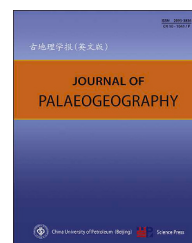


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## Research article

# Sedimentology, provenance, and paleoclimate of Jurassic–Cretaceous red beds: Example from the southern front of the Central High Atlas and Northern Preafrican Trough, Morocco

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**Abstract** Five stratigraphic sections from the Aghbalou N'Kerdouss–Tadighoust area were analyzed using integrated petrographic, granulometric, calcimetric, and mineralogical approaches applied to both bulk samples and clay fractions. The findings reveal a transitional depositional environment shaped by a dynamic interplay of continental and restricted marine influences, particularly within the Ifezouane Formation (Member 2), which reflects low-amplitude sea-level oscillations under confined paleoenvironmental conditions. Whole-rock mineralogy is dominated by quartz, K-feldspar, plagioclase, hematite, calcite, dolomite, siderite, and gypsum. The associated clay mineral assemblages comprise illite, kaolinite, smectite, and chlorite, with compositional variability across sections. Illite crystallinity and illite chemistry index data indicate a dual provenance, with sediment sources originating from both the Anti-Atlas and Sahara regions to the south, as well as the Jurassic uplands to the north. These interpretations are supported by petrographic evidence and mineralogical signatures. Furthermore, the mineralogical data suggest that arid to semi-arid climatic conditions and/or tectonic activity played a significant role during deposition. This study demonstrates how the integration of clay mineral signatures with petrography, grain-size distribution, and calcimetric data offers a reliable basis for reconstructing provenance, unraveling paleoenvironmental conditions, and refining palaeogeographic reconstructions of peri-Tethyan basins, while also providing a comparative framework applicable to analogous red bed systems worldwide.

**Keywords** Clay mineralogy, Red beds, Jurassic-Cretaceous, Central High Atlas, Preafrican Trough, Morocco

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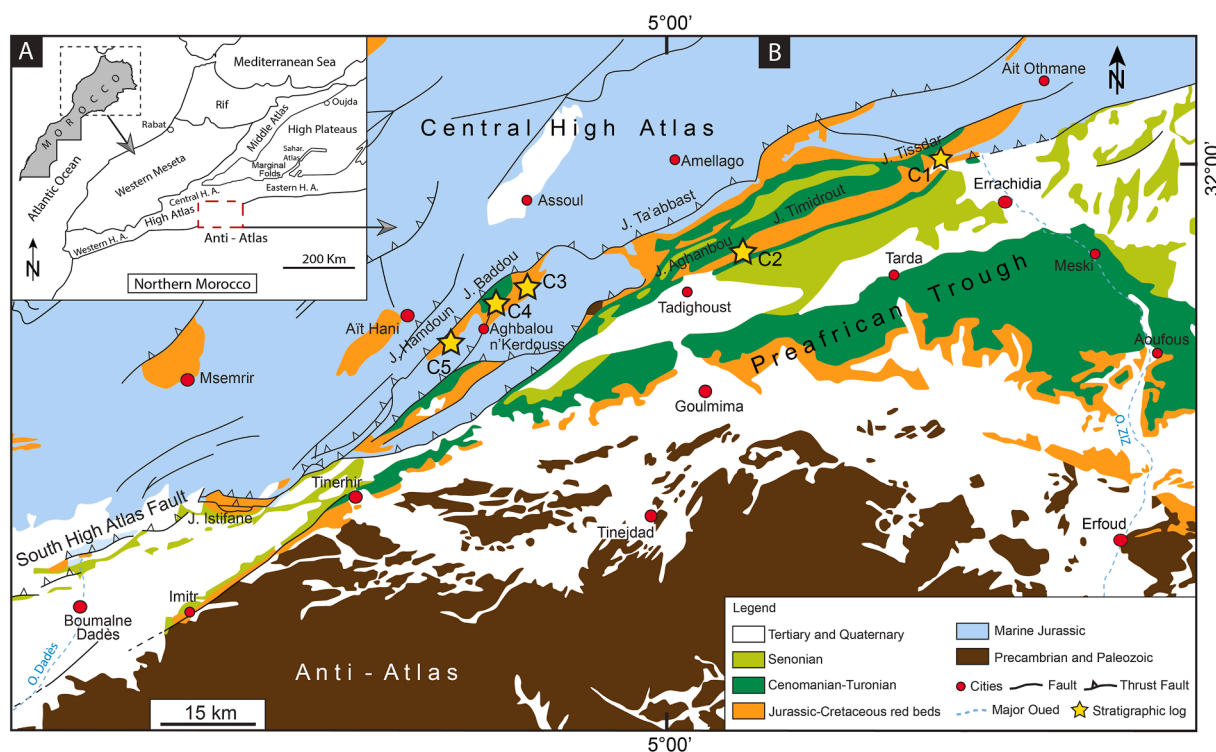
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## 1. Introduction

Along the southwestern margin of the Tethys Ocean, a thick Jurassic-Cretaceous sedimentary succession, originally designated as the “*Continental Intercalaire*” by Kilian in 1931, extends across northern Africa, from Morocco to Egypt and from the Sudan to Niger (Fanti *et al.*, 2012, and references therein). This extensive stratigraphic unit represents a remarkable key archive for understanding the regional geodynamic and sedimentary history of the Atlas domain and its adjacent basins. These strata document a wide range of sedimentary environments, from continental to shallow-marine settings, within various hosting sedimentary basins (e.g. Benyoucef *et al.*, 2017; Haddoumi *et al.*, 2019; Adardor *et al.*, 2021; Boukhalfa *et al.*, 2025). These sequences contain an exceptionally rich and diverse fossil assemblage,

including marine and non-marine taxa, as well as plant remains (Fanti *et al.*, 2012; Haddoumi *et al.*, 2016; Ibrahim *et al.*, 2020, and references therein).

In Morocco, these deposits are locally known as the “*Couches Rouges*” (Jenny *et al.*, 1981), marking a major paleoenvironmental transition beginning in the Bathonian, and are characterized by a shift to siliciclastic-dominated sedimentation. This transition is particularly well-documented in the Central High Atlas and its foreland basin (Hollard *et al.*, 1985). From this period onward, the sedimentary system was largely dominated by alluvial fan and fluvial red beds, characterized by limited fossil content and numerous stratigraphic discontinuities, which complicated interpretations of their sedimentary evolution (e.g. Charrière and Haddoumi, 2016; Adardor, 2022, and references therein). In the southern front of the Central High Atlas and Northern Preafrican Trough, previous research has primarily focused on the



**Fig. 1** Geological map of the southern front of the Central High Atlas and Northern Preafrican Trough, highlighting the studied localities and logged sections. Modified after Hollard *et al.* (1985) and Adardor *et al.* (2021).

tectonic, sedimentological, and stratigraphic features of the red beds and the overlying units (e.g. [Adardor et al., 2021](#) and references therein). Further south, these deposits are referred to as the “Kem beds” or “Kem Group”, and have been the subject of numerous paleontological investigations (e.g. [Cavin et al., 2010](#); [Ibrahim et al., 2020](#), and references therein).

Despite numerous geological studies on the Jurassic–Cretaceous sedimentary successions in the southern front of the Central High Atlas and Northern Preafrican Trough, research specifically focusing on sediment provenance, sedimentological process, and paleoclimate studies remains limited and poorly developed. These aspects are, however, crucial for a better understanding of the deposition model of these formations, especially in light of their paleontological richness and the associated mineralization in different parts of the Atlas system and their adjacent basin. [Lebedel et al. \(2015\)](#) conducted a multi-proxy paleoclimatic analysis of the overlying Upper Cenomanian–Lower Turonian Red Bed terrains in the Errachidia-

Tinghir region (Preafrican Trough), based on sedimentological, paleontological, geochemical, and mineralogical characterizations. Additionally, [Benvenuti et al. \(2017\)](#) and [Cavallina et al. \(2018\)](#) studied sediment composition and paleocurrent directions in two key sectors in the southern front of the Central High Atlas (Dadès valley and Adrar Aglalag syncline) to understand sediment provenance and the tectono-sedimentary evolution of the Central High Atlas. Recently, [Adardor et al. \(2021\)](#) identified a regionally extensive northward-flowing fluvial system in the Aghbalou N'Kerdouss-Tadighoust region, based mainly on paleocurrent analysis.

In this context and building on previous findings, this current research aims to provide a comprehensive assessment of sedimentary dynamics, paleoclimate, and sediment provenance of the Moroccan Jurassic–Cretaceous red beds through an integrated, multi-proxy approach, including detailed mineralogical investigations. The ultimate objective of this work is to better understand the geological evolution

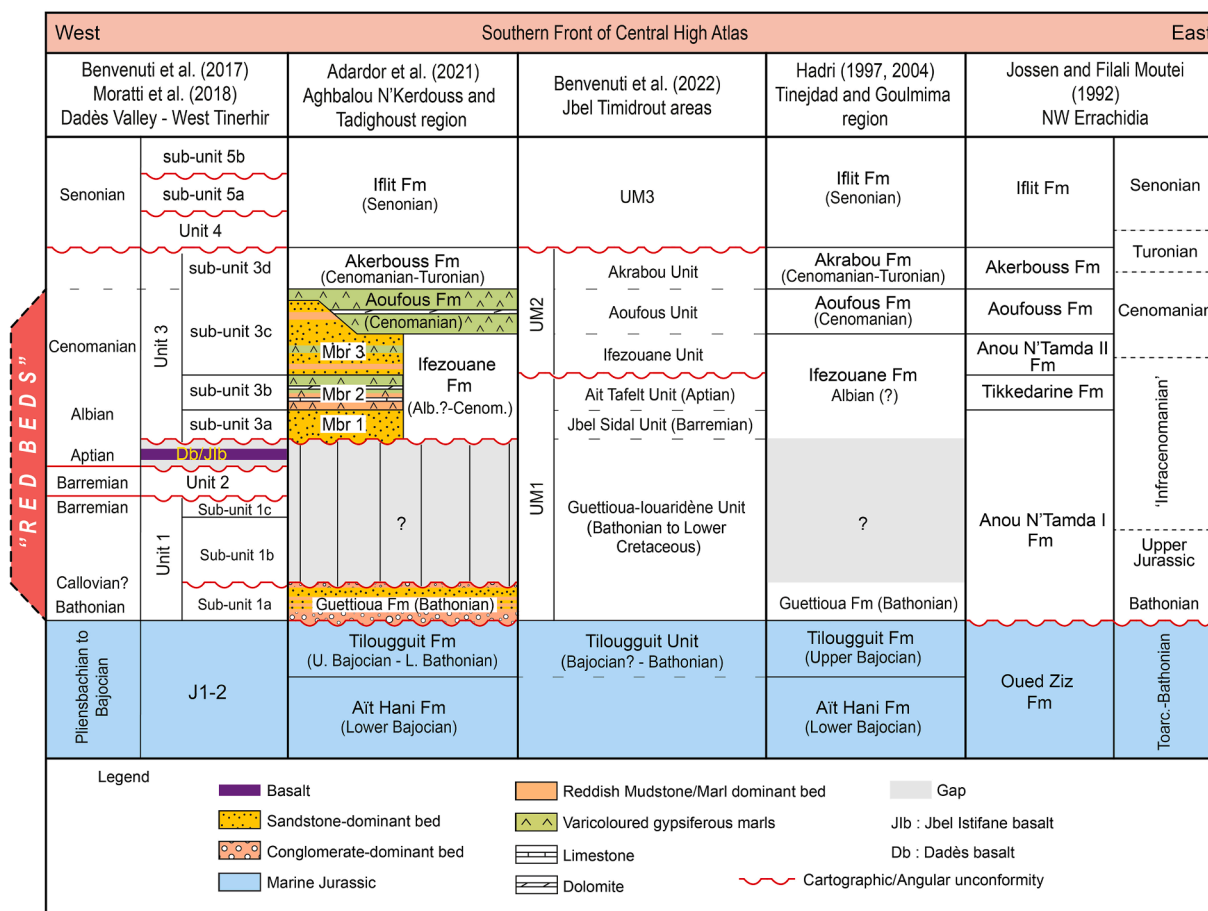


Fig. 2 Lithostratigraphic units identified by different authors from the southern front of Central High Atlas, modified after [Adardor et al. \(2021\)](#).



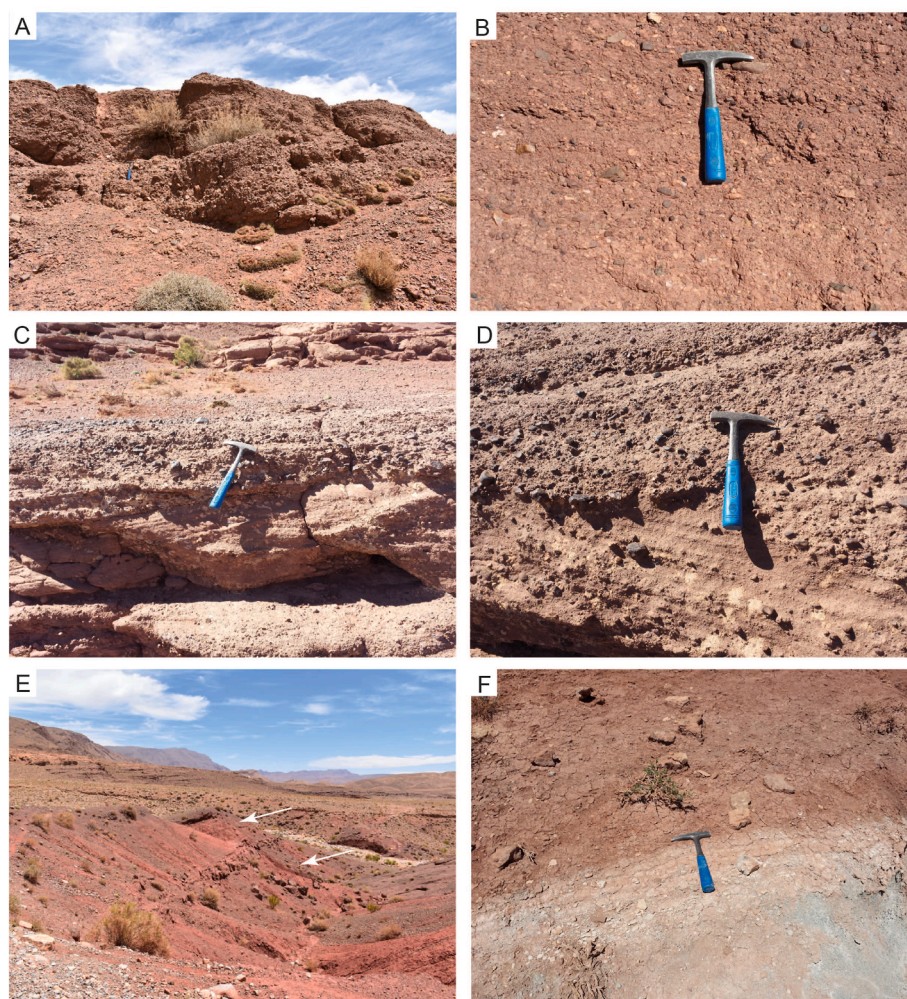
of these sequences at both regional and broader scales.

## 2. Study area: geological setting and lithostratigraphy

The study area, located in southeastern Morocco, is subdivided into two distinct sectors approximately 40 km apart (Fig. 1). The first sector corresponds to the Errachidia-Tadighoust region (north of Goulmima), while the second sector, near the Aghbalou N'Kerdouss village, represents the southwestern extension of the first sector and is characterized by a marked increase in elevation. The geological outcrops in the studied region span the Paleozoic, Mesozoic, and Cenozoic erathems, with Mesozoic and Cenozoic formations predominating (Fig. 1). These strata formed the initial

structures of the Preafrican Trough and the southern front of the Central High Atlas. To the north, the Early Jurassic units overlie the preserved Jurassic-Cretaceous red beds, which were folded into an anticline and a syncline (Hadri, 1997, 2004).

The studied series is stratigraphically positioned between two marine formations: the Upper Bajocian Tilougguit Formation (Hadri, 1997, 2004) and the Cenomanian-Turonian Akerbouss Formation (Jossen and Filali-Moutei, 1992) or Akrabou Formation (Hadri, 1997, 2004). Based on the lithostratigraphic and mapping works, this series has been subdivided into three or four formations, depending on the author (Fig. 2). Hadri (1997, 2004) delineated the Guettoua Formation (Bathonian), the Ifezouane Formation (Albian?), and the Cenomanian Aoufous Formation. Jossen and Filali-Moutei (1992) proposed a more detailed framework, including the Anou N'Tamda I



**Fig. 3** Studied sediments, Aghbalou N'Kerdouss (C5). **A)** Panoramic view of the massive conglomerates, southwest of C5; **B)** Massive conglomerates, southwest of C5; **C)** and **D)** Channelized cross-stratified conglomerates to gravelly sandstone, northeast of C5; **E)** Interbedded mudrock (white arrows), southwest of C5; **F)** Varicolored gypsiferous marls, northeast of C5. The geological hammer (30 cm) provides scale.



Formation (Middle to Upper Jurassic), Tikkedarine Formation, Anou N'Tamda II Formation (Infracenomanian), and Aoufouss Formation (Cenomanian–Turonian).

Previous research within these successions by [Adardor et al. \(2021\)](#) revealed a lack of identifiable biostratigraphic markers, prompting the adoption of [Hadri's \(1997, 2004\)](#) subdivision. However, the Ifezouane Formation was further subdivided into three members: a Lower Member (Mbr1), a Middle Member (Mbr2), and an Upper Member (Mbr3), based on lithofacies and paleoenvironmental interpretations ([Adardor et al., 2021](#)).

The tectonostratigraphic characteristics, particularly progressive unconformities, along with radiometric and biostratigraphic data obtained from the Dadès Valley and Jbel Istifane (west of Tinerhir), have led other researchers to subdivide these deposits into three units: Units 1, 2, and 3, each further separated into sub-units ([Benvenuti et al., 2017](#); [Moratti et al., 2018](#)). These authors interpreted a Lower Cretaceous age, based on fossil flora and on dating an interbedded basaltic layer.

Recently, [Benvenuti et al. \(2022\)](#) proposed a unified stratigraphic framework of these red beds between Ouarzazate and Errachidia cities (Jbel Timidrou area), which partially overlaps with the present study area. In the absence of biostratigraphic markers, [Benvenuti et al. \(2022\)](#) described a continuous stratigraphic framework ([Fig. 2](#)), which is primarily defined by progressive unconformities, interpreted as a response to the initial phases of a

generalized uplift of the Central High Atlas. In this model, the fossil-rich Cenomanian–Turonian marine limestones of the Akerbouss Formation unconformably overlay the red beds series. The Jbel Sidal and Aït Tafelt formations ([Fig. 2](#)), identified by [Benvenuti et al. \(2022\)](#), may be absent (significant discontinuity?) ([Hadri, 1997, 2004](#); [Adardor et al., 2021](#)) or alternatively, may correspond respectively to the lower and middle members of the Ifezouane Formation (cf. [Benvenuti et al., 2022](#)).

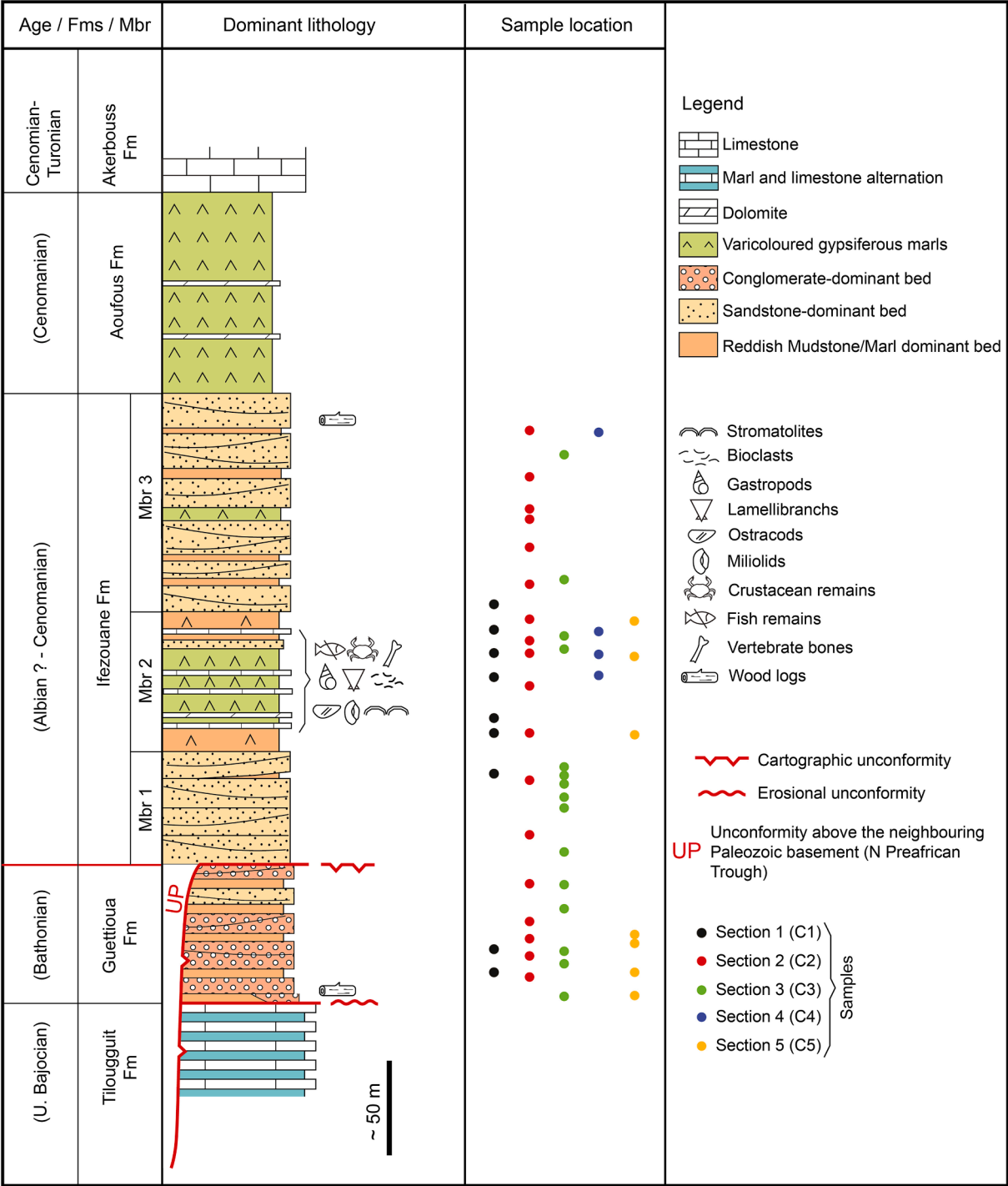
### 3. Results

#### 3.1. Lithological description

This study focuses on the Guettoua (up to 80 m-thick), and Ifezouane Formations (up to 300 m-thick). Lithologically, these formations consist of alternating conglomerates (rarely micro-conglomerates, either massive or stratified), lenticular and channelized sandstone bodies with stratifications, pelites/argillites, sporadically fossiliferous limestone and dolostone, gypsum layers, and gypsiferous marls. The assemblage of these facies reflects a range of paleoenvironments, from continental alluvial to marginolittoral settings ([Adardor et al., 2021](#); [Adardor, 2022](#)). A detailed description of the different lithofacies per formation is provided in [Table 1](#).

**Table 1** Details of the studied facies.

| Facies                                | Occurrences                                    | Description                                                                                                                                                                                                                                   | Microfacies                                                                                                                                                                                                                                 |
|---------------------------------------|------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Conglomerates and gravelly sandstones | Guettoua Fm                                    | Massive ( <a href="#">Fig. 3A and B</a> ), channelized cross-stratified conglomerate and gravelly sandstone ( <a href="#">Fig. 3C and D</a> ), decimeter- to meter-thick, graded to poorly graded, angular to subangular pebbles and cobbles. | Poorly sorted, angular to subangular, medium- coarse-grained quartz, feldspar, micas, and iron oxides, cemented by sparite ( <a href="#">Fig. 6A–F</a> ).                                                                                   |
| Sandstones                            | Guettoua Fm<br>Ifezouane Fm                    | Channelized planar and trough cross-stratified sandstone, decimeter- to meter-thick; lenticular beds up to 40 cm-thick and several meters of lateral extension with different sedimentary structures.                                         | Poorly sorted, angular to subangular fine- to coarse-grained quartz and feldspar, cemented by sparite ( <a href="#">Fig. 6G and H</a> ).                                                                                                    |
| Mudrocks                              | Guettoua Fm<br>Ifezouane Fm<br>(Mbr1 and Mbr3) | Centimeter- to decimeter-thick, reddish layers with intercalations of cross-laminated silty beds ( <a href="#">Fig. 3E</a> ).                                                                                                                 | Poorly sorted, angular to subangular, fine- to coarse-grained quartz, associated with siliceous fragments, gypsum, and undetermined heavy minerals ( <a href="#">Fig. 6J</a> ).                                                             |
| Marlstones                            | Ifezouane Fm<br>(Mbr2 and Mbr3)                | Varicolored, centimeter- to decimeter-thick marl layers (red, green, yellow, grey) ( <a href="#">Fig. 3F</a> ), often interbedded with centimeter- to decimeter-thick layers of gypsum, limestone, and dolomite.                              | Poorly sorted, angular to subangular, fine- to coarse-grained quartz, gypsum, and minor chlorite ( <a href="#">Fig. 6K</a> ). Some marlstones are fossiliferous and contain ostracods, fish remains, crabs, small bivalves, and gastropods. |



**Fig. 4** Summary of the stratigraphy of the red beds in the studied area. The locations of the analyzed samples are also indicated, modified after [Adardor et al. \(2021\)](#).

**3.2. Petrographic analysis**

In order to identify the potential source rocks of the studied sedimentary succession, both macroscopic (Fig. 5) and microscopic (Fig. 6) analyses were

conducted on conglomerate, sandstone, and mudrock bodies from the Guettioua and Ifezouane Formations (Fig. 4 and [supplementary material 1](#)). Macroscopic observations of the pebbles within the conglomerates and sandstones, along with the mudrocks, revealed a



**Fig. 5** Examples of analyzed conglomerate pebbles from southwest of Aghbalou N'Kerdouss. A, C, D, and F: Varicolored rhyolitic pebbles; B and E: Sandstone pebbles.

wide variety of pebble types differing in lithology, color, and size (ranging from millimetric to centimetric scales). These include clasts of limestone, sandstone, siliceous rock fragments, as well as pieces of magmatic, and metamorphic rocks (Figs. 5 and 6). Such diversity is mainly pronounced in the Guettioua Formation, where conglomeratic facies are more frequent, especially in sections C3 and C5, located northeast and southwest of Aghbalou N'Kerdouss, respectively (Fig. 5).

The various pebbles collected from the conglomerate facies of the Guettioua Formation, particularly within the C3 and C5 sections, yielded a variety of petrographic types. These include dark red pebbles (Fig. 5A–C, D, and F), primarily composed of feldspar and biotite (Fig. 6A–C), quartz (Fig. 6B–F), iron oxide, and opaque minerals (Fig. 6D, E, and F). Feldspar and biotite often show alteration and ferruginisation (Fig. 6A). The mesostasis consists of recrystallized volcanic glass, which is a mixture of quartz and feldspar, displaying a felsitic porphyry texture, indicative of a volcanic igneous rock, specifically a rhyolite. Other pebbles consist of jointed quartz with a granoblastic texture (Fig. 6I), indicative of a metamorphic rock, namely quartzite. Additional

pebbles contain dispersed quartz within a sparite, exhibiting two generations of fractures (Fig. 5B–E and 6G, H). The first set comprises closely spaced, parallel fractures commonly filled with quartz, while the second set consists of wider, less frequent fractures oriented perpendicular to the first set and interpreted as postdating the initial fracturing phase.

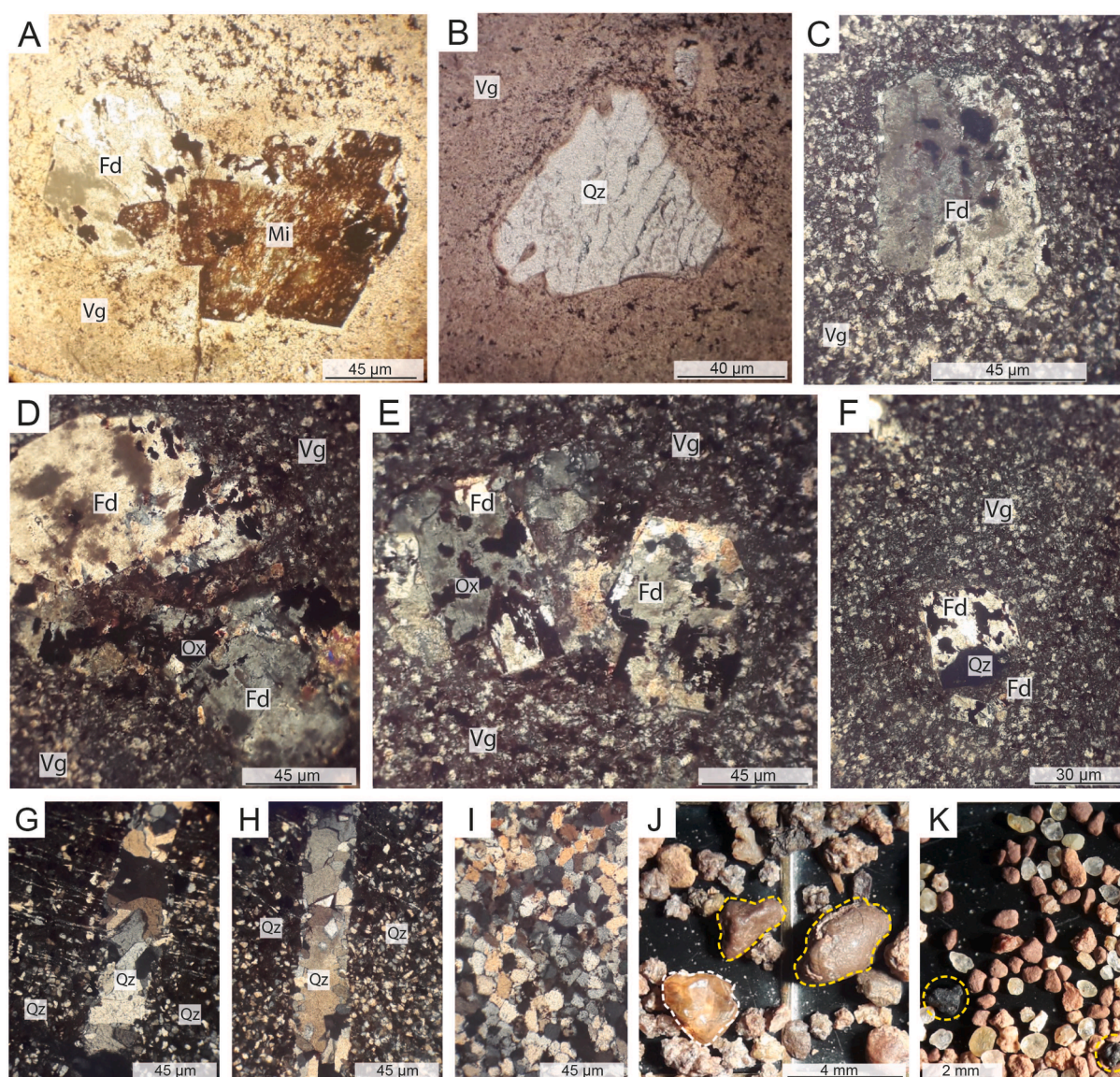
### 3.3. Mineralogy

X-ray diffraction (XRD) analyses revealed significant temporal and spatial variability in the mineralogical composition across the studied sections, both in the bulk samples and the clay fraction.

#### 3.3.1. Bulk mineralogy

XRD analyses of bulk samples (see [supplementary material 2](#)) revealed a mineralogical assemblage dominated by quartz, calcite, dolomite, and total clay minerals. Gypsum, K-feldspar, and plagioclase occur in minor amounts, while hematite and siderite are present in trace concentrations. Average mineralogical compositions and associated standard deviations for each studied section are presented in [Table 2](#).





**Fig. 6** Thin sections and microfacies microphotographs of the pebble in the conglomerates, southwest of Aghbalou N'Kerdouss (C5). **A)** Feldspar and micas in a volcanic glass, LPNA; **B)** Quartz in a volcanic glass, LPNA; **C)** Feldspar in a volcanic glass, LPA; **D)** Feldspar and micas in a volcanic glass, LPNA; **E)** and **F)** Feldspar with iron oxides in a volcanic glass, LPA; **G)** and **H)** Sandstone, LPA; **I)** Quartzite, LPA; **J)** and **K)** Microfacies of a yellow mudrock and marlstone showing brownish and blackish elements (highlighted by a dashed yellow line) and silica (highlighted by a dashed white line), NE of Aghbalou N'Kerdouss (C3). Qz: Quartz, Fd: Feldspar, Vg: Volcanic glass, Mi: Micas, Ox: Iron Oxides.

### 3.3.2. Clay mineralogy

The clay fraction is predominantly composed of illite and kaolinite across the studied sections. Smectite is present but restricted to specific intervals, notably within C1 and C2 sections. Chlorite occurs occasionally in C2 (in the sample Td5), C3 (in the sample A32), and C4 (in the samples: Ag14, Ag19, and Ag25) (see [supplementary materials 3, 4, and 5](#)). The average contents and associated standard deviations of the identified clay minerals for each section is summarized in [Table 3](#).

The spatial distribution of the clay minerals ([Table 3](#)) in the studied region revealed comparable patterns in the first two sections (Jbel Tissdar and Tadighoust), characterized by the abundance of illite and kaolinite, along with the presence of smectite. In contrast, the Aghbalou N'Kerdouss sections, exhibited a mineralogical assemblage dominated by illite and kaolinite; however, smectite is absent, and chlorite appeared locally in minor amounts in the middle of the section. Illite crystallinity ([Table 3](#)) varies within a range of  $0.05\text{--}0.67^\circ\Delta 2\theta$ , with an average value of  $0.36^\circ\Delta 2\theta$ ,

**Table 2** Bulk mineralogy (wt.%) of the studied samples.

| Section           | Samples | Bulk mineralogy |    |      |    |     |     |     |    |     |
|-------------------|---------|-----------------|----|------|----|-----|-----|-----|----|-----|
|                   |         | Total clay      | Qz | K-Fd | Pl | Cal | Dol | Hem | Gy | Sid |
| Jbel Tissdar (C1) | BR2     | 33              | 59 | 3    | 0  | 2   | 1   | 2   | 0  | 0   |
|                   | ER20    | 28              | 39 | 8    | 0  | 22  | 0   | 3   | 0  | 0   |
|                   | Tz2     | 52              | 25 | 6    | 2  | 6   | 8   | 1   | 0  | 0   |
|                   | Tz8     | 22              | 30 | 14   | 4  | 2   | 27  | 0   | 1  | 0   |
|                   | Tz19    | 53              | 32 | 6    | 1  | 2   | 5   | 0   | 1  | 0   |
|                   | Tz28    | 24              | 34 | 0    | 0  | 8   | 31  | 3   | 0  | 0   |
|                   | Tz39    | 56              | 13 | 0    | 0  | 5   | 16  | 3   | 7  | 0   |
|                   | Tz44    | 40              | 57 | 0    | 0  | 1   | 2   | 0   | 0  | 0   |
| Av.               |         | 39              | 36 | 5    | 1  | 6   | 11  | 2   | 1  | 0   |
| S.D.              |         | 14              | 16 | 5    | 1  | 7   | 12  | 1   | 2  | 0   |
| Tadighoust (C2)   | Td17    | 37              | 41 | 10   | 1  | 6   | 2   | 3   | 0  | 0   |
|                   | Td21    | 51              | 29 | 4    | 3  | 7   | 1   | 4   | 1  | 0   |
|                   | Td27    | 30              | 50 | 9    | 0  | 5   | 6   | 0   | 0  | 0   |
|                   | Td43    | 41              | 13 | 2    | 0  | 13  | 16  | 5   | 10 | 0   |
|                   | Td49    | 41              | 33 | 0    | 0  | 9   | 6   | 6   | 5  | 0   |
|                   | Td53    | 35              | 19 | 3    | 0  | 31  | 4   | 2   | 6  | 0   |
|                   | Td57    | 38              | 24 | 5    | 0  | 3   | 28  | 2   | 0  | 0   |
|                   | Td63    | 51              | 7  | 2    | 0  | 39  | 0   | 1   | 0  | 0   |
|                   | Td64    | 44              | 39 | 5    | 0  | 5   | 7   | 0   | 0  | 0   |
| Av.               |         | 42              | 26 | 4    | 0  | 12  | 11  | 2   | 2  | 0   |
| S.D.              |         | 7               | 15 | 3    | 1  | 13  | 14  | 2   | 4  | 0   |
| NE Agh N'Ker (C3) | A4      | 50              | 31 | 8    | 0  | 0   | 11  | 0   | 0  | 0   |
|                   | A11     | 48              | 33 | 6    | 0  | 2   | 8   | 3   | 0  | 0   |
|                   | A29     | 21              | 17 | 0    | 0  | 15  | 22  | 8   | 17 | 0   |
|                   | A32     | 69              | 13 | 9    | 3  | 6   | 0   | 0   | 0  | 0   |
|                   | A40     | 53              | 33 | 0    | 0  | 6   | 8   | 0   | 0  | 0   |
|                   | A43     | 21              | 41 | 16   | 0  | 6   | 9   | 5   | 2  | tr  |
| Av.               |         | 44              | 28 | 7    | 1  | 6   | 10  | 3   | 3  | 0   |
| S.D.              |         | 19              | 11 | 6    | 1  | 5   | 7   | 3   | 7  | 0   |
| NE Agh N'Ker (C4) | Ag14    | 30              | 15 | 4    | 2  | 0   | 43  | 4   | 2  | 0   |
|                   | Ag19    | 46              | 6  | 4    | 1  | 0   | 39  | 4   | 0  | 0   |
|                   | Ag23    | 38              | 27 | 3    | 0  | 0   | 29  | 3   | 0  | 0   |
|                   | Ag25    | 53              | 14 | 4    | 0  | 14  | 12  | 3   | 0  | 0   |
| Av.               |         | 42              | 16 | 4    | 1  | 4   | 31  | 4   | 1  | 0   |
| S.D.              |         | 10              | 9  | 1    | 1  | 7   | 14  | 1   | 1  | 0   |
| SW Agh N'Ker (C5) | A49     | 36              | 28 | 19   | 0  | 1   | 13  | 3   | 0  | 0   |
|                   | A57     | 32              | 29 | 5    | 2  | 4   | 11  | 5   | 10 | 1   |
|                   | A72     | 51              | 41 | 7    | 0  | 1   | 0   | 0   | 0  | 0   |
|                   | A76     | 32              | 7  | 5    | 0  | 1   | 49  | 6   | 0  | 0   |
| Av.               |         | 38              | 26 | 9    | 1  | 2   | 18  | 4   | 3  | 0   |
| S.D.              |         | 9               | 14 | 7    | 1  | 2   | 21  | 3   | 5  | 1   |

Qz = quartz; K-Fd = K-feldspar; Pl = plagioclase; Cal = calcite; Dol = dolomite; Hem = hematite; Gy = gypsum; Sid = siderite; tr = trace. Av. = average; S.D. = standard deviation.

while the illite chemistry index varies from 0.09 to 0.79, with an average of 0.46.

### 3.4. Grain size and calcimetric analysis

The grain size analyses of the mudrock and marlstone facies from sections C1 and C2 indicate relatively consistent trends throughout the vertical profiles, with no abrupt changes from base to top (Table 4).

Calcimetric measurements (Table 4) performed on the different marl-pelitic beds show comparable carbonate contents across the studied series, with values

ranging from a minimum of approximately 3 % to a maximum value near 50 %, and an overall average around 20 %.

## 4. Discussion

### 4.1. New insights on the sedimentological processes in Jurassic-Cretaceous red beds

The grain size data (see [supplementary material 6](#)) and calcimetric analyses (Fig. 7) conducted in this

**Table 3** Clay mineralogy (wt.%) of the studied samples.

| Section           | Samples | Clay mineralogy (<2 $\mu$ m) |       |       |        |                      |                        |
|-------------------|---------|------------------------------|-------|-------|--------|----------------------|------------------------|
|                   |         | K (%)                        | I (%) | M (%) | Ch (%) | Illite crystallinity | Illite chemistry index |
| Jbel Tissdar (C1) | BR2     | 17                           | 83    | —     | —      | 0.51                 | 0.63                   |
|                   | ER20    | 44                           | 56    | —     | —      | 0.28                 | 0.24                   |
|                   | Tz8     | 13                           | 65    | 22    | —      | 0.09                 | 0.09                   |
|                   | Tz19    | 34                           | 66    | —     | —      | 0.10                 | 0.20                   |
|                   | Tz28    | —                            | 82    | 18    | —      | 0.24                 | 0.47                   |
|                   | Tz39    | 13                           | 83    | 4     | —      | 0.47                 | 0.31                   |
|                   | Tz44    | 20                           | 80    | —     | —      | 0.31                 | 0.31                   |
| Av.               |         | 24                           | 74    | 15    | —      | —                    | —                      |
| S.D.              |         | 15                           | 11    | 10    | —      | —                    | —                      |
| Tadighoust (C2)   | Td21    | 44                           | 56    | —     | —      | 0.16                 | 0.20                   |
|                   | Td27    | 25                           | 75    | —     | —      | 0.05                 | 0.79                   |
|                   | Td43    | 8                            | 87    | 5     | —      | 0.20                 | 0.47                   |
|                   | Td53    | 21                           | 68    | 11    | —      | 0.09                 | 0.09                   |
|                   | Td57    | 12                           | 88    | —     | —      | 0.36                 | 0.63                   |
|                   | Td63    | 6                            | 94    | —     | —      | 0.67                 | 0.39                   |
|                   | Td64    | —                            | —     | —     | —      | —                    | —                      |
| Av.               |         | 19                           | 78    | 8     | 0      | —                    | —                      |
| S.D.              |         | 15                           | 32    | 4     | 0      | —                    | —                      |
| NE Agh N'Ker (C3) | A11     | 8                            | 92    | —     | —      | 0.63                 | 0.55                   |
|                   | A32     | 6                            | 90    | —     | 4      | 0.28                 | 0.24                   |
|                   | A40     | 5                            | 95    | —     | —      | 0.24                 | 0.20                   |
| Av.               |         | 6                            | 92    | —     | 4      | —                    | —                      |
| S.D.              |         | 2                            | 3     | —     | 2      | —                    | —                      |
| NE Agh N'Ker (C4) | Ag14    | 24                           | 71    | —     | 5      | 0.18                 | 0.20                   |
|                   | Ag19    | —                            | 71    | —     | 29     | 0.36                 | 0.63                   |
|                   | Ag23    | 10                           | 90    | —     | —      | 0.36                 | 0.63                   |
|                   | Ag25    | 4                            | 79    | —     | 17     | 0.36                 | 0.63                   |
| Av.               |         | 13                           | 78    | —     | 17     | —                    | —                      |
| S.D.              |         | 11                           | 9     | —     | 13     | —                    | —                      |
| SW Agh N'Ker (C5) | A49     | 78                           | 22    | —     | —      | 0.67                 | 0.71                   |
|                   | A57     | 52                           | 48    | —     | —      | 0.55                 | 0.63                   |
|                   | A72     | 33                           | 67    | —     | —      | 0.44                 | 0.79                   |
|                   | A76     | 26                           | 74    | —     | —      | 0.36                 | 0.63                   |
| Av.               |         | 47                           | 53    | —     | —      | —                    | —                      |
| S.D.              |         | 23                           | 23    | —     | —      | —                    | —                      |

I = illite; K = kaolinite; M = smectite; Ch = chlorite.

study provide new perspectives on the sedimentary dynamics that governed deposition of Jurassic-Cretaceous red beds. The temporal evolution of grain size within the mudrock and marlstone facies (Table 4) reveals an inverse relationship between sand and clay contents, while silt content remains relatively stable across the studied sections. According to the Shepard classification (Shepard, 1954), most of the analyzed samples show a mix of clay, silt, and sand, with a predominance of sand. The observed sand dominance is evidence for deposition under high-energy conditions, whereas the presence of substantial clay and silt reflects lower-energy environments (Galloway, 1975; Allen, 1984), indicating dynamic energy fluctuations within the same depositional system. In addition, the observed variability in grain size distribution is consistent with a transitional depositional setting, in

which continental inputs interact with marine processes. This interaction results in a facies diversification characteristic of sedimentary systems evolving at the boundary between continental and marginal marine environments (Reading, 1996; Nichols, 2009). These interpretations are further supported by the heterogeneous nature of the investigated sedimentary record, marked by the coexistence of sandy, silty, and clay-rich sediments. Such heterogeneity reflects the interplay between terrigenous input and marine incursions, reinforcing previous sedimentological interpretations of environments ranging from continental (alluvial/fluvial) to marginal-littoral (protected lagoon/sabkha) (Adardor *et al.*, 2021).

The calcimetric data (Table 4 and Fig. 7) for sections C1 to C5 show  $\text{CaCO}_3$  contents ranging from 3.7 % to 51.6 %, with an average of 18.8 %, corresponding to



**Table 4** Total CaCO<sub>3</sub>, clay, silt, and sand (wt.%) of the studied samples.

| Section                 | Samples | Total CaCO <sub>3</sub><br>(wt. %) | Particle size distribution (wt. %) |                    |                  |
|-------------------------|---------|------------------------------------|------------------------------------|--------------------|------------------|
|                         |         |                                    | Clay<br>(<4 µm)                    | Silt (4<br>–63 µm) | Sand<br>(>63 µm) |
| Jbel Tissdar<br>(C1)    | BR2     | 5.2                                | 41                                 | 33                 | 26               |
|                         | ER20    | 12.4                               | 23                                 | 33                 | 44               |
|                         | Tz2     | 14.9                               | 41                                 | 35                 | 24               |
|                         | Tz8     | 23.4                               | 27                                 | 34                 | 39               |
|                         | Tz19    | 6.7                                | 41                                 | 34                 | 25               |
|                         | Tz28    | 27.3                               | 41                                 | 10                 | 49               |
|                         | Tz39    | 15.7                               | 17                                 | 56                 | 27               |
|                         | Tz44    | 12.2                               | 14                                 | 19                 | 67               |
| Av.                     |         | 14.7                               | 30,6                               | 31,8               | 37,6             |
| S. D.                   |         | 7.6                                | 11,7                               | 13,3               | 15,2             |
| Tadighoust<br>(C2)      | Td17    | 12.2                               | 21                                 | 24                 | 55               |
|                         | Td21    | 6.6                                | 33                                 | 55                 | 12               |
|                         | Td27    | 10.2                               | 38                                 | 27                 | 35               |
|                         | Td43    | 35.4                               | 8                                  | 35                 | 57               |
|                         | Td49    | 7.4                                | 41                                 | 35                 | 24               |
|                         | Td63    | 29.2                               | 34                                 | 30                 | 36               |
|                         | Td64    | 13.5                               | 23                                 | 32                 | 45               |
| Av.                     |         | 17.8                               | 30,9                               | 35,8               | 33,4             |
| S. D.                   |         | 11.3                               | 13,0                               | 10,6               | 19,4             |
| NE Agh<br>N'Ker<br>(C3) | A4      | 20.3                               | —                                  | —                  | —                |
|                         | A11     | 15.1                               | —                                  | —                  | —                |
|                         | A29     | 19.8                               | —                                  | —                  | —                |
|                         | A40     | 16.6                               | —                                  | —                  | —                |
| Av.                     |         | 17.9                               |                                    |                    |                  |
| S. D.                   |         | 2.5                                |                                    |                    |                  |
| NE Agh<br>N'Ker<br>(C4) | Ag14    | 37.9                               | —                                  | —                  | —                |
|                         | Ag19    | 51.6                               | —                                  | —                  | —                |
|                         | Ag23    | 22.4                               | —                                  | —                  | —                |
|                         | Ag25    | 22.6                               | —                                  | —                  | —                |
| Av.                     |         | 33.6                               |                                    |                    |                  |
| S. D.                   |         | 14.0                               |                                    |                    |                  |
| SW Agh<br>N'Ker<br>(C5) | A43     | 3.7                                | —                                  | —                  | —                |
|                         | A49     | 19.9                               | —                                  | —                  | —                |
|                         | A57     | 15.1                               | —                                  | —                  | —                |
|                         | A72     | 5.2                                | —                                  | —                  | —                |
|                         | A76     | 35.5                               | —                                  | —                  | —                |
| Av.                     |         | 15.9                               |                                    |                    |                  |
| S. D.                   |         | 12.9                               |                                    |                    |                  |

a clayey to marly facies. These significant fluctuations in carbonate content suggest temporal variations in carbonate productivity and detrital input. Minimum carbonate concentrations are associated with beds interbedded with continental and evaporitic facies, while higher carbonate contents are recorded in fossiliferous marlstone levels, often interbedded with bioclastic limestones.

Member 2 of the Ifezouane Formation stands out with significantly higher CaCO<sub>3</sub> concentrations compared to other units, indicating increased marine influence, reduced terrigenous influx, and the development of fossiliferous carbonate beds. CaCO<sub>3</sub> percentages observed in the other units are more influenced by terrigenous inputs. The mean CaCO<sub>3</sub>

value for this member is 20.6 %, suggesting conditions favorable to carbonate deposition in a restricted marine setting.

To contextualize these findings, comparative data from modern analogues are instructive. For instance, the Marchica lagoon evaporitic system in northeastern Morocco, shows average CaCO<sub>3</sub> values of 29.38 % (El Ouaty *et al.*, 2022), while the lagoonal system in the Western Peloponnesus Gulfs in Greece can reach up to 35 % of CaCO<sub>3</sub> content (Kontopoulos and Bouzos, 2011), both indicative of restricted marine conditions with moderate terrigenous influence. In contrast, evaporitic sabkha systems, such as those found along the southern coast of Kuwait (CaCO<sub>3</sub> content up to 15 %) (Al-Otaibi, 2020) and the Mediterranean coastal Sabkha of EL-Guettiat in southeastern Tunisia (CaCO<sub>3</sub> content of 18.5 %) (Bouabid *et al.*, 2024), formed in settings with dominant continental inputs and limited carbonate production.

CaCO<sub>3</sub> values recorded in Member 2, positioning it between these two modern analogues, may be due to the deposition of a restricted lagoon/sabkha system characterized by fluctuating salinity and alternating depositional conditions.

The highest CaCO<sub>3</sub> values, sometimes reaching up to 50 % (Fig. 7), coupled with the identified facies, low-diversity euryhaline fauna, and the presence of washover deposits (Adardor *et al.*, 2021), was interpreted to indicate deposition primarily in an inner lagoon environment. This interpretation is consistent with the established depositional models for restricted marine environments (Nichols, 2009; Warren, 2016; Teillet *et al.*, 2024), placing the Ifezouane Formation within a broader palaeogeographic and sedimentological framework of lagoonal-sabkha systems marked by strong terrestrial–marine interaction and episodic carbonate production.

#### 4.2. Sediment provenances

To better constrain the provenance of sediments within the studied Jurassic–Cretaceous succession, illite crystallinity values were plotted against the illite chemistry index (Fig. 8). This relationship reveals two distinct compositional fields. The first, located on the left side of the diagram, corresponds to Fe–Mg rich illites, predominantly derived from Tadighoust and Jbel Tissdar sediments. The second, on the right (illite chemistry index >0.5), corresponds to Al-rich illites, associated with the Aghbalou N'Kerdouss sediments. These contrasting mineralogical signatures suggest the involvement of two distinct source provinces in the genesis of the studied Jurassic–Cretaceous red beds.

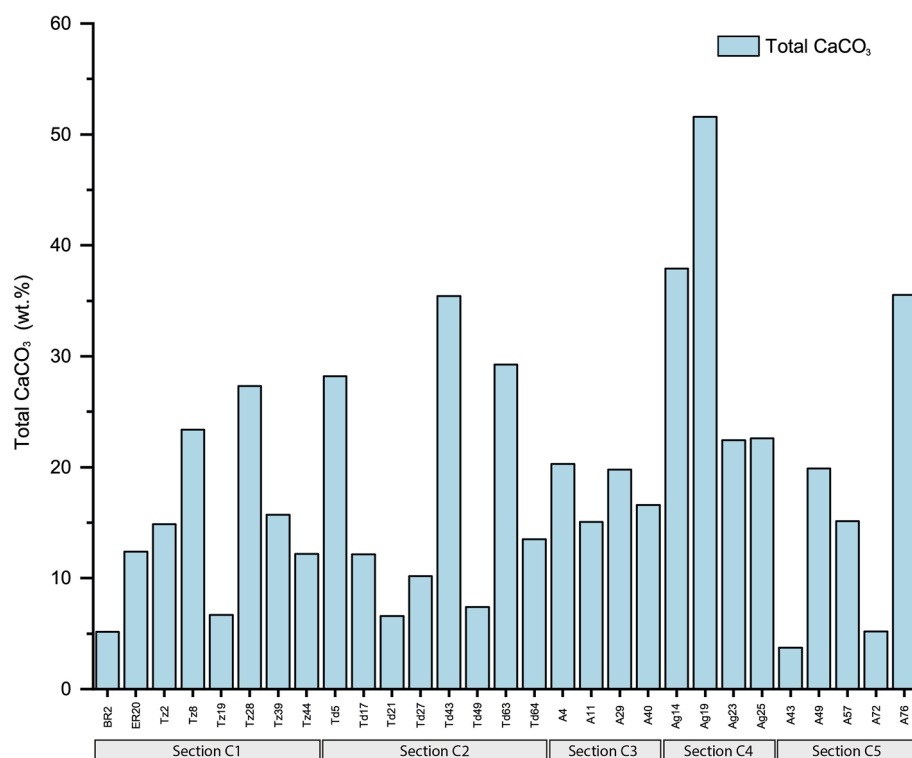


Fig. 7 Total CaCO<sub>3</sub> in mudrock-marlstone beds of the studied sections.

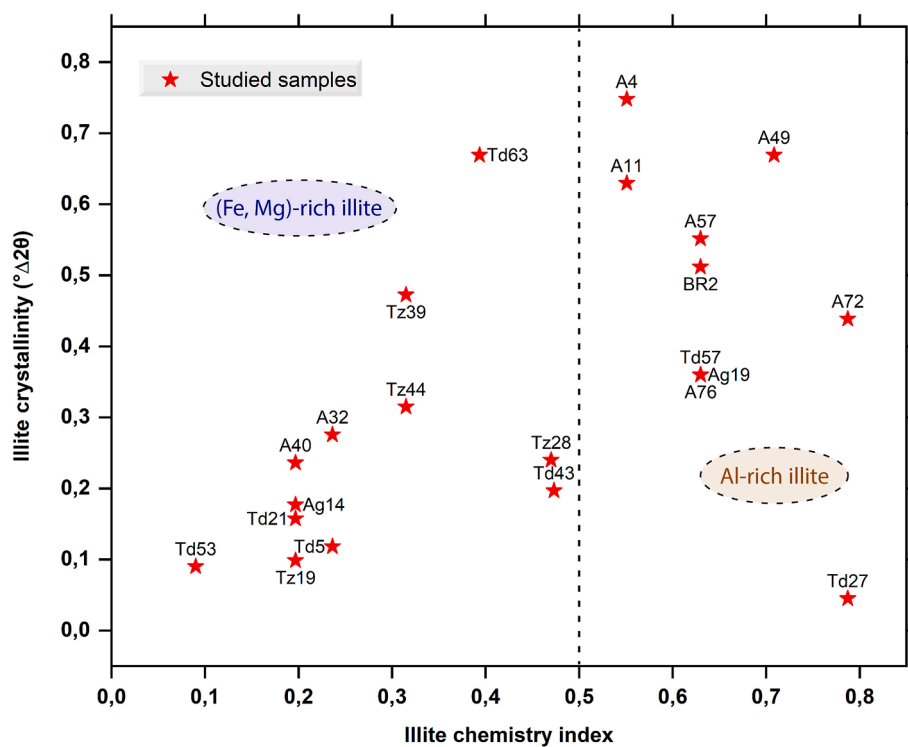


Fig. 8 Clay mineral provenance analysis in the studied sediments based on the correlation between the illite chemistry index and the illite crystallinity of sediments.

The integration of petrographic observations with clay and bulk mineralogy data supports a provenance model in which the primary source (major) of the Jurassic-Cretaceous sediments was located to the south, within the Anti-Atlas and Saharan domains (Fig. 9). This region, known for its complex geodynamic history, is composed by Precambrian–Paleozoic basement rocks with diverse lithologies (Piqué and Michard, 1989; Soulaïmani *et al.*, 1997). These basement terrains likely served as the major contributors to the detrital input in the surrounding basins during the Jurassic-Cretaceous. Conversely, a secondary source (minor) province is probably represented by the adjacent highlands to the northeast and northwest of the study area, composed of Lower Jurassic rocks (Hadri, 1997, 2004) (Fig. 9). These more proximal sources likely supplied localized sedimentary materials, complementing the dominant flux originating from the southern terrains.

#### 4.3. Paleoclimate and paleotemperature

In the southern front of the Central High Atlas and Northern Preafrican Trough, the Jurassic-Cretaceous

series consists of sediments formed under shallow burial conditions, as evidenced by the illite crystallicity (average value =  $0.36^\circ\Delta 2\theta$ ), which falls within the low anchizone domain ( $0.42^\circ\Delta 2\theta$ – $0.25^\circ\Delta 2\theta$ ) (Kübler, 1967; Merriman and Frey, 1999; Mukherjee *et al.*, 2019). Thus, the identified clay mineral assemblages reflect relative paleoclimate variations across the studied stratigraphic series. The dominance of illite over kaolinite and chlorite suggests generally prevailing hot and dry climatic conditions with intermittent humid phases (Chamley, 1989). The local presence of smectite, particularly within Member 2 of the Ifezouane Formation, and its association with gypsum-rich levels, indicates seasonally humid conditions (Chamley, 1989). Previous studies (Lebedel *et al.*, 2015) on the overlying formations further indicate that the Aoufous Formation was deposited under a dry climate during the Cenomanian, which transitioned into a more humid and hotter climate during the Cenomanian-Turonian (Akerbouss Formation), coinciding with major global climatic, oceanographic, and biogeochemical perturbations, resulting from the onset of the Oceanic Anoxic Event 2 (OAE2) (Flögel *et al.*, 2011; Jarvis *et al.*, 2011). These global

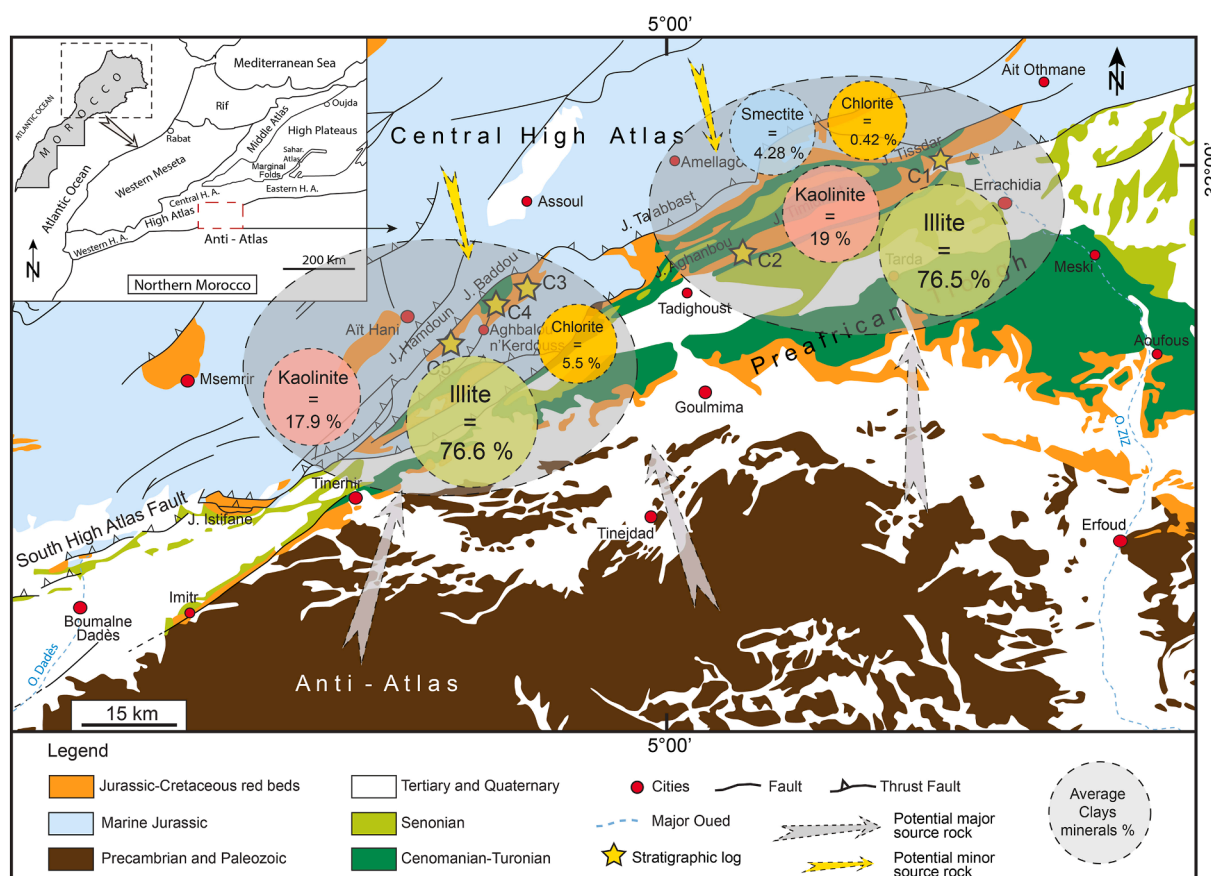
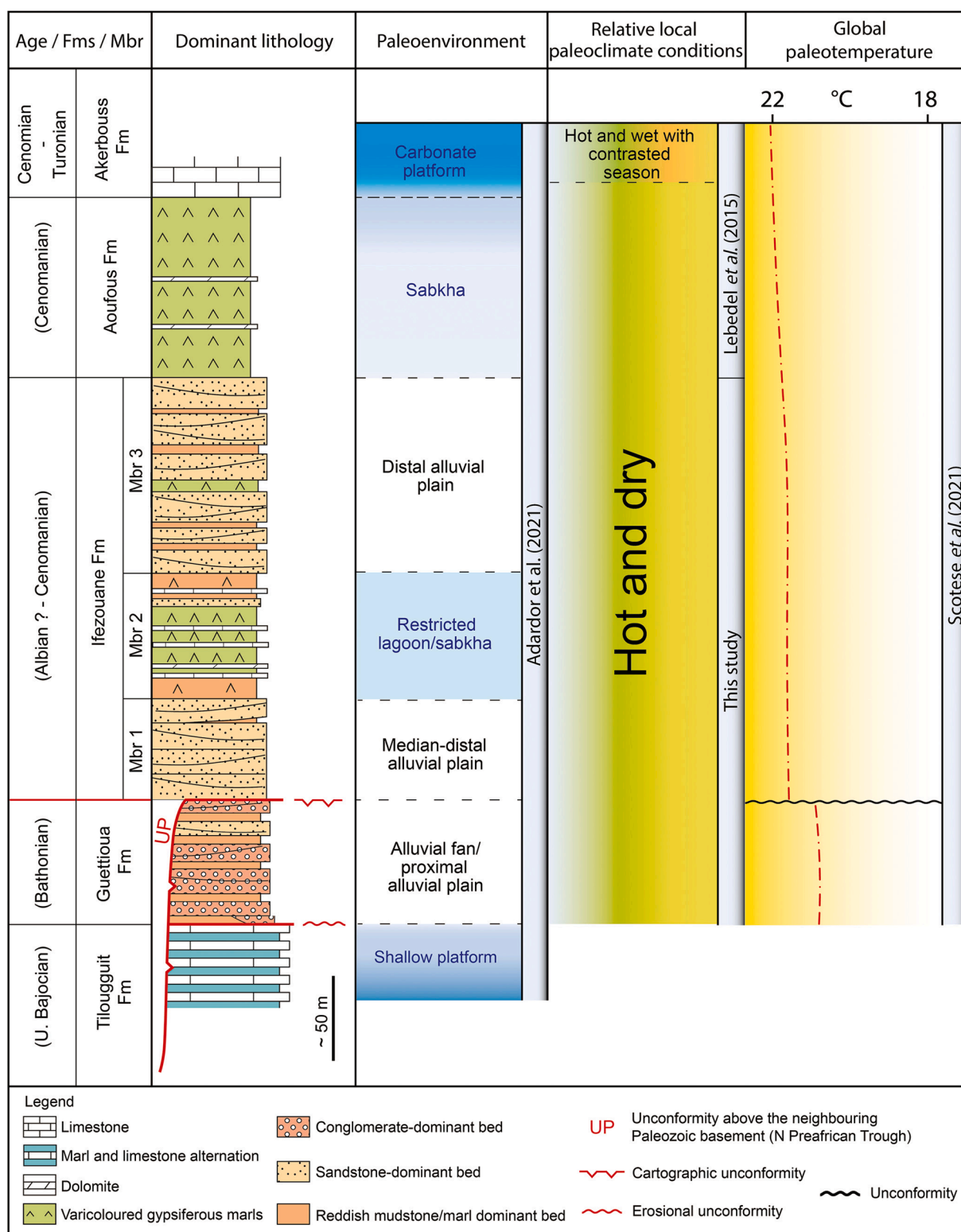


Fig. 9 Simplified geological map showing the average distribution of clay minerals in the studied sectors as well as sediment provenances.





**Fig. 10** Summarized stratigraphic, paleoenvironmental, and relative local paleoclimatic conditions of the studied interval compared to the global paleotemperature trend during the Middle Jurassic to the Upper Cretaceous.

changes likely influenced sedimentary dynamics and climatic signals at the large scale, including the studied sedimentary system. A comparison with the Global Paleotemperature Curve (Scotese *et al.*, 2021) reveals a progressive rise in temperatures from approximately 20 °C during the Middle Jurassic to values exceeding 20 °C in the Upper Cretaceous (Fig. 10), with a thermal maximum during the Cenomanian–Turonian (93 Ma, Ziegler *et al.*, 1985). This global thermal trend is consistent with local sedimentological and mineralogical data, indicating a regional phase of increasing aridity and temperature (Fig. 10), culminating during the Cenomanian–Turonian Thermal Maximum Event. The alignment of regional paleoclimatic signals with global temperature curves supports a robust interpretation of a progressively arid paleoclimate in the studied region. To refine this interpretation, future research incorporating paleotemperature proxies, isotope analyses, and exploring the potential preservation of paleosol profiles within these red beds, will be essential for reconstructing high-resolution climate evolution across the studied interval.

#### 4.4. Climatic and/or tectonic influence on illite abundance: A multi-factor approach

Illite, commonly considered a detrital clay mineral, typically forms in environments where chemical weathering is limited and is subsequently transported and deposited in different depositional environments (Chamley, 1989). However, elevated illite concentrations may also originate from tectonic processes, such as crustal uplift, which enhances mechanical erosion, contributing to the release of large amounts of detrital illite (e.g., Fagel *et al.*, 1994; Hong *et al.*, 2010).

To differentiate between climatic and tectonic influences, the crystallinity of illite was assessed through the Full Width at Half Maximum (FWHM) of the (001) peak at 10 Å, as measured by XRD (Kübler, 1967). The FWHM values in the analysed samples range from 0.05° to 0.67°  $\Delta 2\theta$ . FWHM values below 0.42°  $\Delta 2\theta$  (e.g., samples Tz8, Td 21, A32; Table 3), indicate moderately to well-crystallized illite, typical of diagenetic to low-grade metamorphic conditions. This could support the hypothesis of a tectonic origin of the sediments following the erosion of metamorphic rocks during crustal uplift. Conversely, samples with FWHM values exceeding 0.42°  $\Delta 2\theta$  (e.g., samples Tz39, Td63, A11; Table 3) suggest poorly crystallized illite, probably of detrital origin or formed *in situ* through surface weathering processes, and are consistent with a hot and dry climate signal.

Tectonically, the Jbel Timidrout, Dadès Valley, and Jbel Istifane regions show clear evidence of syn-tectonic sedimentation associated with an early tectonic uplift during the Middle Bathonian to Upper Cretaceous, predating the Cenozoic tectonic inversion (Benvenuti *et al.*, 2017, 2022; Moratti *et al.*, 2018; Cavallina *et al.*, 2018). This supports the hypothesis that tectonic activity played a major role in controlling illite abundance (average value around ~76 %) in the analyzed sediments.

#### 4.5. Palaeogeographic dynamics

The paleocurrent measurements and sediment provenance studies in the southern front of the Central High Atlas and Northern Preafrican Trough (Benvenuti *et al.*, 2017; Cavallina *et al.*, 2018; Adardor *et al.*, 2021), together with the current findings, confirmed the dual provenance of the terrigenous-dominated deposits in this region. In the Adrar Aglalag syncline, Cavallina *et al.* (2018) reported a gradual decrease in conglomeratic clasts derived from Jurassic carbonate formations, alongside an increase in clasts originating from Triassic basalts and Paleozoic metamorphic rocks. Similarly, in the Aghbalou N'Kerdouss–Tadighoust region (Adardor *et al.*, 2021), the conglomeratic facies display a dominance of various angular to sub-angular Precambrian and Paleozoic pebbles and cobbles. In addition, the revisiting paleocurrent analysis in these studies (Cavallina *et al.*, 2018; Adardor *et al.*, 2021), indicates a generalized southern source for sediments, while, in adjacent areas, at the Dadès Valley and Jbel Istifane, the terrigenous materials originated from the proto-Central High Atlas to the north, as indicated by the south-southeast paleo-flow direction (Benvenuti *et al.*, 2017).

The integrated results presented in this study based on the illite crystallinity and chemistry index correlations, coupled with petrographic analysis, further support this dual provenance, highlighting distinct sedimentary contributions from both the southern sources (Anti-Atlas and Saharan Domain) and northern sources (Jurassic uplands).

## 5. Conclusions

Based on sedimentological and mineralogical analyses of the Jurassic–Cretaceous series from the southern front of the Central High Atlas and Northern Preafrican Trough, this study highlights the following key findings:

- 1) Grain size and CaCO<sub>3</sub> data provide deeper insights into transitional depositional settings, with lagoonal to sabkha conditions particularly well expressed in the Ifezouane Formation (Member 2).
- 2) Clay mineral assemblages are dominated by illite and kaolinite, with variable amount of smectite and chlorite.
- 3) Provenance is dual: (i) southern sources from the Anti-Atlas–Sahara domains, and (ii) northern sources from the Jurassic highlands.
- 4) High illite content and illite crystallinity point to tectonic uplift and enhanced erosion, in addition to climatic controls.
- 5) Sedimentological and mineralogical evidence points to an arid to semi-arid paleoclimate with intermittent humid phases during the Bathonian to the Albian? - Cenomanian interval.

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### CRediT authorship contribution statement

**Said Adardor:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hicham Nasri:** Writing – review & editing, Validation, Methodology, Data curation. **Hamid Haddoumi:** Writing – review & editing, Investigation. **Radouan El Bamiki:** Writing – review & editing. **Rachid Chennouf:** Investigation. **Hanane Miri:** Investigation.

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### Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jop.2025.100299>.