	15%	19%	65%	0%	0%	0%				84%	0.18
	A3-2	Conglomerate	75%	13%	41%	46%	0%	0%	0%				87%	0.15
	A3-1	Conglomerate	77%	0%	53%	36%	0%	11%	0%				89%	0.00
	A2	Calcarenites	83%	0%	47%	53%	0%	0%	0%				100 %	0.00
Aoreora	B4	Crust	80%	18%	27%	0%	7%	14%	0%				27%	0.67
	B3-3	Calcarenites	76%	45%	6%	10%	9%	30%	0%				16%	2.81
	B3-2	Calcarenites	72%	28%	45%	14%	3%	10%	0%				59%	0.47
	B3-1	Calcarenites	69%	7%	22%	16%	45%	0%	0%				38%	0.18
	B2	Conglomerate	51%	0%	27%	24%	37%	0%	0%	12%			51%	0.00
	B1	Lumachel	77%	68%	17%	26%	0%	0%	0%				43%	1.58
Draa	C3	Crust	76%	27%	35%	12%	0%	16%	0%				47%	0.57
	C2	Conglomerate	69%	15%	0%	22%	45%	18%	0%				22%	0.68
	C1	Conglomerate	71%	0%	17%	28%	55%	0%	0%				45%	0.00
Chebeika Nord	D7	Crust	79%	0%	29%	44%	0%	27%	0%				73%	0.00
	D6	Sandstone	60%	5%	0%	0%	0%	95%	0%				0%	
	D5	Calcarenites	36%	0%	28%	32%	40%	0%	0%				60%	0.00
	D3	Sandstone	72%	9%	32%	46%	$ 13%	0%	0%				78%	0.12
Chebeika Sud	E5	Crust	66%	0%	27%	0%	0%	73%	0%				27%	0.00
	E4-2	Calcarenites	49%	0%	31%	5%	0%	0%	64%				36%	0.00
	E4-1	Calcarenites	67%	0%	25%	22%	0%	54%	0%				47%	0.00
	E2	Coarse sandstone	22%	21%	49%	14%	0%	16%	0%				63%	0.33

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Lithostratigraphic section	***Sample ID***	***Facies name***	***CaCO3***	***Kaolinite***	***Illite***	***Chlorite***	***Smectite***	***Palygorskite***	***Sepiolite***	***Chl/ Verm***	***Smec / Verm***	***Chl/ Smec***	***Il +Chlorite***	***K/I+ CL***
EL Waar	F5	Crust	70%	0%	28%	12%	0%	27%	33%				40%	0
	F4-3	Calcarenites	63%	14%	13%	8%	58%	0%	7%				21%	0.67
	F4-2	Calcarenites	51%	14%	26%	17%	26%	0%	17%				43%	0.33
	F4-1	Calcarenites	74%	5%	24%	0%	0%	0%	2%			69%	24%	0.21
	F3	Calcarenites	69%	13%	0%	28%	29%	25%	5%				28%	0.46
	F2	Calcarenites	43%	3%	16%	12%	41%	17%	11%				28%	0.11
Sidi Akhfennir	G5	Crust	65%	17%	31%	15%	0%	27%	10%				46%	0.37
	G4	Calcarenites	58%	2%	10%	2%	0%	75%	11%				12%	0.17
	G3	Calcarenites	44%	0%	30%	8%	0%	43%	19%				38%	0
Sebkha Tazra	H6	Crust	89%	18%	26%	0%	7%	14%	0%		19%	15% IL/Smc	26%	0.69
	H5	Calcarenite	45%	45%	6%	10%	8%	31%	0%				16%	2.81
	H4	Sandstone	42%	28%	45%	14%	3%	10%	0%				59%	0.47
	H3	Calcarenites	35%	8%	22%	10%	42%	12%	0%				32%	0.25
	H2	Calcarenites	34%	0%	27%	36%	37%	0%	0%				63%	0
	H1	Conglomerate	25%	68%	17%	15%	0%	0%	0%				32%	2.13
Carriere Shell	I6	Crust	79%	0%	73%	27%	0%	0%	0%				100 %	0
	I5	Lumachel	74%	33%	0%	19%	48%	0%	0%				19%	1.74
	I4	Calcarenites	80%	17%	35%	0%	0%	9%	7%	17%			35%	0.49
	I3	Lumachel	58%	8%	29%	19%	33%	11%	0%				48%	0.17
	I2	Calcarenites	62%	0%	49%	21%	30%	0%	0%				70%	0
	I1	Lumachel	77%	12%	39%	12%	37%	0%	0%				51%	0.24
Sidi Aila	J3	Crust	76%	0%	0%	17%	34%	49%	0%				17%	0
	J2	Sandstone	70%	20%	54%	26%	0%	0%	0%				80%	0.25
Sebkha Tisfourine	K5	Crust	89%	0%	51%	17%	0%	32%	0%				68%	0
	K4	Lumachel	75%	16%	30%	26%	0%	28%	0%				56%	0.29
	K2	Calcarenites	68%	0%	59%	41%	0%	0%	0%				100 %	0

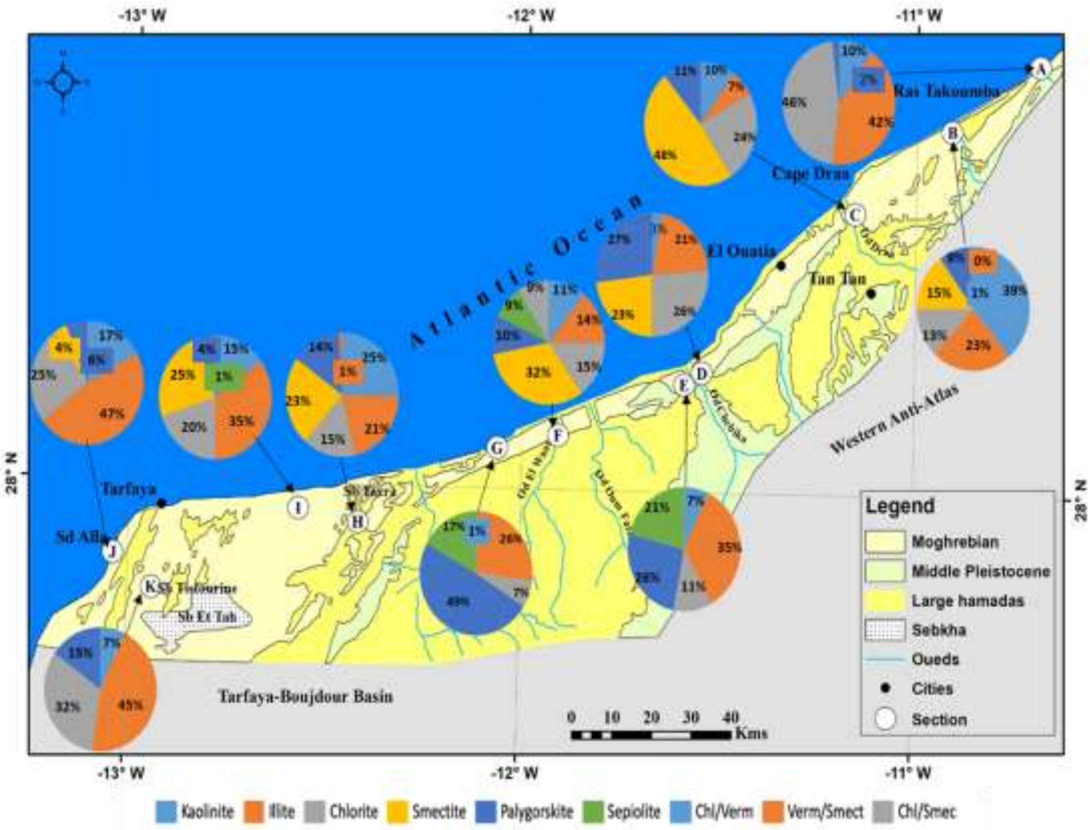

Figure 6: The distribution of the weighted average of clay minerals by section in Moghrebian sediments: A: Bou Issafen; B: Aoreora; C: Draa; D: Chebeika North; E: Chebeika South; F: El Waar; G: Sidi Akhfennir; H: Sebkha Tazra; I: Carriere Shell; J: Sidi Aila; K: Sebkha Tisfourine.

Prevailing clay minerals are illite, chlorite, smectite, palygorskite and sepiolite. Their abundances show a northeast-to-southwest trend in the Tarfaya coastal basin. Abundance changes of clay minerals in the Moghrabian sediments of the Tarfaya coastal basin are evidenced by the study of forty-seven samples taken in the different facies. In the NE part of the basin, chlorite (0-65%), illite (6-53%), smectite (0-45%) and kaolinite (0-68%) are the most in the midstream of the basin, and from the mouth of the wadi Draa to Foum Agoutir in the SW, smectite (13-58%) and chlorite (2-44%) are dominant. Illite (10-35%) and kaolinite (2-27%) in average representation. Fibrous clays palygorskite and sepiolite show a strong dominance in this area with respectively (18-95%) and (2-64%) in calcarenites and sandstone facies and, (16-73%), (10-33%) in superficial crusts.

In the southwestern area of the basin, dominant clay minerals are kaolinite (8-68%), illite (6-73%), chlorite (10-41%), smectite (3-48%), and palygorskite (9-31%) in calcarenites and sandstones (14-49%) in superficial crusts. Sepiolite is almost absent in this part of the basin. Chlorite/smectite (69%), chlorite/vermiculite (12-17%) and smectite/vermiculite (19%) interlayers were found very locally in the Moghrebian of the Tarfaya coastal basin.

5. Discussion

The results of our study showed that the Moroccan platform in the Tarfaya coastal basin was subject to an isostatic uplift process during the entire Pleistocene. This led to an uplift of the Moghrebian strata from the southwest of the basin to the northeast and a relative paucity of Pleistocene levels. Consequently, only the Moghrebian and Uljian strata represent the

Pleistocene marine units. The Uljian stage represents the last stage in the classical stratigraphy of marine Pleistocene units in North Africa. It is believed that a basin-specific tectonosedimentary process led to the developing the limestone crusts in the Tarfaya basin. Our sedimentological surveys supported this, which revealed a great lateral variability of facies and thickness of the Moghrebian strata and their high contents (up to 90°/°) of calcium carbonate in the superficial crusts. These facts are consistent with alternating sedimentary deposition/erosion phases, probably linked to regional sea-level variations. Consequently, Calcium Carbonate was brought into the basin from the hinterland formations either by runoff or eolian action. The carbonate saturation of the Moghrebian sediments favored calcite precipitation and, subsequently, the genesis of superficial calcareous crusts.

Our study has shown that calcium carbonate originates from two different sources, an external origin to the basin as a result of the alteration of the Western Anti-Atlas formations and those of the Tarfaya-Boujdour basin, and an internal origin to the basin by the dissolution of bioclasts induced by the physicochemical conditions of the environment.

The microfacies of the Moghrebian facies is characterized by high porosity and bioclasts surrounded by a micritic envelope in the lumachel and calcarenites levels. These facies are marked by the micritization of bioclastic debris and their dissolution, which is responsible for secondary porosity. This process is a primary diagenetic process [27]. The micritization of carbonate particles is an indication of deposition in a shallow environment [27] [28] [29]. This indication is also demonstrated by the association of Ostreidae, Pectinidae, Cirripedes and Echinidae, which testify to a very coastal depositional environment of high energy. These species were found by Alia Medina (1949) in the Moghrebian of Cape Garnet between the Rio de Oro and Cape Bojador [10]. The diagenetic evolution of the Moghrebian facies is also marked by the beginning of the recrystallization of a micritic matrix into microsparite and the filling of primary and diagenetic pores with calcite in drusy cement. The microfacies of the crust showed the corrosion of quartz grains before its dissolution and its isovolumetric replacement by calcite. It is thus an isovolumetric calcareous epigenia [30]. The calcareous epigeny of silicates in originally non-calcareous detrital sediment was responsible for developing a calcareous crust of variable thickness on the surface of the Moghrebian formations of the coastal basin of Tarfaya. This calcareous epigenium has been the subject of several studies and has been described by [3] in central Morocco, by [31] in Tunisia, and by [32] in Northern Algeria. The superficial crust in the Tarfaya coastal basin includes dissolution with variable-shaped voids where microsparite calcite (drusy cement) begins to crystallize (Figure 4A). This crust is also rich with continental gastropods and irregularly shaped nodules of a calcareous matrix that cross the rock. All these data make it possible to relate the calcareous crusts of the Moghrebian formations of the Tarfaya coastal basin to crusts of the "calcrete" type as described by [33] in Tunisia; by [34] in India; by [3] in central Morocco; By [35] in Turkey and by [36] in Mexico.

Clay mineral content in the Moghrebian facies in the Tarfaya coastal basin reveals much information regarding paleoclimates, erosion processes, and sediment origin. Accordingly, various combinations of this class of minerals have been considered. These include primary minerals such as illite and chlorite [37] [9] and secondary ones such as kaolinite [30] [9] [38]. Vermiculite-smectite and illite-smectite interlayers and Magnesian fibrous clays (sepiolite and palygorskite).

The clay mineral quantitative analyses revealed the relative abundance of the main clay minerals illite and chlorite. Relative illite dominance indicates a decrease in hydraulic processes within the continental weathering and an increase in direct rock erosion under cold and arid climatic conditions, as demonstrated by [9].

On the other hand, tropical and humid conditions are indicated by secondary minerals such as kaolinite [9] [39]. Its dominance in the Moghrebian facies of the Tarfaya coastal basin is the result of its detrital origin from the alteration of feldspars of magmatic rocks of the hinterland rich in this mineral [40]. This mineral's relatively high dimensions are thought to reflect the proximity of the depositional environment of these facies to the shoreline areas.

The abundant occurrence of smectites in the Moghrebian strata leads to three hypotheses about their formation process, which are (1) the reworking of exposed soils and sedimentary covers under a warm and less humid climate, (2) the diagenetic authigenesis and (3) the alteration or submarine modification of volcanic materials. Smectites may be either inherited from selected mineral-rich formations [41] or newly formed. A formation process from Si and Mg-rich interstitial solutions [42] [43] is much more plausible.

Sediments in the Tarfaya coastal basin since the Late Cretaceous have been derived primarily from the metamorphic and sedimentary cover of the Western Anti-Atlas [44] [45], which excludes any volcanic origin of the smectite. [46] surveyed the clay minerals in the deep Atlantic sediments off the Moroccan coast and found no evidence of the diagenetic alteration of smectite minerals. They concluded that smectite was mainly derived from the detrital source and deposited off the Moroccan coast. The occurrence at the different facies in the sections we studied could lead to the hydrolysis of silicates in a basic environment rich in Mg [47]. These conditions explain the low values recorded for interstratified in the Moghrebian facies in the Tarfaya coastal basin [48]. Concerning fibrous magnesian clays, the palygorskite, frequently found together with the sepiolite, may also originate from sedimentary rocks bearing magnesian clays and result from smectite transformation[49]. Therefore, its abundance in calcarenite levels can be accounted for by suspended flow or short-range eolian transport. On the other hand, fibrous magnesian clays often grow in calcareous crusts formed in arid climates [2] [50] [51]. Next to their neoformation in superficial crusts, coupled with extensive drought and evaporation, the magnesian clays seem to stem from the Lower Eocene strata of the Tarfaya Basin, where they are very abundant [8]. Magnesian fibrous clays in dry coastal climatic conditions have been reported at several locations in the northeast Atlantic, Mediterranean and Indian basins [8], where they were commonly transported by river flows, turbidity currents and runoff or winds [52].

The abundance of clay minerals in the studied facies is independent of their lithological nature. Moreover, the diagenesis of these facies is negligible, confirming the detrital origin of these species and their inheritance of minerals rich in Fe-Mg and minor silicates rich in Si-Al, which are very frequent in the basic rocks [53]. In our case, the origin of these minerals would probably be the volcano-sedimentary units of the Western Anti-Atlas [54] [55].

The low kaolinite/(illite+chlorite) values indicate significant physical erosion in the hinterland formations and transfer of detrital material into the basin. The strong physical erosion was probably caused by the tectonics of the western Anti-Atlas [56] [57] [8], in particular, the large-scale uplift movements recorded in this area during the Miocene-Pliocene [58].

Post-depositional evolution of Moghrebian sediments is therefore marked by a structural modification related to mineralogical variations during epigenia, mostly quartz by calcite recorded in the crusts, and by the transformations recorded in the carbonate matrix by the dissolution/precipitation conditions of a very porous medium with a physicochemical atmosphere saturated in calcium carbonate [31]. This led to calcification which can only occur in an alternating climate of wet and dry seasons. In the humid season, the oversaturation of the carbonate solutions creates silica instability and thereafter, the dissolution of quartz and the release of silica into the environment. During the dry seasons, evaporation becomes important. The solutions are supersaturated, and the pH increases, and the calcite precipitates. The dry seasons are also marked by the isovolumetric epigenesis of quartz by calcite and by the neoformation of fibrous magnesian clay (palygorskite and sepiolite) [2] [42].

6. Conclusion

The diagenetic evolution of the Moghrebian Pleistocene strata of the Tarfaya coastal basin is very early. This evolution is characterized by micritization, the dissolution of bioclastic debris by the isovolumetric calcareous epigeny of the quartz and drusy cementation. The development of calcareous crusts at the top of the Moghrebian strata results from an enrichment of the basin with calcium carbonate from the formations of the western Anti-Atlas and those of the Cretaceous rocks in the south. The fine fraction of the Moghrebian strata consists of an assemblage of clay minerals (illite, kaolinite, smectite, chlorite, sepiolite, palygorskite and interstratified clay) of detrital origin. The low Kaolinite/(Illite+chlorite) ratio values in these strata indicate a physical erosion of the source regions and an important sedimentary transport during the Pleistocene. The richness of superficial crusts in palygorskite and sepiolite suggests their neoformation in a climate marked by alternating wet and dry seasons. Wet seasons favored the mobility of ions in solution, while the dry seasons favored the neoformation of magnesian clays, the calcareous epigeny and the crystallization of micritic matrix into microsparite and sparite in the intergranular spaces.

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