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Stratigraphic and tectonic architecture of the Middle Jurassic-Upper Cretaceous at the southern front of the Central High Atlas (Morocco): a cartographic revision

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ABSTRACT

The Middle Jurassic (Bathonian)-Upper Cretaceous (Maastrichtian) deposits exposed at the southern front of the Central High Atlas (CHA, Southern Morocco) include thick fluvial successions largely undifferentiated in previous studies. These continental strata record a long period of relief formation due to crustal shortening and subsequent denudation that predated the Cenozoic, syn-collisional, tectonic inversion of the CHA. This study, carried out through mapping along more than 270 km between Ouarzazate and Errachidia towns, firstly proposes a rock-stratigraphic unified scheme based on a framework of unconformity-bounded stratigraphic units, including sub-units, differentiated for their specific depositional meaning. Secondly, the geological maps and related cross-sections illustrate the evidence of syn-depositional shortening with distinct deformation styles, outlining pre- and syn-collisional tectonic inversion.

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1. Introduction

In the evolution of the High Atlas system (Southern Morocco; Frizon de Lamotte et al., 2008; Figure 1(a)), Middle Jurassic-Upper Cretaceous mostly continental successions (Figure 1(b)) have been differently interpreted in tectono-sedimentary terms. An early interpretation of crustal shortening with consequent uplift and denudation (Choubert & Faure-Muret, 1960-1962) has been superseded with the advent of Plate Tectonics. Triassic rifted basins invaded by the sea during the early Jurassic recorded the Gondwana break-up followed by the opening and spreading of the Central Atlantic and NW Tethys oceans. Consequently, the Middle Jurassic-Late Cretaceous sedimentary record has been ascribed to successive cycles of sea-level fluctuations during a post-rift stage unaffected by significant tectonic deformation (Frizon de Lamotte et al., 2008). More recently, evidence of syn-tectonic deposition during the Late Mesozoic in the High Atlas basins has been related to (1) generic regional shortening (Bertotti & Gouiza, 2012; Gouiza, 2011); (2) compression generated by intraplate stresses propagated across the northern margin of the Africa plate by the competing expansion of the Central Atlantic and NW Tethys oceans (Benvenuti et al., 2017; Moratti et al., 2018); (3) syn-depositional growth of salt diapirs in a persisting extensional regime (Bouchouata et al.,

1995; Ettaki et al., 2007; Michard et al., 2011; Moragas et al., 2018; Saura et al., 2014; Vergés et al., 2017).

After the geological mapping of a limited sector of the southern front of the Central High Atlas (CHA) (Massironi & Moratti, 2007; Schiavo & Taj Eddine, 2007), we carried out a systematic survey of the upper Mesozoic successions along the 270 km-long southern front of the CHA resulting in a collection of four geological maps at 1:50,000 scale, in the Adrar Aglalal, Dadès valley, Jbel Istifane and Jbel Timidrou areas, and reported in Plates 1–4. These maps constructed with the aim of revising the stratigraphic architecture of Upper Cretaceous (Cenomanian-Maastrichtian) successions in existing maps (Figure 2), disclose a more complex scenario for the evolution of the CHA (Benvenuti et al., 2017; Moratti et al., 2018).

2. The late Mesozoic of the Central High Atlas

The lithostratigraphy of Middle Jurassic-Upper Cretaceous dominantly continental deposits includes formations not uniformly distributed and differently named across the CHA (Figures 1(b), 2 and 3). In the northern CHA front, these continental red beds are well exposed in synclinal basins (Couches Rouges, Charrière et al., 2005; Charrière & Haddoumi, 2016;

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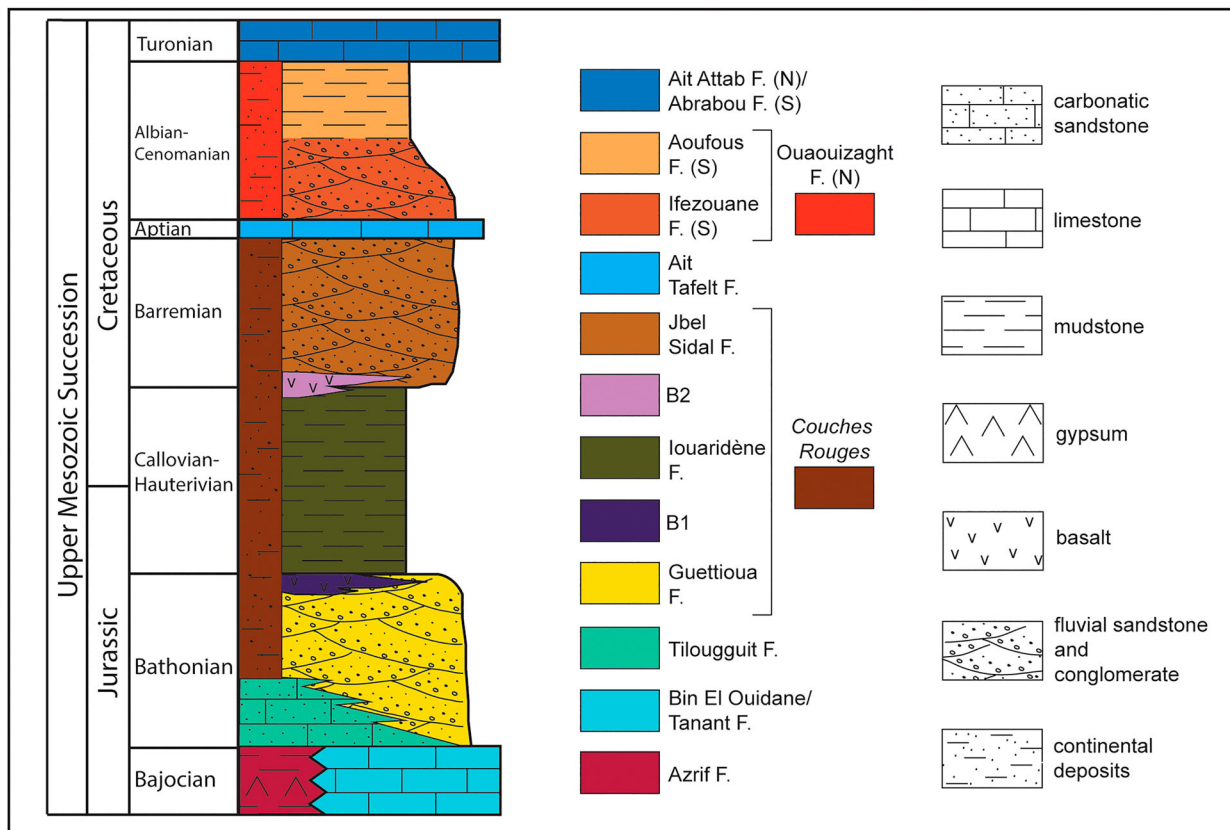


Figure 3. Lithostratigraphic scheme of the Middle Jurassic-Cretaceous of the CHA.

a time-transgressive onset of these deposits: from the Bathonian-Callovian to the latest Jurassic-Early Cretaceous (Hauterivian).

- Jbel Sidal Formation: fluvial reddish sandstone and mudstone resting unconformably over the previous formation and referred to the Barremian-early Aptian (Andreu et al., 2003; Mojon et al., 2009).

Basalt units $\beta 1$ and $\beta 2$ occur in the successions, resting on the top of the Guettioua Formation and at the base of the Jbel Sidal Formation, respectively (Charrière et al., 2005; Haddoumi et al., 2002, 2008, 2010; Mojon et al., 2009).

The Aptian interval is apparently recorded only at the northern CHA front by limestones and marls of the Ait Tafelt Formation (Charrière et al., 2005; Haddoumi et al., 2002, 2008, 2010; Souhel, 1986) which document a marine ingressions followed by re-establishment of continental conditions during the Albian-Cenomanian. This regression is documented also along the southern margin of the CHA by fluvial red sandstone (Ifezouane Formation) and mudstone (Aoufous Formation) (Cavin et al., 2010; Ettachfini & Andreu, 2004 for a review). All over the CHA, deposition continued during the late Cenomanian-Turonian in coastal settings and shallow carbonate ramps represented by the Akrabou Formation, outlining an overall new transgressive trend

(Ettachfini et al., 2005; Ettachfini & Andreu, 2004). Finally, the Late Cretaceous was regionally characterized by continental deposits grouped in the Iflit Formation, also referred to as *Sénonien* in existing geological maps.

3. Methods

We adopted standard techniques of geological mapping supported by a side-by-side integration of facies and structural analyses in the field. Given the suitable conditions of almost continuous rock exposures, the field mapping has been constantly checked with high-resolution satellite images provided by the Google and Bing online platforms. Thanks to the 3D views, Google Earth™ offered a very suitable tool that allowed the lateral tracing of mappable units and structures. A unifying stratigraphic framework has been established, revising the existing geological maps and stratigraphic studies (Figure 2). Specifically, starting with the regional Middle Jurassic-Cretaceous lithostratigraphy (Charrière & Haddoumi, 2016; Haddoumi et al., 2010; Jenny et al., 1981; Souhel, 1986), the criteria supporting this correlation are represented by: (1) major angular unconformities bounding distinct portions of the mapped successions; (2) sedimentary facies architecture analogies; (3) scanty chronostratigraphic constraints available for specific areas. The result is represented by three major groups, UM1-

UM3, recording as many long-term regressive-transgressive cycles which affected the CHA domain during the late Mesozoic. Each group includes unconformity-bounded units and sub-units attesting to distinct tectono-sedimentary stages, which signed the CHA evolution in the considered time interval.

4. Stratigraphy

4.1. UM1 group

4.1.1. The Guettoua-Iouaridène unit

In the mapped areas, dominantly fluvial deposits, resting unconformably on Lower-lowermost Middle Jurassic marine-coastal successions, are ascribed to the Guettoua-Iouaridène (GI) unit. In the Dadès Valley, the occurrence of an erosional unconformity and a fluvial to lacustrine facies transition allowed to distinguish sub-units GI_a and GI_{b-c}, respectively correlated to the Guettoua and Iouaridène formations (Benvenuti et al., 2017). In the other three mapped areas, the GI unit is characterized exclusively by fluvial deposits preventing a clear recognition of the Guettoua and Iouaridène equivalents.

The GI deposits are mostly represented by an alternation of reddish conglomerate composed of clasts derived from the Paleozoic basement as well as by Lower Jurassic limestones (Dadès Valley, Jbel Istifane; Benvenuti et al., 2017; Moratti et al., 2018) or pebbly sandstone (Jbel Timidrout; Cavallina, 2019; Adrar Aglal; Cavallina et al., 2018) interbedded with massive dark reddish mottled mudstone. A lithological variation is documented in the topmost GI_b of the Dadès Valley, by massive to finely laminated greyish-whitish mudstone and siltstone, including carbonized vegetal remains and the imprint of ferns and conifers (Benvenuti et al., 2017).

In depositional terms, coarse-grained deposits record the infill of channel complex, whereas the mudstone document areas of muddy flow expansion and pedogenic modification. Paleocurrents measured from channel orientation, clast imbrication and cross-lamination depict an articulated drainage pattern (Cavallina, 2019; Cavallina & Benvenuti, 2019) varying from an ENE direction in Adrar Aglal, becoming SSE-directed in the Dadès Valley and Jbel Istifane, turning into a NNE-direction in the Jbel Timidrout. This evidence attests to a proto-CHA actively rising between the Middle Jurassic and the Early Cretaceous, denudated by an extensive river network. The topmost GI_b strata are ascribed to a lacustrine environment similar to the wider lakes recorded in the Iouaridène Formation. Paleoflora collected in these lacustrine deposits has been preliminarily attributed to the Early Cretaceous (Benvenuti et al., 2017), a period recorded within the Iouaridène

Fm (Charrière & Haddoumi, 2016; Haddoumi et al., 2010).

4.1.2. The Jbel Sidal unit

The following Jbel Sidal unit (JS) is recognized in the four areas as a composite succession made of alternating channelized sandstone and reddish mudstone. In the Jbel Timidrout, the reddish sandstones, JS_d, are overlain by whitish sandstones, JS_e distinctly mappable all over the area. The regional paleocurrent pattern of JS derived from the channel orientation and cross-lamination is almost the same as for the GI unit (Cavallina, 2019), pointing to a paleo-topographic configuration persisting during the late Early Cretaceous.

The radiometric age of about 119 Ma (mid-Aptian), from hypo-abyssal (Dadès Valley) or lava flow (Jbel Istifane) basalts resting above the JS unit (Moratti et al., 2018), provides a constraint for correlating the latter unit to the Barremian Jbel Sidal Formation. A recent revision of the succession exposed in the Jbel Timidrout anticline (Adardor et al., 2021) subdivided the post-Jurassic deposits into the Albian?-Cenomanian-Turonian Ifezouane, Aoufous and Akrabou formations (cf. Hadri et al., 2001). Three members are distinguished in the Ifezouane Formation with member 1 that, due to a lacking chronostratigraphic calibration and basing on facies analogies, is ascribed in this study to the JS unit.

4.1.3. The Ait Tafelt unit

The Ait Tafelt unit (AT) is mapped in the Jbel Timidrout area only, including sub-units AT_{a-c}. AT_a consists of alternated reddish fine-grained sandstones in tabular beds and mudstone. The following AT_b is composed of whitish-reddish mudstone interbedded with whitish dolomudstone in dm-thick tabular beds. Mudcracks occur on the bed surface, attesting to periods of exposure and desiccation. The uppermost AT_c consists of alternated whitish mudstone and anhydrite in meter-thick tabular beds.

The AT unit records a depositional transition from a distal alluvial plain which replaced the JS sandy river system (AT_a) to an intertidal coastal plain characterized by mixed terrigenous-chemical deposition (AT_b) and finally to an arid coastal area under an increasing marine influence.

This unit corresponds to member 2 of the Ifezouane Formation (Adardor et al., 2021) whose carbonate strata, coinciding with the AT_b sub-unit, bear varied invertebrate fossils confirming a marine influence but unsuitable for biostratigraphic calibration. The chronostratigraphic attribution to the Albian?-Cenomanian (Adardor et al., 2021) appears weakly constrained by regional correlation, leaving room for an alternative hypothesis. In the present study, the AT deposits are tentatively ascribed to the Aptian

when a marine transgression, recorded by the Ait Tafelht Formation (Souhel, 1986), affected the northern flank of the CHA and, up to now, never documented to the south. The AT coastal-shallow marine setting marks a transgression that interrupted the continental conditions documented by the GI and JS units and successively by the IFZ unit. This partial transgressive record for the southern front of the CHA may suggest a lack of preservation elsewhere westward or an eastward land-sea gradient existing during the Aptian.

4.2. UM2 group

4.2.1. The Ifezouane unit

The Ifezouane unit (IFZ) is made of reddish-greyish conglomerate, sandstone and subordinate mudstone. In the Adrar Aglalal and the Dadès valley, it includes rhythmically stacked channelized conglomerates and tabular pebbly sandstones passing upward into reddish mudstone. In the Jbel Istifane, this unit is subdivided into a lower IFZ_a, lithologically equivalent to the IFZ of the previous areas, overlain by the upper IFZ_b, consisting of tabular reddish trough-cross bedded sandstones. A similar sandstone unit continuously exposed along a 50 km front, represents the IFZ in the Jbel Timidrout corresponding to the Ifezouane member 3 of Adardor et al. (2021). Here the sandstones, characterized by large festoon-shaped sets of cross strata, are stacked in distinct tabular bedsets separated by mudstones.

Summing up, from west to east, the IFZ records a new stage of regional drainage reorganization at the onset of the Late Cretaceous, as indicated by the pattern of paleocurrents. In the Adrar Aglalal, a paleovalley incised in older rocks was attracted to the NNW (Cavallina et al., 2018), whereas in the Dadès valley and Jbel Istifane exposures (IFZ_a) the paleoflow funneled in further palaeovalleys was directed to the SSE (Benvenuti et al., 2017; Moratti et al., 2018). The wide sandy-bed river characterized by fields of 3D-dunes recorded at Jbel Istifane (IFZ_b) and Jbel Timidrout flowed to the E and to the NE, respectively. This pattern again outlines a drainage developed on a relief coinciding with the central-western sector of the CHA. The latter imparted a diverging river network at Adrar Aglalal and Dadès Valley-Jbel Istifane (IFZ_a), respectively and funneled the sediment dispersal between the eastern Ouarzazate foreland (IFZ_b) and the Jbel Timidrout area.

4.2.2. The Aoufous unit

The following Aoufous unit (AO) shows lithological variation across the selected mapped areas. In the Adrar Aglalal, it is represented by massive reddish mudstones with subordinate intervening lenticular sandstones mostly concentrated in the lower part. In

the other three areas, AO is subdivided into two sub-units. The lower AO_a is dominated by reddish-greenish massive mudstones with variably intervening whitish dolomudstone and nodular anhydritic gypsum. The latter occurs in pluri-meter thick beds in the outcrops of the Dadès Valley becoming thinner in the Jbel Istifane and almost missing in the wide exposures of Jbel Timidrout. The upper AO_b sub-unit is recognized from the Dadès Valley to the Jbel Timidrout outcrops as poorly exposed and strongly deformed pebbly sandstone (Dadès Valley) or as massive to cross-stratified sandstones in pluri-meters thick bedsets persistently elongated in NW-SE (Jbel Istifane) and WSW-ENE (Jbel Timidrout) directions.

The depositional pattern regionally recorded by the AO unit points to the development of a floodbasin initially crossed by a network of broad channels and later on dominated by massive mud aggradation within the residual IFZ paleovalley (Adrar Aglalal; Cavallina et al., 2018). In the other areas sub-unit AO_a records the establishment of sabkha-like coastal plains where a background muddy deposition in fluctuating waterlogged conditions was periodically interrupted by chemical sedimentation. An eastward decreasing occurrence of interbedded evaporites points to a restricted marine influence advancing from west, i.e. from the Central Atlantic. The AO_b sub-unit marks a return to fluvial systems associated with valleys incised on the AO_a coastal plain and again dominated by a sandy load carried in relatively deep channels. In Jbels Istifane-Timidrout areas, the channel network accommodated frontally accreted barforms. Based on paleocurrent data sediment transport, similarly to the IFZ, AO was attracted to the SSE in the Dadès Valley and Jbel Istifane areas (Benvenuti et al., 2017; Moratti et al., 2018) and toward ENE in the Jbel Timidrout.

4.2.3. The Akrabou unit

The Akrabou unit (AK) marks drastic lithological and depositional changes documented all over the study region, though not mapped in the Adrar Aglalal. AK is made of whitish carbonates from 20 to 50 meters thick biostratigraphically calibrated to the late Cenomanian-Turonian (Dadès valley; Benvenuti et al., 2017) and stacked in three major lithological divisions. In the Dadès Valley and Jbel Istifane, AK strata are strongly deformed, including a lower division made of bioclastic wackestone-packstone followed by the intermediate thinly-bedded cherty mudstone. The topmost division consists of packstone that in the Jbel Istifane outcrops are arranged in clinoforms prograding to WSW. The AK unit in the Jbel Timidrout has been previously described in the late Cenomanian-early Turonian Goulmima section (Lebedel et al., 2015; Lézin et al., 2012) made of about 40 meters of mostly mudstone-wackestone with the variable

occurrence of chert and subordinate bioclastic packstone-grainstone. These facies record a carbonate ramp cyclically shifting between its outer and mid portions (Lebedel et al., 2015; Lézin et al., 2012).

4.3. UM3 group

This group (IF) refers to the previously undifferentiated Iflit Formation ascribed to the post-Turonian Late Cretaceous (Senonian) and exposed along the southern margin of the CHA. This group, mapped only between the Dadès River and Jbel Istifane, is subdivided into four units shortly described from the stratigraphic bottom.

4.3.1. IF_a unit

It forms the basal portion of IF and is recognized only at Jbel Istifane resting above the AK unit. It consists of alternated reddish-withish sandy mudstones and withish dolomudstone referred to a coastal sabkha (Moratti et al., 2018) in a regressive trend following the AK regional marine flooding.

4.3.2. IF_b unit

This unit occurs in the Dadès River Valley and Jbel Istifane areas consisting of an alternation of reddish mudstone and nodular anhydrite gypsum. These deposits record the development of a playa lake within a progressive isolation of the basin from the marine influence.

4.3.3. IF_c unit

It is mapped in all three areas as a succession of reddish sandstones in tabular beds alternated with massive mudstones referred to distributary fluvial systems that entered the southern foreland plains building up advancing fluvial fans. Paleocurrent data collected in the Dadès River valley suggest a paleoflow direction to SSW.

4.3.4 IF_d unit

It forms the top of the IF made of pebbly sandstones at its base filling paleovalleys incised in the previous unit, followed by tabular sandstone alternated to reddish mudstone. The topmost strata are made of highly bioturbated whitish marls bearing ostreid assemblages. The depositional pattern recorded by this unit points to a cycle of base level variation starting with incision during a falling stage and aggradation within fluvial valleys later on influenced by sea ingression. The topmost mollusc-bearing deposits outlining such a maximum transgressive signal have been referred either to as the Maastrichtian (Marzoqi & Pascal, 2000) or to the early Paleocene (Herbig & Trappe, 1994).

5. Tectonics

The Jurassic-Cretaceous successions mapped in the four study areas (Plates 1–4) are affected by thrusts and thrust-related folds elongated in an E-W to ESE-WNW direction subparallel to the southern CHA front (sites 1, 2, 3, Plate 1; site 6, Plate 2; site 7, Plate 3). The mapped units underwent syn-sedimentary and polyphasic deformation. In all areas, the main E-W folds are refolded along an about E-W trending shortening direction, at places also responsible for faulting. All units are unconformable (often angularly) one onto the other, and in many cases, are affected by internal angular and progressive unconformities (site 4, Plate 1; sites 5, 6, Plate 2; site 7, Plate 3; sites 8, 9, 10, Plate 4). Minor (mesoscale) almost E-W-trending reverse faults and related folds affect different portions of the succession dying out upwards and being sealed by the overlying deposits. The structural analysis of both faults and folds at all scales confirmed the activity of three different shortening directions, from the oldest to the youngest: NNE-SSW, E-W and NW-SE.

5.1. Synthesis of the main structural patterns in the mapped areas

The Adrar Aglagal doubly-folded syncline shows two axes oriented approximately NE-SW and NNW-SSE (geological map and cross-sections A-A' and B-B'-B'', Plate 1). The flanks of the syncline show a growth fold geometry outlined by the wedging of strata within units of UM1 group (site 4), interrupted by multiple angular unconformities, suggesting a polyphasic and syn-sedimentary growth of this structure. An E-W, south-verging thrust observed along the northern limb of the syncline, brings units LJB-c directly over units AZ-GI, and is sealed by unit JS, thus reasonably confirming the early development of the syncline under a compressive horizontal stress sub-perpendicular to the South Atlas front.

In the Dadès Valley area (Benvenuti et al., 2017), a series of thrust- and backthrust-related folds involve, from north to south, the three groups UM1-3 from the oldest to the youngest, pointing to continuous shifting of depocenters under a compressive stress. The sinistral transpressive Dadès fault separates UM1 to the west from UM2-3 and the post-Cretaceous succession to the east, pointing to a certain amount of pre-Cenozoic shifting of this fault under an about N-S compression. The northernmost anticline and syncline affecting TIL-GI deposits show very steep to overturned limbs, internal angular unconformities, and a steep north-dipping axial plane (cross-sections C-C' and D-D', site 6, Plate 2). They are successively refolded by NNE-SSW minor folds and sealed by Palaeogene deposits (cross-section C-C'). To the south, the angularly unconformable JS deposits

delineate growth folds (site 7, Plate 2) forming an E-W-trending synclinal-anticlinal pair, at whose core the 119 Ma old *Db* basalt is nested. Progressive unconformities also affect units of the UM2-3 groups (site 5, Plate 2), unconformable one onto the other and deformed by folds and minor reverse faults related to blind thrusts. All thrust-related E-W folds have north-dipping axial planes. Activation of the main thrust faults can thus be dated through their influence on the development of UM1-3 unconformity-bounded units, southward shift of their depocentres, syntectonic angular and progressive unconformities within each unit. Major shortening suffered by GI compared to younger units is indicated by decreasing tightness of folding, from tight to isoclinal in GI, to open in IF (sites 5 and 6, cross-section C-C', Plate 2). North of Ait Youl, a dextral transtensional fault coherent with an almost E-W shortening direction, affects UM2 deposits and displaces the E-W backthrust that affects unit AK, being sealed by UM3 deposits. Previous studies, attributing all the red beds to the Late Cretaceous, focussed on the Cenozoic tectonic inversion (e.g. Fraissinet et al., 1988; Tesón & Teixell, 2008).

In the Jbel Istifane area, UM1-3 groups, arranged in poly-deformed arcuated folds elongated E-W to NW-SE, are overthrust to their northern and north-western side by the Lower Jurassic units. In the western portion of the area, the core of the Istifane anticline is a complex pop-up structure made of Liassic units, consisting of a series of thrusts and backthrusts mainly related to an NNE-SSW trending compression (geological map, cross-sections E-E' and F-F', site 7, Plate 3). To the north, the pop-up overthrusts the already structured Tamesgerouine folds, made of the UM1-3 folded sediments, both in the N-to NE and in the NW direction, pointing to a post-Cretaceous reactivation (cross-sections E-E' and F-F', Plate 3). To the south, the pop-up overthrusts the southern limb of the Istifane anticline represented by the upright succession made by LJg and UM1-3 sediments. All units show bedding attitudes varying from steeply inclined to vertical and overturned (cross-sections E-E' and F-F', site 7, Plate 3). The *Jlb* lava unconformably covers both unit GI and JS, supporting a subaerial emplacement over a surface deeply incised in these older units (geological map, Plate 3). A slight angular unconformity between JS and GI is present in the northern portion of the area, where the pop-up overthrusts UM1 deposits (cross-section E-E', Plate 3). Sub-unit IFa deposits of the UM3 group are angularly unconformable with an angle up to 30-40° onto the vertical UM2 deposits (cross-section E-E', Plate 3). In the southwestern hinge of the anticline, two refolding events are particularly evident at map scale. Decametric folds with N-S axes seem to be related to an about E-W-trending shortening, while

the main refolding event is tied to the NW-SE thrusting of the Aguerd 'n Syad thrust, postdating the structuration of the Istifane anticline (site 9, Plate 3). The core and hinge of the anticline are also affected by syn-sedimentary NE-SW left-lateral faults, across which the thickness of sub-unit GIb is strongly reduced, and unit JS disappears. Both faults dislocate UM2 and are sealed by UM3 deposits.

The ENE-WSW 30 Km long Jbel Timidrount anticline shows a northern limb generally gently inclined to the N, and a vertical to overturned southern limb (see all related cross-sections, Plate 4). This apparently continuous structure presents at its core a series of smaller ENE-WSW to E-W anticlines with arcuated axes doubly plunging to the W and E, thus possibly refolded according to an almost E-W compression that overprints the NNW-SSE main shortening direction. The lowermost TIL and GI units crop out at the core of these anticlines at the eastern and western terminations of the major anticline. In the westernmost minor core, the synsedimentary growth of the anticline is particularly evident, as units JS and AT were sedimented onto the already folded lower units, TIL and GI, that form a boxfold with axial planes and axes plunging to the north and to the south (geological map and cross-sections G-G' and I-I', Plate 4). Unit AT is in turn angularly unconformable on the already folded unit JS, showing thinning and wedging both to the north and the south on the opposite flanks of the anticlinal core (sites 8 and 9, Plate 4). This boxfold geometry may indicate a first shortening verging to the north, then followed by a preminent vergence to the south, that affects all units along the southern limb of the Timidrount anticline. Onlaps of the younger units onto the anticlinal cores all along the major anticline agree with sedimentation onto continuous growing folds. The western portion of the anticline, bordered to the south by the stiff anti-Atlas basement, in the N-S direction is less wide than the central and eastern portions. The stiff Anti Atlas crust thus could have represented a major obstacle to the progressive southward propagation of the thrust system, now in part emerging in the eastern portion of the anticline (cross-section O-O', Plate 4), so that shortening may have been accommodated by an early activation of north verging backthrusts.

6. Discussion

The presented data delineate a coherent scenario of Late Mesozoic uplift of the High Atlas, dismantlement and fluvial transport of the basement and Early Mesozoic sediments, early inception of vertical tectonic mobility at the South Atlas front. In other parts of the High Atlas, deformation of Late Mesozoic sediments has been ascribed to salt tectonics and formation of mini-basins in an extensional regime (e.g.

Bouchouata et al., 1995; Ettaki et al., 2007; Michard et al., 2011; Moragas et al., 2018; Saura et al., 2014; Vergés et al., 2017). At the South Atlas margin, paleogeographic reconstructions locate the presence of Triassic salt only in the western portion of the studied areas (e.g. Choubert & Faure-Muret, 1960-1962), not far from the Adrar Aglagal syncline. Fieldwork on this area, nonetheless, does not reveal the presence of the Triassic succession, while the geometrical setting of the syncline shows an impressive coherence with an almost N-S late Mesozoic compression revealed by both the described growth fold geometry of the UM1 units and the E-W, south-verging thrust observed along the northern limb of the syncline and sealed by unit JS (geological map, cross-sections A-A' and B-B'-B'', sites 1 and 4, Plate 1). In the Dadès area, the architecture of the UM1-3 groups points to the continuous shifting of depocenters and thrusting to the south. The Triassic succession is a clastic one, with no salt, involved in the thrust folds affecting the area, as also evidenced in the cross-sections of previous papers (e.g. cross-sections 1 and 2 in Fig. 4 of Tesón & Teixell, 2008). At Istifane and Timidrout no Triassic rocks crop out (geological maps in Plates 3 and 4). At Timidrout, in particular, the 1:100,000 Goulmima map (Hadri et al., 2001) shows that the studied succession lies onto Liassic rocks directly covering the Precambrian basement, with no Triassic rocks inbetween.

On the other hand, multiple findings of Late Mesozoic deformations coherent with compressive/transpressive tectonics sub-perpendicular to the Atlas trend have been reported by previous authors (e.g. Choubert & Faure-Muret, 1960-1962; Mattauer et al., 1977; Jenny et al., 1981; Laville, 1988; Laville & Piqué, 1992; Gouiza, 2011; Bertotti & Gouiza, 2012). Some of them proposed a unique scenario to explain such findings (Mattauer et al. 1977; Laville & Piqué, 1992; Benvenuti et al., 2017; Moratti et al., 2018), where the Cenozoic compression strongly added to an incipient uplift of the High Atlas, enhancing the previous structures to complete the Atlas building. Late Mesozoic E-W compressive deformation detected on both sides of the Atlantic Ocean (Bertotti & Gouiza, 2012; Withjack et al., 1998) may have affected the more distant areas presented here, possibly superposing to the main shortening direction.

7. Conclusions

The presented geological maps provide a new stratigraphic and structural picture of the Upper Mesozoic, mostly continental successions exposed along the southern flank of the Central High Atlas. Despite the uncertainty of the chronostratigraphic calibration, facies analogies, major bounding unconformities and scanty dating allowed to define a unifying stratigraphic

scheme comparable with the Middle Jurassic-Late Cretaceous (Bathonian-Maastrichtian) lithostratigraphy of the Central High Atlas. For the study areas Middle Jurassic-Lower Cretaceous strata were recognized into previously mapped Upper Cretaceous formations. UM1-3 unconformity-bounded groups, including lower-rank units, mark a complex tectono-sedimentary evolution controlled by generalized crustal uplift and major sea-level fluctuations. The syn-depositional tectonic influence on the development of the UM1-3 groups with the presence of angular and progressive unconformities, the southward shift of their depocenters and the presence of structures sealed by younger strata, together with sedimentological data (composition of the conglomeratic portions of unit GI, paleocurrent fluxes, development of a coherent fluvial network) points to early uplift of the High Atlas and strongly supports activation of main thrust faults well before the Cenozoic tectonic inversion of the Triassic rifted basins tied to the convergence of Africa-Europe plates.

Software

The collected data have been managed as point, line and polygon features in an ESRI Arcgis Desktop™ environment, and plotted over different types of base-map such as satellite images available from Arcgis online, digital terrain models from the Alos project (<https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm>). The final editing was realized exporting the GIS projects in Adobe Illustrator™.

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No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [M. B.], upon reasonable request.

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