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TECTONO-STRATIGRAPHIC REVISION OF THE AIT KANDOULA FORMATION (MIDDLE MIOCENE-PLIOCENE), WESTERN OUARZAZATE BASIN (SOUTHERN MOROCCO)

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Abstract. This paper reports the results of a stratigraphic revision of the Ait Kandoula Formation exposed in the western Ouarzazate Basin (Middle Miocene-Lower Pliocene, Southern Morocco). This formation is part of the upper Eocene-Quaternary continental Imerhane Group considered to record the main stage in the building of the Central High Atlas (CHA) under a regime of tectonic inversion of Mesozoic rifted basins. The development of this chain during the late Cenozoic generated a south-verging structural front and the related Ait Kandoula and Ait Seddrat sub-basins facing the wider Ouarzazate foreland basin. The revision of the Ait Kandoula Formation, occurring in both the Ouarzazate Basin and Ait Kandoula sub-basin, was carried out through new field observations, remote sensing and exploiting the distribution and the biochronologic range of fossil micro- and macro-vertebrate associations available from previous studies. In the western Ouarzazate Basin four stratigraphic-depositional subunits (AK1-4) were distinguished in this formation, attesting to the development of a fluvio-lacustrine setting. This was strongly influenced by the syn-depositional deformation of the growing southern front of the CHA and by the episodic activity of shear zones oriented transversally to this front. The chronostratigraphic constraint provided by the mammal assemblages and by their magnetostratigraphic calibration, suggests a five-stage scenario for the tectono-sedimentary development of this actively deforming front and its related foreland and satellite depocentres between the Middle Miocene and the Early Pliocene. In the proposed reconstruction, the interplay of front-parallel thrust faults and front-transverse shear zones controlled the fluvial supply to the Ouarzazate Basin and later on the activation of the Ait Kandoula sub-basin.

Introduction

The Ouarzazate basin represents the southern foreland of the Central High Atlas (CHA) offering one of the wider exposures of Neogene-Quaternary continental sediments of Morocco. These sediments bear vertebrate remains that, as for most of the Moroccan Neogene, consist of micromammal assemblages. The Neogene macrovertebrate record is relatively scanty in Morocco, as well as in North Africa, and the recent discovery of a late Miocene assemblage in the western Ouarzazate Basin (Tizi N'Tadderht site, Zouhri et al. 2012; Fig. 1) extends this record previously limited to two distinct sites (late Middle Miocene Beni Mellal; Choubert and Faure-Muret 1961; Lavocat 1961; Late Pliocene/Earliest Pleistocene Ahl al Oughlam near Casablanca; Geraads 2006; Raynal et al. 1990). Further studies on the Tizi N'Tadderht fauna (Geraads et al. 2012; Cirilli 2018; Cirilli et al. 2020) stimulated a stratigraphic revision of the encasing continental

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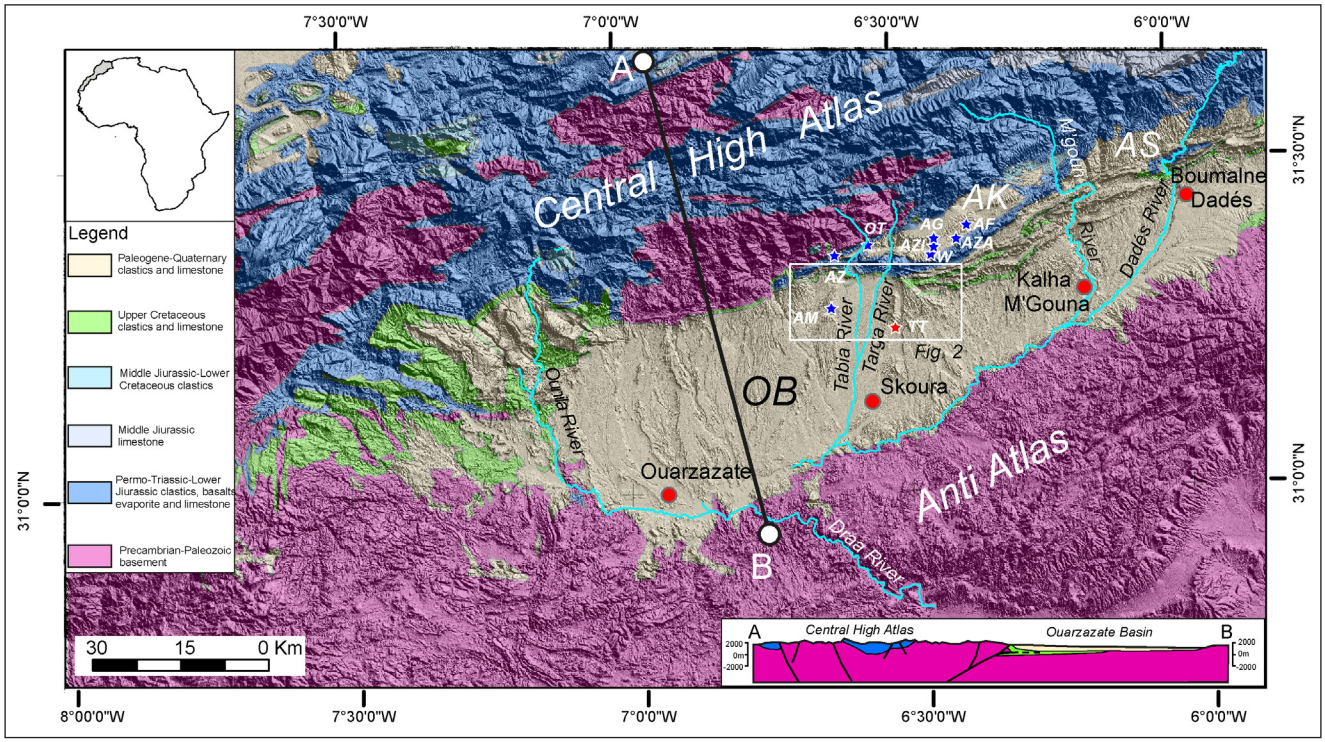

Fig. 1 - Location of the study area in Southern Morocco and schematic geological map of the region between the Central High Atlas and the Anti Atlas mountain ranges.The cross section A-B modified from Teixell et al. (2003). OB: Ouarzazate Basin; AK: Ait Kandoula sub-basin; AS: Ait Seddrat sub-basin. Codes for the fossil vertebrate localities (blue star: micro-vertebrate site; red star: macro-vertebrate site): AF: Afoud; AZA: Azaghar; AG: Aghouri; AZI: Azib; W: Wanou; OT: Oued Tabia; AZ: Azdal (from Benammi et al. 1996); AM: Amekchoud (from Tesón et al. 2010); TT: Tizi N'Tadderht (from Zouhri et al. 2012)

deposits ascribed to the Ait Kandoula Formation (Zouhri et al. 2012). The present paper reports the results of this revision in the frame of successive tectono-sedimentary stages in the development of the western sector of the southern CHA front. The chronostratigraphic constraint of the mammal assemblages previously collected in the Ait Kandoula Formation (Benammi et al. 1996; Benammi & Jaeger 2001; Benammi 2006; Tesón et al. 2010; Gerrads et al. 2012; Zouhri et al. 2012) is of paramount relevance for restoring a coherent picture of this evolution.

General setting

The Ouarzazate Basin, confined between the southern front of the Central High Atlas (CHA) and the Anti Atlas range (Fig. 1), is a flexural depression whose formation is ascribed to the Early Cenozoic tectonic inversion of the Mesozoic CHA rifted basins, related to the Africa-Europe plates collision (Frizon de Lamotte et al. 2008). Tectono-sedimentary lines of evidence collected at the southern front of the CHA suggest that possibly since the Middle Jurassic the basin accommodated sediments derived from the denudation of an embryonic chain hinting to a more articulated evolution of the CHA (Benvenuti et al. 2017; Moratti et al. 2018). The basin fill includes a relatively thick succession of alluvial and lacustrine deposits dating back to the late Eocene and referred to as the Imerhane Group (IG, El Harfi et al. 2001; Fig. 2). The latter is considered to record the main stage of the CHA build up as suggested by its unconformable relations with the Mesozoic-Early Cenozoic syn- and post-rift successions (Frizon de Lamotte et al. 2008 for a review; Teixell et al. 2016). The syntectonic character of the IG is also proven by 1) the sedimentary composition largely derived from the denudation of the thrusted and folded older deposits of the CHA and 2) its progressive deformation related to southward propagation of crustal shortening (e.g., Laville et al. 1977; Görler et al. 1988; Benammi et al. 2005). Tectonic movements brought to a structural compartmentalization with the development of the two adjacent Ait Kandoula and Ait Seddrat sub-basins (Görler et al. 1988; El Harfi

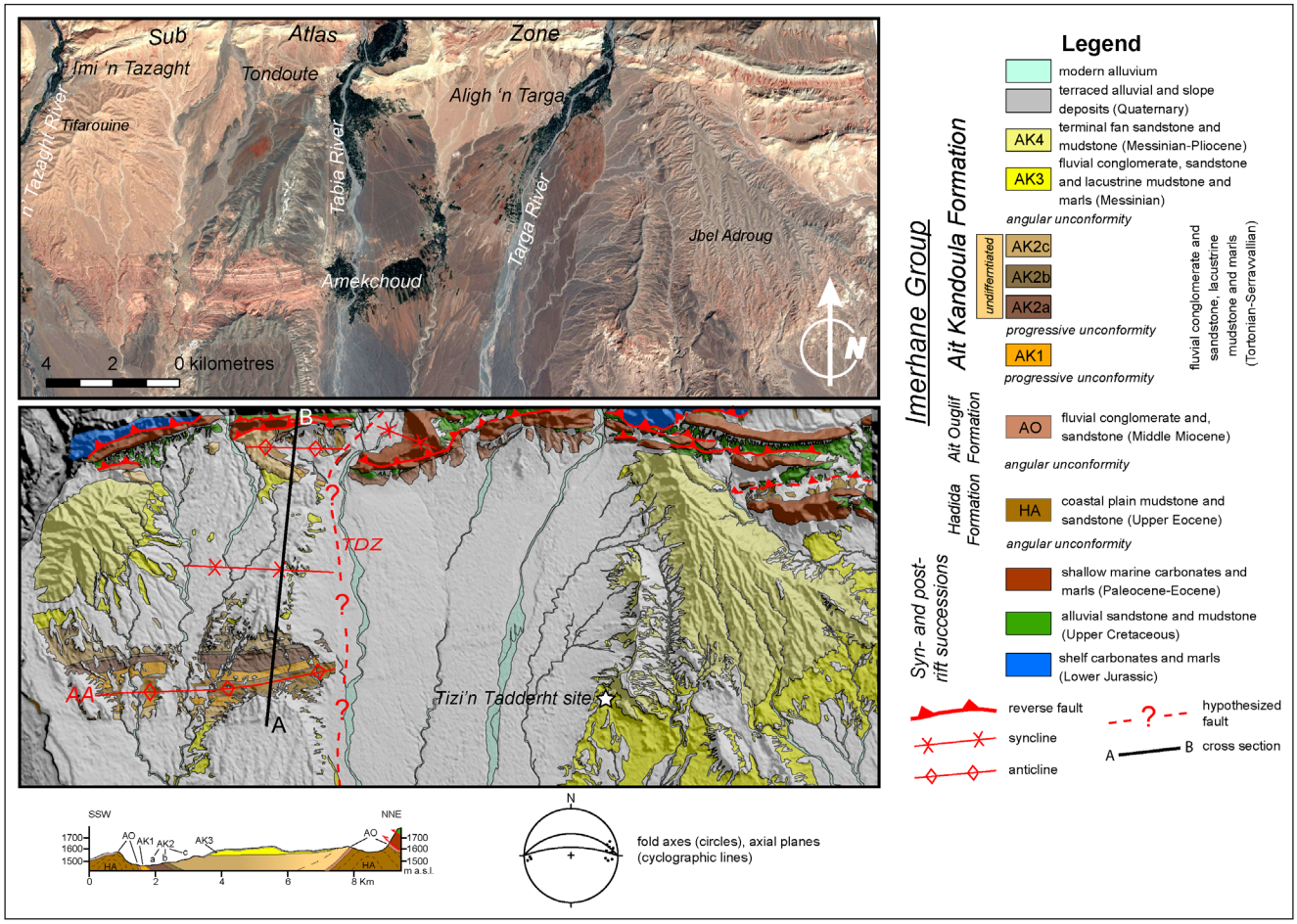

Fig. 2 - Aerial view (from Google Earth™) and geological map of the study area (location in Fig. 1). Note that the Ait Kandoula Formation adjacent to the Sub Atlas Zone is undifferentiated because of the lack of clear elements for a correlation with the AK1-2 sub-units recognized to the south. AA; Amekchoud anticline; TDZ: Tabia deformation zone.

et al. 2001), facing the wider Ouarzazate depocentre. In all these areas the late Paleogene-Quaternary interval is recorded by the stacking of clastic formations in a succession attesting to an overall transgressive-regressive cycle within the long-term evolution of a fluvio-lacustrine setting. The first term of this succession is represented by the Hadida Formation ascribed to the upper Eocene and made of reddish mudstones with variable amount of gypsum and subordinate sandstones recording coastal sabkhas and alluvial plains. These basinal areas were fed by fluvial systems sourcing to the north and represented by the lateral-equivalent conglomerates and sandstones of the Ait Arbi Formation (El Harfi et al. 2001). The following Ait Ouglif Formation made of alluvial conglomerates, initially referred to the Upper Oligocene (Fraissinet et al. 1988; El Harfi et al. 2001) and recently ascribed to the early Middle Miocene (Tesón et al. 2010), represents the early syn-tectonic deposition followed by the Middle Miocene-Pliocene Ait Kandoula Formation, consisting of lacustrine sandstone, mudstone and limestone (Ait Ibrirn member in Tesón et al. 2010), recently investigated through stable isotope and facies analysis (Boulton et al. 2019). The latter is overlain by alluvial conglomerates and sandstones (Ait Seddrat member in Tesón et al. 2010). Quaternary terraced clastic deposits, related to the fluvial entrenchment forced by the interplay of continued deformation (Pastor et al. 2012) and climate fluctuations (Arboleya et al. 2008), rest on top of the succession (Fig. 2). The lacustrine mudstone of the Ait Kandoula Formation exposed in the homonym sub-basin, yielded associations of fossil microvertebrates (Benammi et al. 1996; Benammi & Jaeger 2001; Benammi 2006) attesting to the MN6-MN14 zones of the European Mammal Biochronology. A micromammal fauna ascribed to the MN11 zone has been reported also from the lower portion of the Ait Kandoula Formation cropping out in the

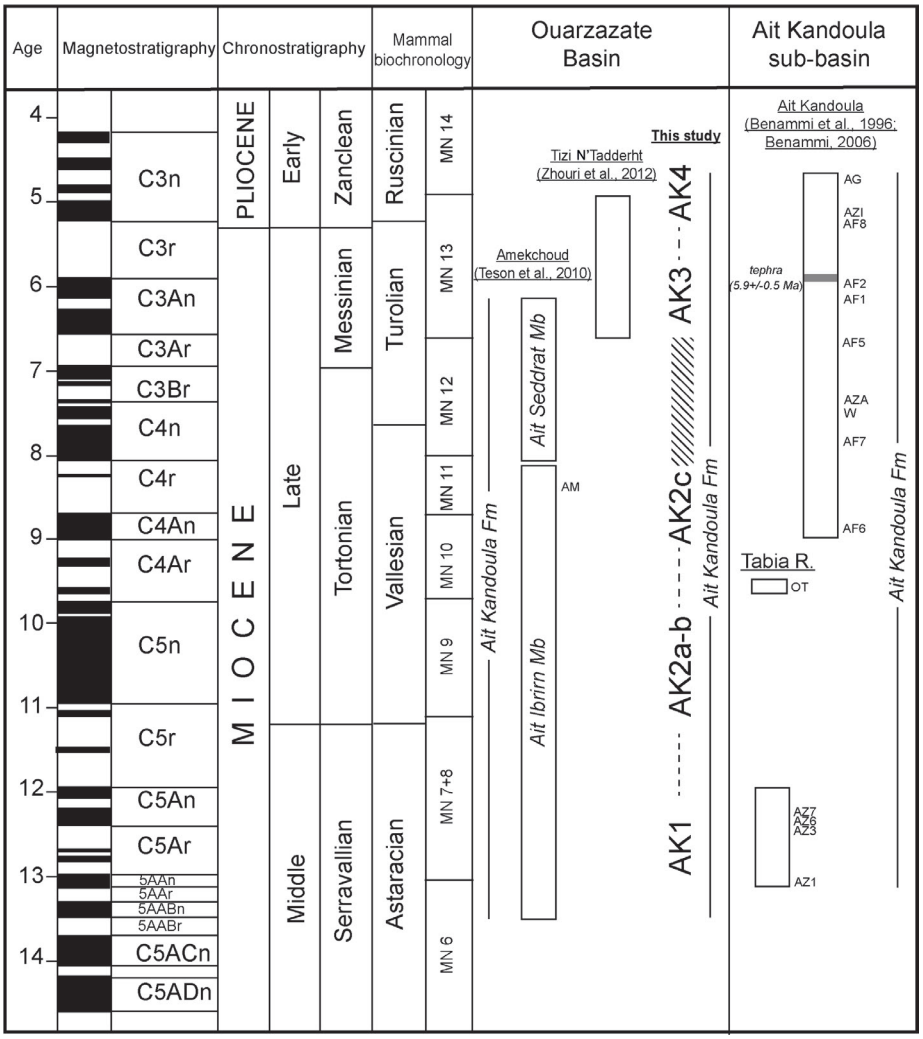

Fig. 3 - Integrated stratigraphic scheme for the Ait Kandoula Formation exposed in the study area and in the homonym sub-basin according to previous studies and to the revision discussed in this paper. Hatched rectangle indicates the maximum hiatus between AK2 and AK3 subunits. Codes for the fossil vertebrate localities as in Fig. 1. The geomagnetic polarity time scale after Cande and Kent (1995), the biochronological scales as in Benammi et al. (1996), Benammi & Jaeger (2001), Benammi (2006).

western Ouarzazate Basin (Tesón et al. 2010) not far from the Tizi N'Tadderht site (Fig. 1). The latter yielded a macrovertebrate assemblage referred to the MN13 zone (Zouhri et al. 2012). The integration of magnetostratigraphic data reported by the authors, allowed to establish a chronostratigraphic framework for the micromammal faunas which are bracketed between an advanced Serravallian and the early Zanclean (Fig. 3).

Methods and data

The analysis of the macrovertebrate fauna of Tizi N'Tadderht and its reference to the Messinian (Zourhi et al. 2012; Cirilli 2018; Cirilli et al. 2020) opened the question of the chronostratigraphic extent of the Ait Kandoula Formation in the adjacent areas of exposure. Basing on the microvertebrate biochronology and magnetostratigraphic calibration the base of this formation has been referred to the Serravallian in both the western Ouarzazate Basin (Tesón et al. 2010) and the Ait Kandoula satellite basin (Benammi et al. 1996; Benammi & Jaeger 2001; Benammi 2006). The maximum extent is here referred to the early Pliocene whereas it is ascribed to the early Messinian in the Ouarzazate Basin (Tesón et al. 2010). Nevertheless, the reference of the Tizi N'Tadderht fauna to the MN13 zone spanning the Messinian and the earliest Pliocene, suggests a longer duration for the deposition and/or more preservation of the Ait Kandoula Formation also in the Ouarzazate Basin.

Basing on this assumptions, stratigraphic and structural fieldwork and interpretation of high-resolution aerial photographs were performed on the Ait Kandoula Formation exposed on the slopes flanking the Tabia River between Toundoute and Tizi N'Tadderht (Fig. 1). The observed lithological and structural features suggested a new subdivision of a lithostratigraphic unit previously undifferentiated (Görler & Zucht 1986; Görler et al. 1988;

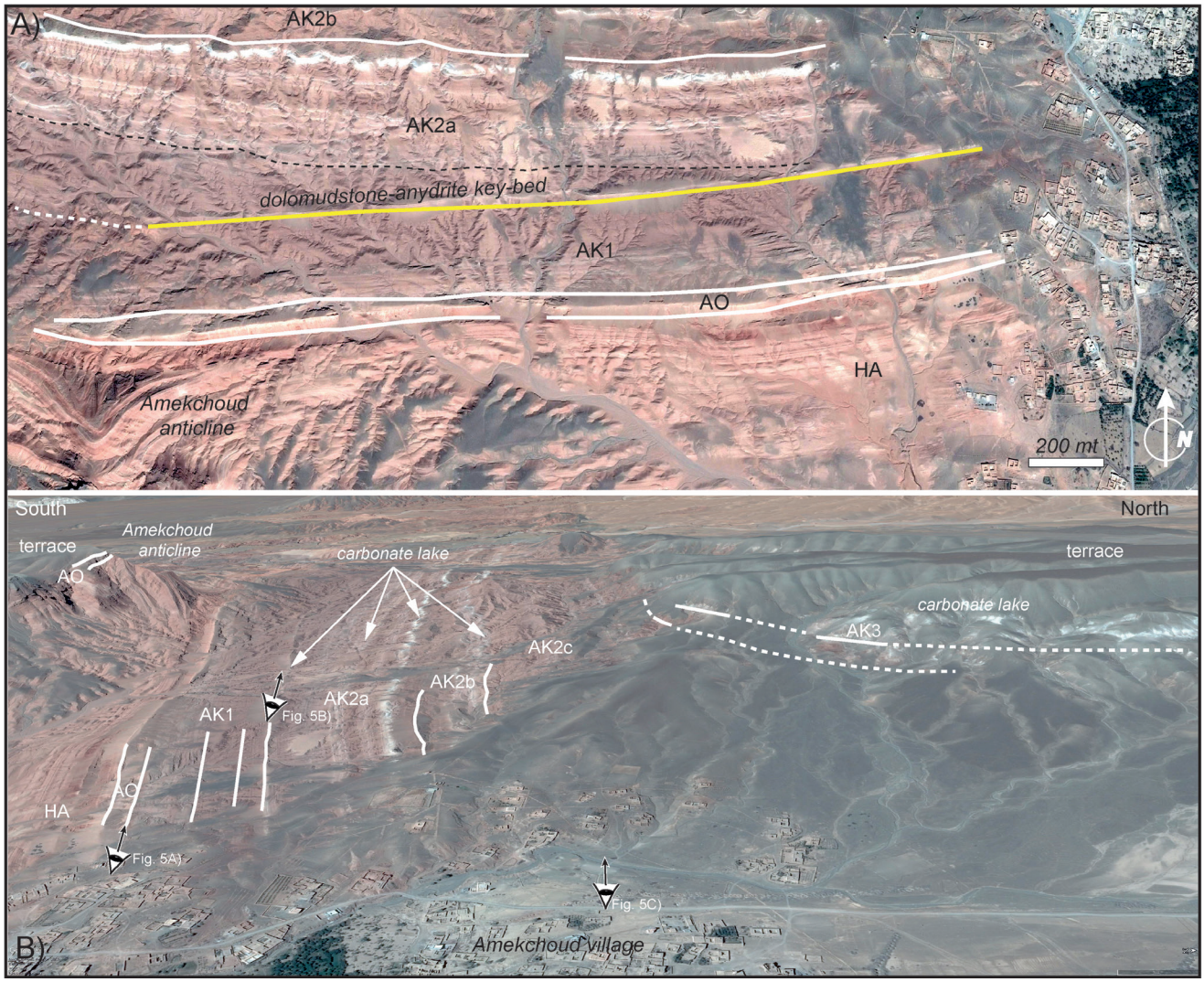

Fig. 4 - Aerial views of the study area west of the Tabia River (from Google Earth™). A) plane view showing the lithostratigraphic stack north of the Amekchoud anticline: note the contact between AK1 and AK2 characterized by an angular truncation to the west becoming concordant to the east; the yellow line represents a progressive unconformity separating AK1 from AK2 sub-units; B) oblique view looking to the west outlining the stratal wedge of the succession, attesting to a syn-tectonic control on the deposition. Codes: HA: Hadida Fm., AO: Ait Ouglif Fm., AK: Ait Kandoula Fm.

Benammi et al. 1996; Benammi & Jaeger 2001) or grossly subdivided in a lower lacustrine and an upper alluvial member (El Harfi et al. 2001; Tesón et al. 2010).

Structural setting and stratigraphic-depositional revision of the Ait Kandoula Fm

A first general observation concerns the structural arrangement of the formation as detectable from aerial photographs and ground control. Though widely covered by Quaternary alluvial and slope deposits, the Cenozoic strata of the considered area show clear evidence of progressive deformation punctuated by the occurrence of angular truncations. The latter provide arguments for establishing a new subdivision based on distinct unconformity-bounded units. In this perspective a key area is represented by the wide exposures of the IG on the right bank of the Tabia River between Amekchoud and Tondoute. The northern end of this area represents the sub-Atlas zone, where the IG is thrusted by the Paleogene-Mesozoic deposits of the southern fronts of the CHA (Fig. 2). Deposition of the IG was syntectonic to the building of the sub-Atlas stack, that formed since the Late Eocene to the Pliocene, according to previous studies (Görler et al 1988; Benammi et al. 2005). Jurassic-Paleogene deposits form the core of E-W to NNE-SSW-trending thrust related anticlines, with mainly north plunging axial planes. Axes and

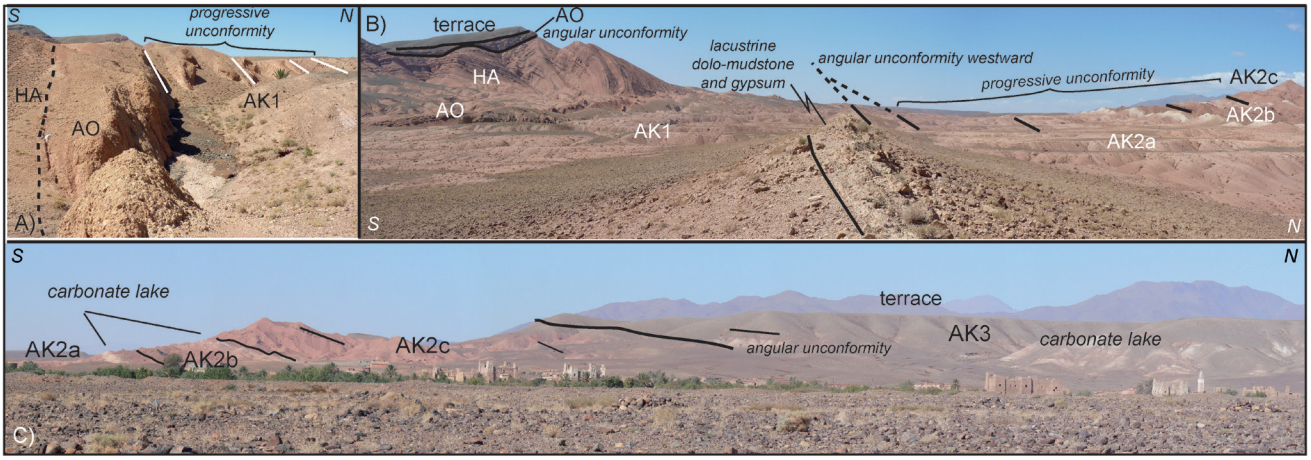

Fig. 5 - Ground views of the succession exposed west of the Tabia River (location of the viewpoints looking to the west in Fig. 4B). Codes: HA: Hadida Fm., AO: Ait Ouglif Fm., AK: Ait Kandoula Fm. A) Erosive contact of the Ait Ouglif Formation on the Hadida Formtion and progressive unconformity outlined by the stratal wedging-out marking the transition from the Ait Ouglif conglomerates to the AK1 sandstones; B) panoramic view showing the Amekchoud anticline in the background to the south and the dolomudstone-anydrite key-bed on top of AK1 in the foreground. The stratal wedging out in the AK2-3 to the north is annotated; C) panoramic view from the road to the Tondoute village on the upper portion of the Ait Kandoula Formation showing the angular unconformity between the AK2 and the AK3 strata.

axial planes of minor folds, measured in the Paleogene deposits of the Sub-Atlas zone are reported in the stereonet of Fig. 2. They well accord to the major structures, onto which lie unconformable IG deposits, in turn involved in the southward shifting deformation.

Southward shortening propagation determined in the western Ouarzazate basin the development of the W-E trending fold system of Amekchoud, located west of the Tabia River valley (Figs. 2, 4A-B). To the east, the basin fill presents nearly horizontal topmost Ait Kandoula deposits, while deformation remains concentrated in the sub-Atlas zone (Fig. 2). The different IG succession together with its attitude and geometry west and east of the Tabia River valley identifies a complex NNE-SSW oriented shear zone centered into the Tabia River.

The prominent Amekchoud anticline is the southernmost exposed fold affecting the IG on the right of the Tabia River and showing at its core the Upper Eocene Hadida Fm (Fig. 4B) representing the base of IG (El Harfi et al. 2001). The Ait Kandoula Formation (Ait Ibrirn member of Tesón et al. 2010) rests on a relatively thin Ait Ouglif Formation in turn erosively over the Hadida Formation (cf Tesón et al. 2010) (Fig. 5A-B). Along the northern limb of this fold the Ait Kandoula strata show a pattern characterized by three major angular variations supporting a subdivision in the AK1-3 unconformity-bounded sub-units (Figs. 2, 4A-B).

The AK1 is a succession composed of whitish/pale red channelized sandstones with intervening mudstones in the lower half which overlay the Ait Ouglif conglomerates through a progressive unconformity (Figs. 2, 5A). The basal AK1 strata, hinting to sediment transport southward, are followed by reddish muddy sediments with intervening sandstones toward the top. This sub-unit ends with few meters thick whitish anhydrite gypsum alternated to dolomudstone (Figs. 4A-B, 5B). The AK2 rests angularly over these topmost AK1 deposits toward the west becoming geometrically concordant eastward (Fig. 4A). This sub-unit is characterized by a cyclic stack of coarser and finer sediments allowing a further distinction of three portions (Fig. 5C). AK2a starts with an alternation of pale red sandier tabular strata passing upward to muddier deposits culminating into prominent white marlstone/dolomudstone intervals. AK2b is made at the base of channelized conglomerate and sandstone showing channel orientation and internal cross bedding indicative of sediment transport to SSE. These coarse-grained deposits intergrade upward with reddish-whitish mudstone becoming dominant upward and being in turn replaced by alternating conglomerate, sandstone and mudstone. AK2c consists of reddish tabular sandstones and mudstones becoming prevalent and more whitish to the top.

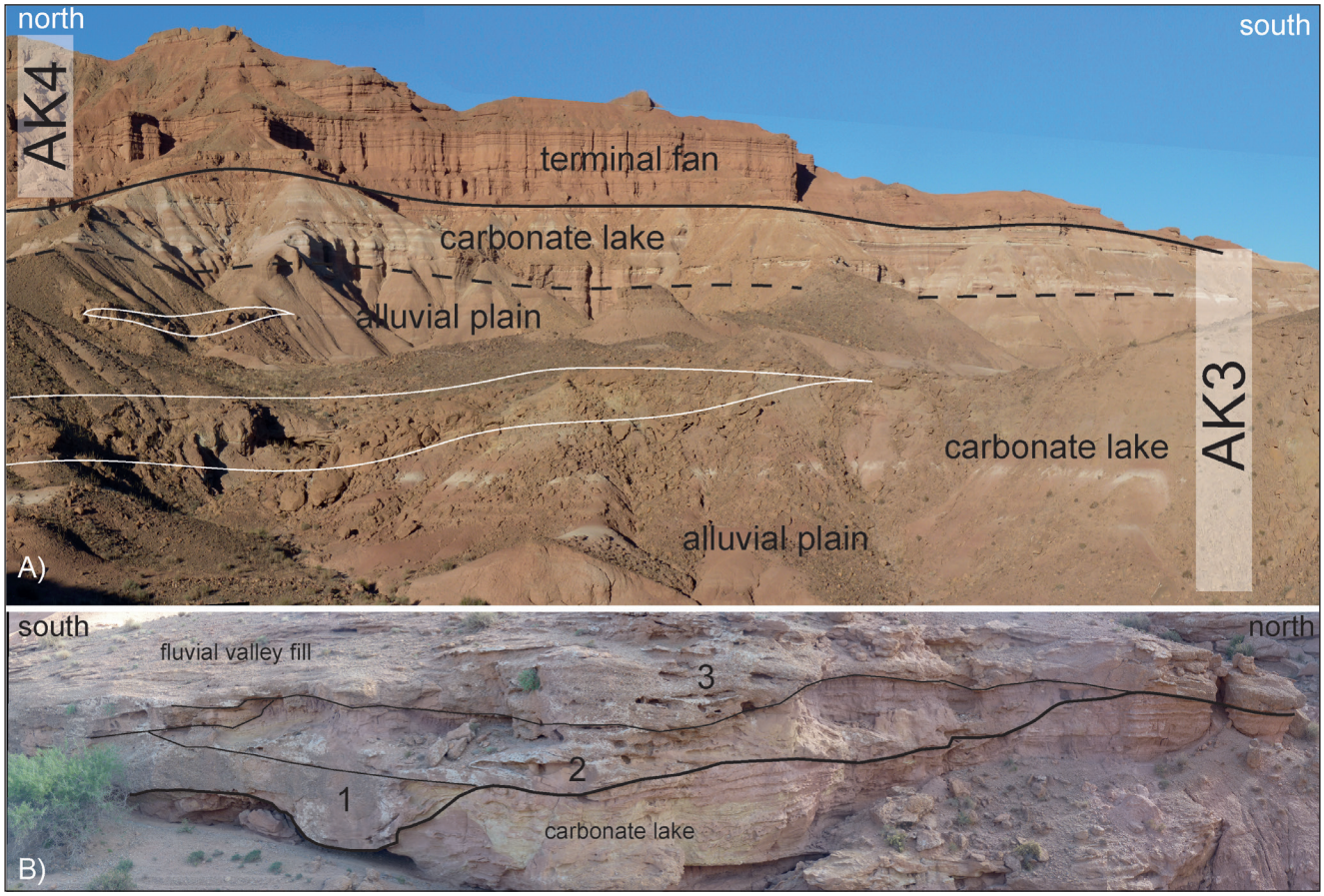

Fig. 6 - A) Panoramic view of the Tizi N'Tadderht site (location in Fig. 1) looking to the east and showing the fluvio-lacustrine facies stacking within AK3 and the sharp contact with the AK4 alluvial conglomerates; B) detail of a channel complex cut into lacustrine mudstone of the basal AK3 sub-unit. The channel is ESE-WNW trending hinting to plaeoflow sub-parallel to the axis of the Ouarzazate Basin; 1: conglomerate channel fill; 2: sandy-muddy channel overfill; 3) multistorey gravelly channel fill.

AK3 overlies the previous deposits through a further angular truncation (Figs. 2, 4B, 5C). This sub-unit is poorly exposed in the Amekchoud area being well visible on the left of the Tabia River at the Tizi N'Tadderht site (Fig. 2, 6A). Here, it is sub-horizontal and includes from the base an alternation of channelized fine conglomerates and sandstones with a massive or through-cross stratified structure, outlining sediment transport from the ESE, and banded pale reddish/whitish mudstone (Fig. 6B). Macrovertebrate remains are mostly dispersed in the sandstones. Upward, the succession becomes muddier culminating into a white marlstone, easily traceable also on the covered slopes on the right of the Tabia River. AK4 sub-unit is conformably above these deposits (Figs. 2, 6A) and consists of tabular reddish conglomerates and sandstones alternated to mudstones, missing on the right bank of the Tabia River due to the later terracing of this succession but forming the Tifarouine relief farther to the northwest (Fig. 2).

Discussion

Depositional evolution of the Ait Kandoula Formation

The AK1 represents a single depositional cycle starting with fluvial channels and floodplains testifying to a wide alluvial plain fed from the front of the CHA and opening to the south. The progressive unconformity observed at the Ait Ouglif-AK1 transition, suggests a syn-tectonic control on the transformation from a gravelly (Ait Ouglif) to a sandy (AK1) alluvial plain (Fig. 5A). The overlying AK1 strata record a muddy playa and a fan, advancing to the south. The sharp contact with gypsum and dolomudstone hints to a sudden development of a lacustrine setting starved with clastics and dominated by chemical sedimentation (Fig. 5B). The angular unconformity observed to the west between these strata and the overlying AK2 (Fig. 4A), suggests a localized tilting pulse of the northern flank of the Amekchoud anticline, not propa-

gating to the east, as the possible cause of such an abrupt depositional transition in the late development of the AK1 sub-unit. The AK2 attests to a re-established terrigenous-carbonate fluvio-lacustrine setting particularly well expressed by AK2a (Figs. 4A-B, 5B-C). The whitish marls recurring in the upper part of this interval record relatively permanent water bodies in a setting otherwise dominated by ephemeral lacustrine conditions (Fig. 5C). The AK2b interval documents a return to fluvial channels anticipated by the coarse-grained tail of the underlying AK2a. The fluvial system entered the basin from NNW hinting to a persistent sediment supply from the CHA front. The following evolution was similar to that of the previous interval with reestablishment of a mud playa. This area of flood expansion was then filled by advancing terminal fans recorded by the AK2c interval grading again upward in a further playa lake. The angular unconformity separating these deposits from the AK3 sub-unit points to a further tectonic pulse shortening the basin (Figs. 4B, 5C). The newly created depocentre was initially filled by fluvial deposits bearing the macro-vertebrate remains and carried by a channel network flowing to the WSW, that is sub-axially to the Ouarzazate Basin trend. The successive return to lacustrine condition is on the line of alternating creation of sediment accommodation as recorded in the older sub-units (Fig. 6A). Recently published stable isotopic data on the lacustrine carbonates of the Ait Kandoula Formation (Boulton et al. 2019), provide further elements for defining the paleoenvironmental setting. Specifically, oxygen isotopic patterns identified in the lower portion of this formation equivalent to the AK1-2 sub-units, attest to hydrologically closed lacustrine conditions. The carbonates in the AK3-equivalent portion on the contrary suggests open lacustrine conditions hinting to a different paleohydrological scenario. These contrasting conditions are referred to a tectonic control over change of accommodation space and regional hydrographic reorganization being predominant on a climatic forcing (Boulton et al. 2019).

Finally, the AK4 sub-unit documents a definitive filling of the basin again related to terminal fan systems advancing from the north (Fig. 6A). In the study area this event represents the last stage of the Ouarzazate basin infilling before the progressive fluvial entrenching and terracing (Arboleya et al. 2008; Pastor et al. 2012).

Chronostratigraphic extent of the Ait Kandoula Formation with reference to the fossil vertebrate faunas

Basing on the magnetostratigraphic calibration of the fossil micromammal assemblages collected in the western Ouarzazate (Tesón 2009; Tesón et al. 2010) and Ait Kandoula depocentres (Benammi et al. 1996; Benammi & Jaeger 2001) and taking into account the reference to the MN13 zone for the Tizi N'Taddhert macro-vertebrate fauna (Zouhri et al. 2012; Cirilli et al. 2020), we propose the following chronostratigraphic extent for the revised Ait Kandoula Formation (Fig. 3). The AK1 sub-unit corresponds to the basal portion of the Ait Ibrirn Member (Fig. 7) that yielded a series of local normal and reverse intervals correlated to the C5AABn-C5An Chron of the geomagnetic polarity time scale (Tesón et al. 2010) (Fig. 3). This interval corresponds to the mid-upper part of the Serravallian, the same time span inferred in the Azdal section (AZ site in Fig. 1) from the biochronology of micromammals referred to the MN6-7+8 zones, and its magnetostratigraphic calibration (Fig. 3), (Benammi & Jaeger 2001; Benammi 2006). This chronostratigraphic attribution makes reasonable the hypothesis of an early Middle Miocene (Langhian-early Serravallian; Tesón et al. 2010), rather than a late Oligocene (Fraissinet et al. 1988; El Harfi et al. 2001) age of the underlying Ait Ouglif Formation in the light of the transition to AK1 through a progressive unconformity (Fig. 5A). Basing on the magnetostratigraphic calibration of the Ait Ibrirn Member (Tesón et al. 2010), the AK2 sub-unit accumulated between the end of the Serravallian and the Tortonian. The occurrence of a micromammal fauna (AM site in Fig. 1), presumably collected in the AK2c sub-unit (location in Tesón et al. 2010) and pointing to the MN11 zone, allows to correlate the topmost AK2 to the lower portion of the Afoud section in the Ait Kandoula sub-basin (AF site in Fig. 1), including micromammals referred to the MN10-12 zones (Benammi et al. 1996) (Figs. 3, 7). On the base of the macro-vertebrate assemblage indicating the MN13 zone, the AK3 sub-unit is correlated to the Messinian, being coeval with the upper part of the Afoud section, bearing an ash layer dated at about 5.9 Ma (Benammi et al. 1996), and other fossil localities in the Ait Kandoula sub-basin (Figs. 3, 7). Finally, the AK4 may reasonably encompass the Messinian-Zanclean transition ex-

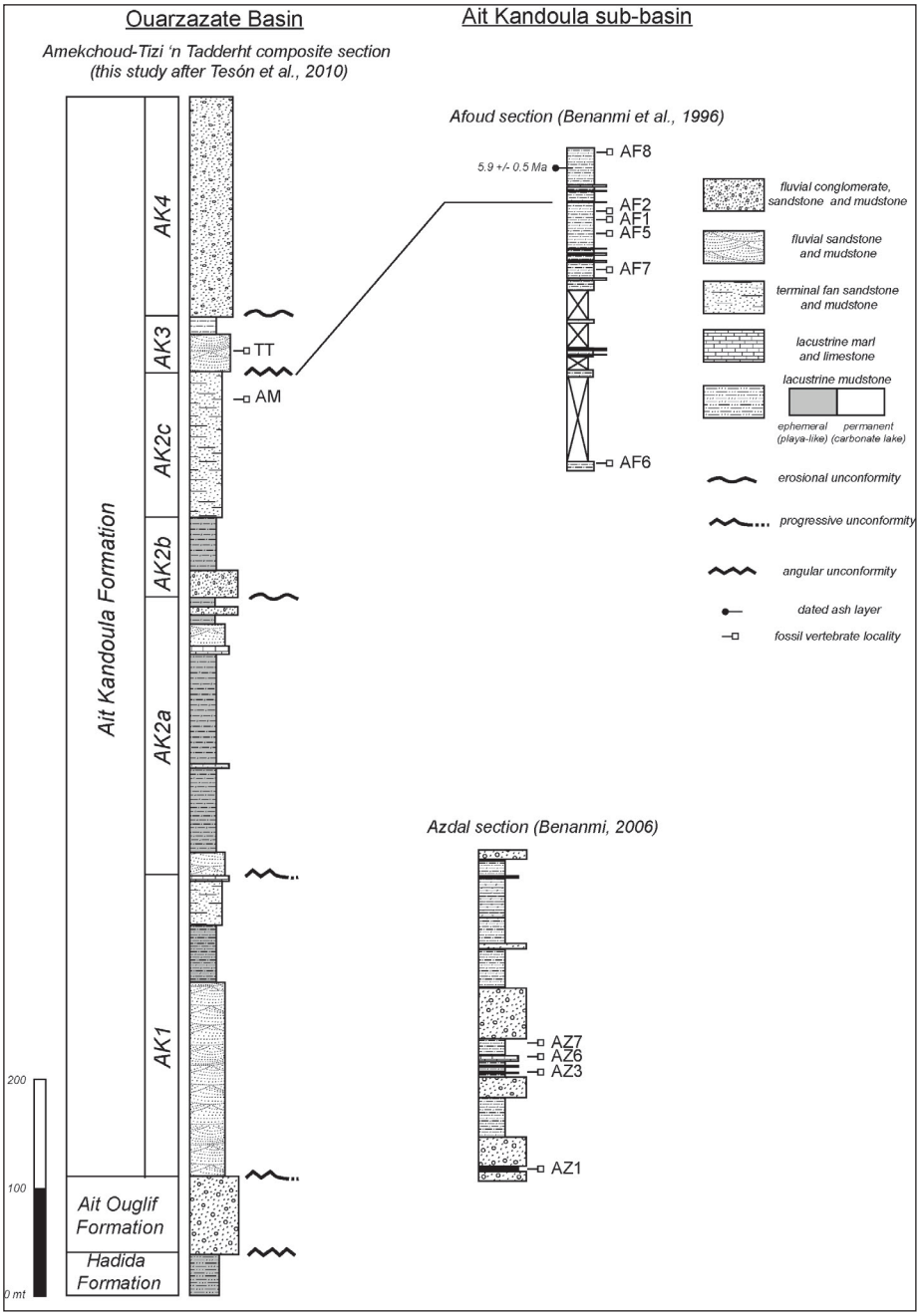

Fig. 7 - Proposed physical correlation among sections representative of the Ait Kandoula Formation in the study area, north of the Sub-Atlas Zone (Azdal section) and in the homonym sub-basin (Afoud section). Codes for the fossil vertebrate localities as in Fig. 1; TT: Tizi N'Tadderht site.

tending in the Early Pliocene. A significant consequence of this recalibration is a possible reassessment of the magnetostratigraphic record provided by Tesón et al. (2010) for their Ait Seddrat Member. The hypothesis of the authors, suggesting an almost continuous deposition in the Ait Kandoula Formation, resulted in a chronostratigraphic reference to the late Tortonian for the Ait Seddrat member. This conclusion should be revised considering the angular unconformity separating the AK2 from the AK3 sub-units and the MN13 vertebrates in the basal AK3. A hiatus including the upper part of the Tortonian, has to be considered for a correct correlation of the local magnetostratigraphic record reported by the authors (Figs. 3, 7). The proposed recalibration of the Ait Kandoula Formation opens at reconsidering the significance of the closed-versus-open lacustrine conditions geochemically recorded in the transition from AK1-2 to AK3 sub-units (cf Boulton et al. 2019). Despite the prevalent syntectonic control over the development of the Ait Kandoula Formation (Boulton et al. 2019; see the following discussion), such a hydrological change is here considered to have been also driven by climate. Specifically, the hydrologically open lakes developed in the Ouarzazate Basin and in the Ait Kandoula

sub-basin as recorded in the AK3 sub-unit, may have resulted from a marked increase of moisture that affected the North Africa during the Messinian related to the onset and activity of the Asian monsoonal circulation (Griffin 1999, 2002).

Implications for the Middle Miocene-Early Pliocene tectono-sedimentary development of the southern front of the CHA

The evidence of syn-tectonic control on the deposition of the Ait Kandoula Formation and its chronostratigraphic constraint provided by the integration of biochronological and magnetostratigraphic data from the western Ouarzazate Basin and the Ait Kandoula sub-basin, stimulate few considerations about the structuration of the southern front of the CHA during the Neogene. This aspect involves also the adjacent Ait Kandoula sub-basin, where the Ait Ouglif-Ait Kandoula formations show evidence of syn-depositional deformation (Görler et al. 1988; El Harfi et al. 2001), later on referred to the development of a piggy-back basin (Benammi et al. 2005; Tesón 2009). Accordingly, there must have been a time when the Ouarzazate and the Ait Kandoula depocentres became separated depositional areas. The distribution of the Ait Ouglif-Ait Kandoula formations in the two adjacent areas provides suggestions for tracing such a separation. In the western Ouarzazate Basin, the Ait Ouglif Formation occurs on both sides of the Tabia River though folded on the right, as specifically exposed in a prominent anticline thrusted by the Paleogene-Cretaceous deposits of the Sub-Atlas zone (Fig. 8A, C). On the left of the river the related conglomerates dip to the south being both thrusted and resting farther to the east in onlap on the Sub-Atlas front (Fig. 8B). North of the Sub-Atlas Zone, Ait Ouglif Formation is reported between the Tabia River and the Ouazalad Creek (El Harfi et al. 2001; Fig. 8) whereas it is apparently lacking in most of the Ait Kandoula sub-basin. The deposits exposed east of the Tabia River, consist predominantly of reddish and whitish lacustrine mudstone with subordinate fine-grained conglomerates and sandstones (c.f. Fig. 6.10 in Tesón 2009). This succession is lithologically equivalent to the Ait Kandoula Formation exposed in the western Ouarzazate Basin . As discussed in the present paper, the latter formation shows in the western Ouarzazate Basin an internal architecture made of four sub-units, all visible only west of the Tabia River, marking a clear syntectonic depositional stage bracketed between the advanced Serravallian and the Messinian-Zanclean transition. North of the Sub-Atlas Zone, the Ait Kandoula Formation occurs limitedly in the Ouazalad Creek valley to the west, whereas it is widely exposed into the Ait Kandoula sub-basin to the east (Fig. 8). This distribution is positively associated to a stratigraphic younging, revealed by the biochronological and magnetostratigraphic data (Benammi et al. 1996; Benammi 2006). The latter indicate that the older portion of this formation, equivalent to the AK1 sub-unit, is recorded in the outcrops of the Ouazalad Creek valley (Azdal section; Benammi 2006) (Figs. 3, 7, 8). The younger portion, equivalent to the AK2-4 sub-units, is recorded in the various sites of the Ait Kandoula sub-basin, which yielded micromammal remains (Benammi et al. 1996) (Figs. 3, 7, 8).

On the base of these lines of evidence we suggest the following sequence of tectono-depositional stages (Fig. 9):

1) Assuming that the Ait Ouglif Formation may have deposited during the early Middle Miocene (Tesón et al. 2010) then, at that time the Sub-Atlas thrust belt should have been a distinct frontal relief producing subtle surface warping in the Ouarzazate Basin related to the growth of its southernmost splays (Fig. 9A). This is suggested by the angular unconformities separating the Ait Ouglif from the Paleocene-Cretaceous deposits (Fig. 8A, B) and from the Hadida Formation in the Ameckchoud anticline (Figs. 2, 5B), respectively. The occurrence of the Ait Ouglif conglomerates north of the Sub-Atlas Zone, limitedly to the west of the Tabia River, may express a sediment supply transferred toward the Ouarzazate Basin through narrow fluvial valleys crossing this complex deformation zone. The latter has been differently interpreted in the frame of the structural evolution of the southern CHA front. The reference to a *Nappe* tectonics operating since the late Cretaceous (Laville et al. 1977) has been more recently replaced by a gravitative (Görler et al. 1988) or a thin-skinned thrust (Benammi et al. 2005; Tesón 2009; Tesón et al. 2010) tectonics active since the late Eocene and following to a long post-rift, tectonically quiescent stage in the evolution of CHA. Nevertheless, tectono-stratigraphic lines of evidence (Moratti et al. in prep.) suggests that crustal shortening and uplift affected this area even before the Late Cretaceous as documented both westward (Cavallina et al.

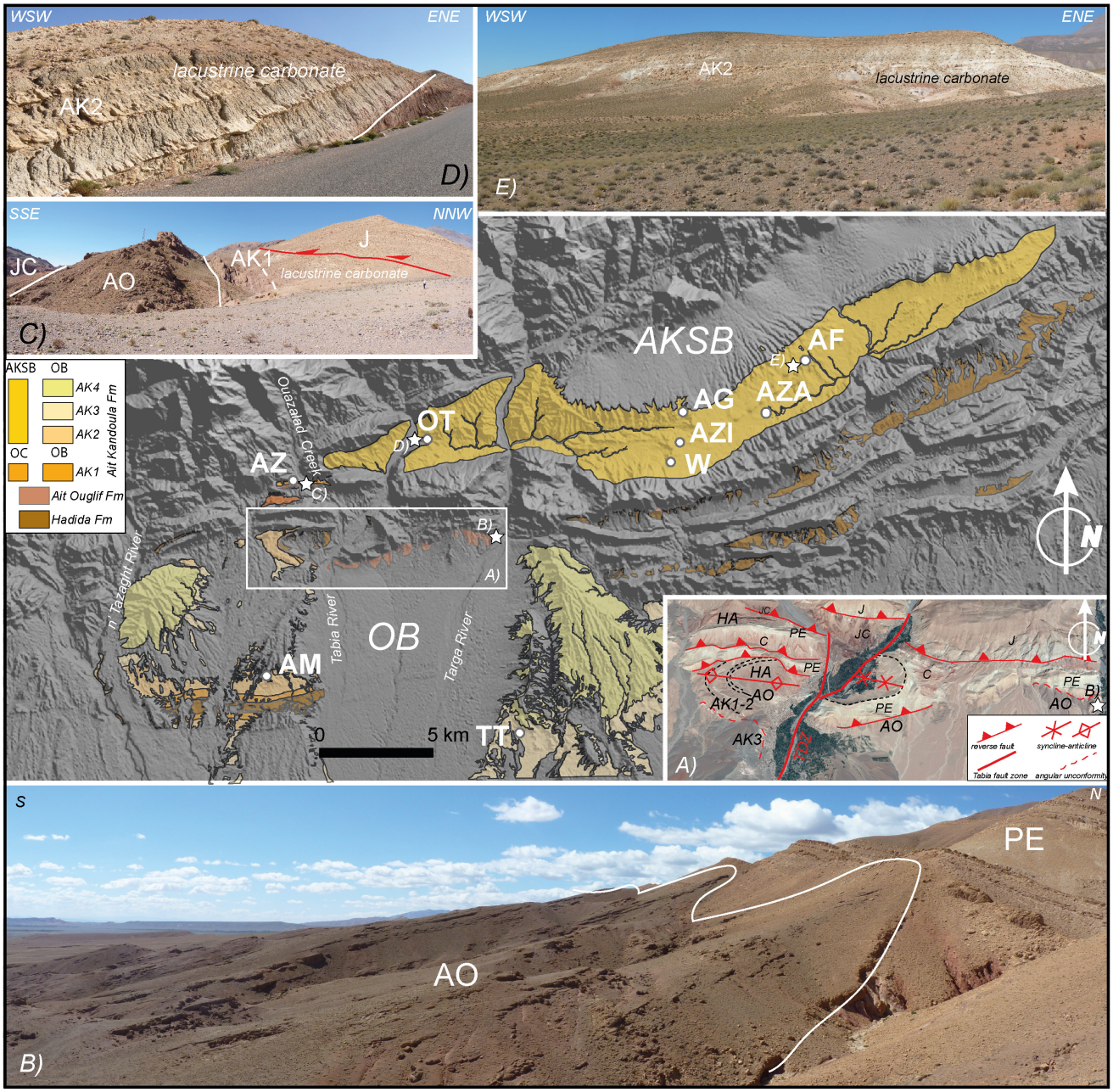

Fig. 8 - Outcrop distribution of the Imerhane Group between the west Ouarzate Basin (OB) and the Ait Kandoula sub-basin (AKSB), including the exposures along the Ouazalad Creek (OC), white stars locate the B-E viewpoints. Codes for fossil vertebrate localities (white circles) as in Figs. 1 and 7. A) aerial view (from Google Earth™) of the sector just southward the Sub-Atlas Zone with annotation of the complex structural setting. The different structural pattern west and east the Tabia River is evident hinting to some control operated by the inferred Tabia Deformation Zone (TDZ, see Fig. 2) during the deposition of the Ait Ouglif and Ait Kandoula formations. Codes: J: lower Jurassic limestones; JC: Middle Jurassic-lower Cretaceous red beds; C: upper Cretaceous red beds and limestone; PE: Paleogene-Eocene carbonates; HA: Hadida Fm.; AO: Ait Ouglif Fm.; AK: Ait Kandoula Fm.; B) panoramic view looking to the west from the right bank of the Targa River showing the onlap of the Ait Ouglif conglomerates (AO) onto the Paleogene carbonates and marlstone (PE); C) the outcrop of the Azdal section showing the AK1 lacustrine deposits thrusted by the Lower Jurassic carbonates (J). On the left the Ait Ouglif conglomerates (AO) resting unconformably on Middle Jurassic-lower Cretaceous red beds (JC); D) Outcrop of lacustrine carbonates referred to the AK2 sub-unit in the Oued Tabia section; E) the exposure of AK2 lacustrine marlstone and limestone in the Afoud section.

2018) and eastward (Benvenuti et al. 2017; Moratti et al. 2018) along the southern CHA front. Finally, the Ait Kandoula sub-basin may have been not active during the Ait Ouglif deposition.

2) Across the advanced Serravallian, the AK1 sub-unit accumulated west of the Tabia River (Fig. 9B) under a marked syntectonic control related to the reactivation of the Sub-Atlas thrust belt and re-

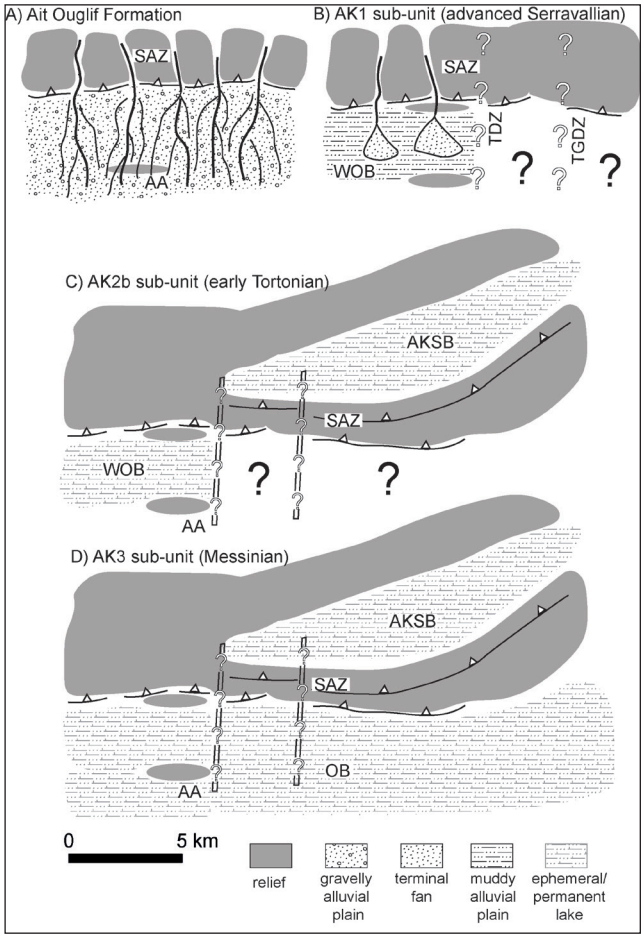

Fig. 9 - Palaeogeographic sketches illustrating the main stages in the tectono-sedimentary development of the study area; WOB: west Ouarzazate Basin; OB: Ouarzazate Basin; AA: Amekchoud anticline; TDZ: Tabia Deformation Zone; TGDZ: Targa Deformation Zone (white question marks express the uncertain occurrence of these zones; dashed line: inactive; black question marks indicate unknown depositional setting),

lated splays, documented by the progressive unconformities affecting this sub-unit (Fig. 5A). The creation of accommodation in the syncline confined by the Amekchoud anticline to the south and by the Sub-Atlas front to the north, forced the transition from a fluvial plain fed from the north into a muddy playa. Reduced tectonic activity allowed the progradation of terminal fans in the late AK1 development. The limited outcrops of equivalent deposits to the north of the Sub Atlas Zone still centered in the Ouazalad Creek valley (Fig. 8), hints to a persisting fluvial feeder crossing the front and opening in the Ouarzazate Basin. In this stage a) the Ait Kandoula sub-basin seems still not active and b) the Sub-Atlas Zone and associated splays appear to be not deforming as a continuous frontal structure from west to east. This suggests a role of the inferred Tabia shear zone as a discontinuity transverse to the CHA front that actively controlled the tectono-depositional dynamics. Specifically, this structure may have acted as a transfer fault releasing the portion to the west, that accommodated the deformation through folding, from the portion to the east apparently less deformed. This hypothesis, though speculative, offers a different perspective from the predominant interpretative framework of the late evolution of the CHA-southern foreland system based exclusively on the role of frontal thrusts (Laville et al. 1977; Görler et al. 1988; Benammi et al. 2005; Tesón 2009; Tesón et al. 2010).

3) AK2 sub-unit, with its internal architecture, attests to significant tectono-depositional changes occurred between the late Serravallian and the Tortonian (Fig. 9C). The first important event is the activation of the Ait Kandoula sub-basin that in this stage accommodated mostly fine-grained lacustrine deposits (Fig. 8D, E). At the same time the depocenter west of the Tabia River continued to be filled by cyclic fluvio-lacustrine deposition, recorded by the AK2a-c intervals, under a persisting activity of the Sub-Atlas thrust belt (Figs. 2, 5C). Such a scenario implies again a structural discontinuity along a trend transverse to the orogenic front and centered in the Tabia-Targa river valleys. West of this trend the deformation concentrated in front of the Sub-Atlas Zone meanwhile the relieves to the north fed fluvial catchments opening in the Amekchoud area. To the east thrusting concentrated in a more internal area bringing the Jurassic units over the Sub-Atlas Zone with the consequent activation and development to the north of the Ait Kandoula piggy-back sub-basin (Fig. 8A).

4) The AK3 sub-unit started to accumulate after a major shortening pulse along the Sub-Atlas front as documented west of the Tabia River by the angular truncation of the underlying AK2 deposits (Figs. 2, 5C). The occurrence of this unit across the inferred Tabia shear zone (Fig. 9D) suggests a reduced role of this discontinuity transverse to the external front of the CHA. This is confirmed also by the AK3 basal fluvial deposits which mark a significant change of drainage orientation in the western Ouarzazate Basin representing the first record of sediment routing sub-parallel to the basin trend and directed to the WSW along the external fronts of the chain. Furthermore, this evidence supports the full separation of the Ait Kandoula sub-basin dur-

ing the Messinian. Such a scenario is suggested also by the facies contrast in the AK3-equivalent deposits considering the inner and outer location of the two depocenters in respect with the Sub-Atlas zone. Specifically, lacustrine mudstone characterizes the Ait Kandoula sub-basin whereas fluvio-lacustrine sandstone and mudstone occur in the Ouarzazate Basin (Figs. 2, 5C), implying the coexistence of an isolated lake and an alluvial plain only later evolving in a wide and hydrologically open lake (Boulton et al. 2019), respectively north and south the Sub-Atlas Zone.

5) The AK4 sub-unit documents a return to alluvial deposition in the western Ouarzazate Basin fed by catchments to the north. The remnants of this unit, exposed as almost tabular strata in the Tifarouine and Jbel Adroug relieves, outline two major alluvial fans possibly fed by the N'Tazaght and Targa rivers, respectively (Fig. 2). AK4-equivalent deposits, covered by Quaternary alluvial fans, are confined to the northern margin of the Ait Kandoula sub-basin, suggesting a persistent lack of connection with the Ouarzazate basin. Again, there is a striking contrast between the zones west and east the Tabia-Targa rivers in terms of depositional dynamics possibly evidencing renewed effects of the structural discontinuity transverse to the CHA front.

Conclusions

This study exploited the spatial and chronostratigraphic distribution of fossil micro- and macromammals assemblages for attempting a stratigraphic-depositional revision of the Ait Kandoula Formation exposed in a portion of the western Ouarzazate Basin at the southern front of the Central High Atlas. This resulted in the distinction of the AK1-4 sub-units which attest to the alternating establishment of fluvial and lacustrine settings between the advanced Serravallian and the earliest Zanclean. Progressive or angular unconformities bounding these sub-units point to a primary syntectonic control over the depositional dynamics, exerted by thrust faults and related splays of the Sub-Atlas zone which propagated crustal shortening southward. An inferred shear zone oriented transversally to this structural trend seems to have played a role in releasing differently deformed zones to the west and the east of the study area. This had consequences also for the development of the Ait Kandoula sub-basin, a satellite depocenter located north of the Sub-Atlas Zone and filled by the homonym formation. The interplay of front-parallel and transverse structural discontinuities accounted for the differential sediment routing and storing in adjacent syn-tectonic depocentres as recorded in the facies architecture of the Ait Kandoula Formation. Though active deformation represented the prevalent control over the sedimentary patterns, a climate signal may be identified in the paleohydrological signature of the lacustrine deposits within the architecture of this formation. A Messinian wet climatic regime over North Africa related to a monsoonal activity, may account for the occurrence of hydrologically open and wide lakes in the late development of the Ait Kandoula Formation.

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