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Shoulder to shoulder architecture of a salt-related rift basin at the onset of continental break-up: The Central High Atlas Jurassic diapiric province (Morocco)

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ABSTRACT

Continental passive margins are often defined by early salt-related rift systems buried beneath thick sedimentary piles, with structural and sedimentary architectures only directly observable when inverted in orogenic systems where primary salt structures are overprinted by compression. The Central High Atlas diapiric province (Morocco) is an inverted salt-related rift basin with active salt tectonics since early Mesozoic times that provides an exceptional view of early syn-rift sediments and structure. We present the first regional balanced and restored cross-sections of the Central High Atlas evidencing the role of salt tectonics. The cross section includes seven salt walls and six minibasins, with associated Early Jurassic to Cenozoic halokinetic strata that indicates a shortening of 38 km (24%). The Jurassic rifting stage is characterized by shallow water sediments along the basin margins and around localized salt walls, separated by minibasins filled with deep-water sediments undergoing higher subsidence rates. Subsequently, a longitudinal deltaic system prograded eastwards coevally with shallow marine deposition associated with active salt walls. Thus, local diapir uplift enhanced shallow-water deposition and local aerial exposure in central parts of the basin throughout the whole rifting stage. These features provide insights for the study of rift basins and the early stages of continental break-up worldwide, and for the exploration and production of hydrocarbons in equivalent settings.

1. Introduction

The initial stages of continental passive margins are characterized by the development of rift systems, which eventually become buried beneath thick sedimentary successions and with distal domains located few kilometers below sea level. Therefore, the detailed subseismic architecture of rift basins is hard to unveil and only directly observable when inverted and preserved in orogenic systems, where the compressional overprint partially obliterates extensional features (Bahroudi and Koyi, 2003; Graham et al., 2012; Saura et al., 2016; Casini et al., 2023). Salt tectonics is a frequent feature in rift basins (Mart and Ross, 1987) and passive margins (Fig. 1a). Passive margins with post-rift salt are often characterized by stretching upslope in the proximal domain and shortening downslope in the distal domain (e.g., Letouzey et al., 1995; Tari et al., 2003). However, this configuration can be far more complex in basins where the salt is syn-rift, and extensional and compressional domains are amalgamated (Tari et al., 2003) (Fig. 1b). When such domains are inverted, it is difficult to discern salt-related deformation structures from tectonic compressional structures, which typically led to underestimating the importance of salt tectonics.

The Atlas Mountains in north-western Africa are a classic example of an inverted intracontinental rift system (Mattauer et al., 1977) and considered again two decades later (Vially et al., 1994; Ziegler et al., 1995) where diapirism related to syn-rift salt is reported to take place since early Mesozoic times (Vially et al., 1994; Letouzey et al., 1995; Hlaiem, 1999; Frizon de Lamotte et al., 2000; Hafid, 2000; Bracene et al., 2003; Zouaghi et al., 2005, 2013; Moragas et al., 2016; Teixell et al., 2024). Within the Atlas Mountains, the Central High Atlas diapiric province in Morocco provides an exceptional view of the early syn-rift sediments and structure of the Atlas system (e.g., Saura et al., 2014; Teixell et al., 2017; Vergés et al., 2017; Martín-Martín et al., 2017; Teixell et al., 2024), in which the subsequent compressional signature

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can be, at least in part, resolved (e.g., Moragas et al., 2017; Dooley and Hudec, 2020).

The structure of the Central High Atlas is characterized by a doubly verging chain with peripheral fold-and-thrust belts in the North and South, where most shortening is localized (e.g., Poisson et al., 1998; Teixell et al., 2003), associated with peripheral foreland basins. By contrast, the central zone is characterized by thick Early to Middle Jurassic syn-rift sedimentary successions that form broad synclines (i.e., minibasins) or tabular plateaus separated by narrow SW-NE structural ridges (i.e., former salt walls and salt welds) exposing Triassic materials and Middle Jurassic intrusions (Fig. 2). Deformation in the central zone is mild and mostly occurring around the diapiric ridges. The diapiric nature of the ridges was noted since the 1990s' (Bouchouata et al., 1995; Ettaki et al., 2007b; Michard et al., 2011; Saura et al., 2014), although they were initially interpreted either as complex strike-slip faults of Jurassic age (Laville and Harmand, 1982; Laville, 1988; Laville and Piqué, 1992; Laville et al., 2004) or Alpine thrust anticlines (Poisson et al., 1998; Teixell et al., 2003).

Despite numerous diapiric structures were reported throughout the basin, the regional cross-sections published until now do not completely provide evidences for the role of salt tectonics in the configuration of the Central High Atlas (Poisson et al., 1998; Teixell et al., 2003; Michard et al., 2011, Casas-Sainz et al., 2023). Therefore, the structure of the Central High Atlas needs to be revisited considering the diapirism associated with syn-rift salt deposited in the High Atlas Basin during the Late Triassic.The goal of this paper is to present a shoulder-to-shoulder cross-section of the Atlas Mountains in order to highlight the structure of the inverted Atlas rift basin and the effect of diapirism during Mesozoic extension and subsequent Alpine compression. Specifically, the objectives of this work are: 1) to construct a balanced cross-section of the Central High Atlas of Morocco; 2) to restore the cross-section to visualize the structure of the Mesozoic diapiric rift basin and calculate the amount of shortening, and 3) to reconstruct the distribution across time and space of the sedimentary depositional systems, especially those associated with diapiric highs. It is an ultimate goal of the paper to provide a field analogue for buried examples of salt related rift basins and passive margins worldwide (Fig. 1), settings that historically, in the O&G industry, have been a focal point due to the role of salt structures as effective seals or traps for hydrocarbons. Also, more recently, diapirs have regained attention for their efficacy as seals in CO_2 storage and for their H_2 storing potential within natural salt caverns, emphasizing the increasing significance of studying these systems for a cleaner energy and climate change mitigation strategies.

2. The Atlas diapiric province

The Atlas Mountains are an ENE–WSW-trending, about 2000-km long inverted rift basin extending from Morocco to Tunisia (e.g., Vergés et al., 2017) (Fig. 2A). This salt-related rift basin formed coevally with the Late Permian–Early Jurassic Central Atlantic opening (Piqué et al., 2000). The Jurassic to Early Cretaceous stage is characterized by well-documented diachronic diapirism from the High Atlas (Saura et al., 2014; Moragas et al., 2017; Martín-Martín et al., 2017; Teixell et al., 2017, 2024) to Tunisia (Patriat et al., 2003; Masrouhi et al., 2013; Khomsi et al., 2022; Khelil et al., 2021) through the Algerian and Saharan Atlas (Bracene et al., 2003).

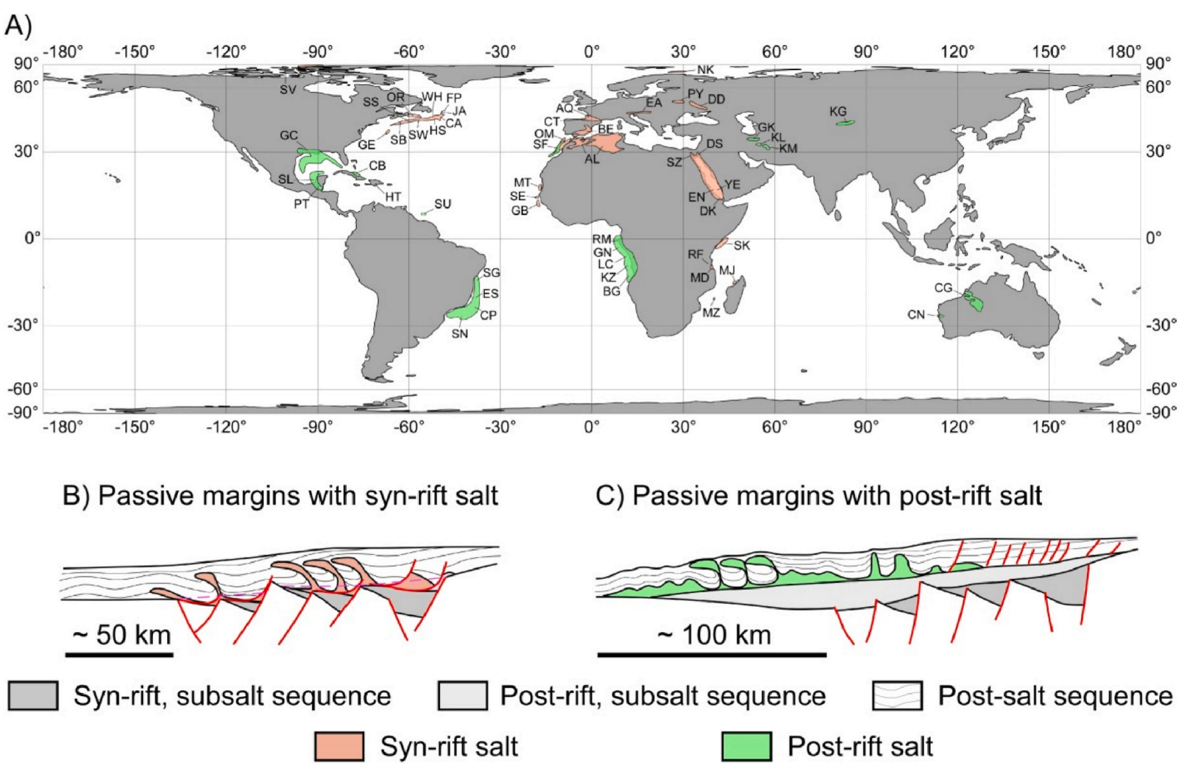

Fig. 1. A) Salt related rift basins and passive margins of the world (modified from Hudec and Jackson, 2007). AL Atlas; AQ Aquitaine; BE Betic; BG Benguela–Namibe; CA Carson; CB Cuban; CG Canning; CN Carnavon; CP Campos; CT Cantabrian–West Pyrenees; DD Dnepr–Donetz; DK Danakil; DS Dead Sea; EA East Alpine; EN Eritrean; ES Espirito Santo; FP Flemish Pass; GB Guinea-Bissau; GC Gulf Coast; GE Georges Bank; GK Great Kavir–Garmsar–Qom; GN Gabon; HS Horseshoe; HT Haitian; JA Jeanne d'Arc; KL Kalut; KM North Kerman; KQ Kuqa; KZ Kwanza; LC Lower Congo; MD Mandawa; MJ Majunga; MN Moesian; MT Mauritania; MZ Mozambique; NK Nordkapp; OM Offshore Moroccan basins; OR Orpheus; PT Petenchiapas; PY Pripyat; RF Rufiji; RM Rio Muni; SB Sable; SE Senegal; SF Safi; SG Sergipe–Alagoas; SK Somali–Kenya; SL Salina–Sigsbee; SN Santos; SS Scotian Slope; SU Suriname; SV Sverdrup; SW South Whale; SZ Suez; WH Whale; YE Yemeni. B and C) Structure of salt-related passive margins according to the age of the salt with respect of the rift system (modified from Tari et al., 2003). In syn-rift salt systems (B) the compressional and extensional domains are amalgamated, whereas in post-rift salt systems (C) the extensional and compressional domains, respectively, develop in proximal and distal areas.

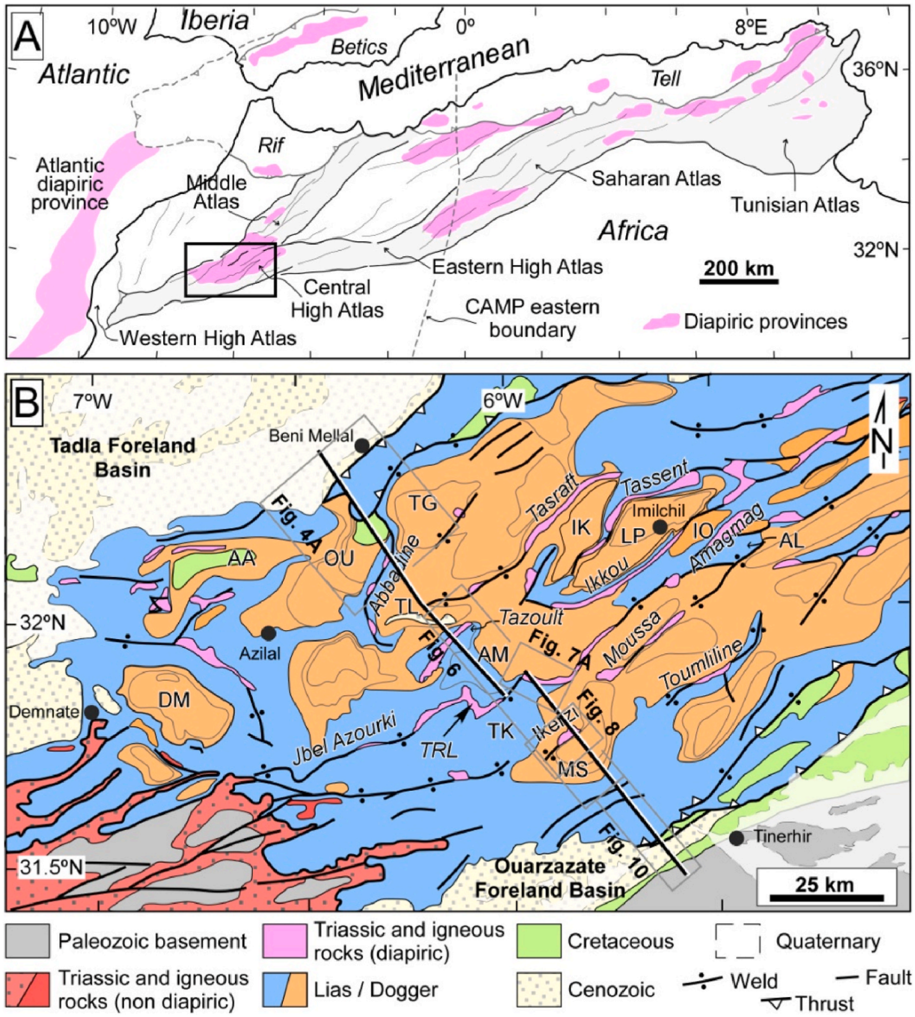

Fig. 2. A: Location of the study area in the framework of NW Africa, modified after Saura et al. (2014). Black box indicates the location of Fig. 2B. B: Structural map of the Central High Atlas. Diapiric ridges and minibasins are labeled. Minibasins: AA – Aït Attab; AL – Almghou; AM – Amezraï; DM – Demnate; IK – Ikassene; IO – Ikkou; LP– Lake Plateau; MS – Msemrir; OU – Ouaouizaght; TG – Taguelft; TL – Tilouguite. TK – Takrakart. TRL – Taghia Relay Zone.

The Central High Atlas Triassic syn-rift sediments were deposited in half-graben basins bounded by ENE–WSW trending faults (Fig. 2B) (Piqué et al., 2000; Frizon de Lamotte et al., 2008). Triassic deposits consist of more than 1-km thick reddish siltstones and evaporite-bearing shales including irregularly distributed Rhaetian (?) halite and gypsum (Benaouiss et al., 1996; Courel et al., 2003), which are unconformably overlain by Upper Triassic to lowermost Jurassic tholeiitic basalts of the Central Atlantic Magmatic Province (CAMP) (Marzoli et al., 2004) (Fig. 2A). The Late Triassic schizohaline environment in the Central High Atlas graded eastwards to hypersaline and open Tethys marine deposition in Tunisia (Oujidi et al., 2000; Courel et al., 2003). The evaporite bearing Triassic materials became the source layer for the diapiric structures of the Atlas Mountains (Vially et al., 1994; Letouzey et al., 1995; Hlaiem, 1999; Frizon de Lamotte et al., 2000; Bracene et al., 2003; Zouaghi et al., 2005; Zouaghi et al., 2013; Saura et al., 2014; Casas-Sainz et al., 2023).

The Jurassic sedimentary succession is composed of Hettangian–-Pliensbachian platform carbonates that extent across the Central High Atlas, interfingering with hemipelagic and slope basin-related deposits towards the center of the basin and eastwards. The Hettangian–-Pliensbachian carbonates are covered by Pliensbachian–Aalenian eastward prograding platform mixed clastic–carbonates with source areas located around the western closure of the Tethys realm (Fig. 1; Souhel et al., 2000). These mixed platform sediments are conformably overlain by a shallowing upwards succession ranging from oolitic and coral limestones to continental red beds, deposited across the High Atlas Basin from Aalenian to Callovian times (Fig. 1; Bouchouata et al., 1995; Fadile, 2003). The Middle Cretaceous-Paleogene succession is defined by a basal shallow marine carbonate unit conformably overlain by red beds and finally by Eocene shallow-marine carbonates. The Cretaceous sediments are only preserved in the frontal thrust systems and in a few minibasins within the Central High Atlas (Fig. 2). However, burial and thermal modeling suggests that more than 1.5 km of sedimentary overburden was eroded in the Central High Atlas since the Alpine inversion, which could correspond largely to the Cretaceous successions (Domènech et al., 2016; Moragas et al., 2017). The Cretaceous sediments are unconformably overlain by the Eocene –Quaternary conglomerate units of the foreland basins (e.g., Tesón et al., 2006; Si Mhamdi et al., 2024), which can also be locally found in intramontane basins unconformable on top of the Jurassic succession (i.e., La Cathédrale alluvial fan). For simplicity, the names of the different formations are introduced in the detailed structural description below.

The Central High Atlas is also characterized by alkaline transitional gabbroic magmatic bodies intruded during the late Dogger and Malm (Fig. 3), which resulted in multiple intrusive, subvolcanic and volcanic rocks across the study area (Hailwood and Mitchell, 1971; Rahimi et al., 1997; Armando, 1999; Zayane et al., 2002; Bensalah et al., 2013). Gabbroic magmatism continued during the Early Cretaceous and later

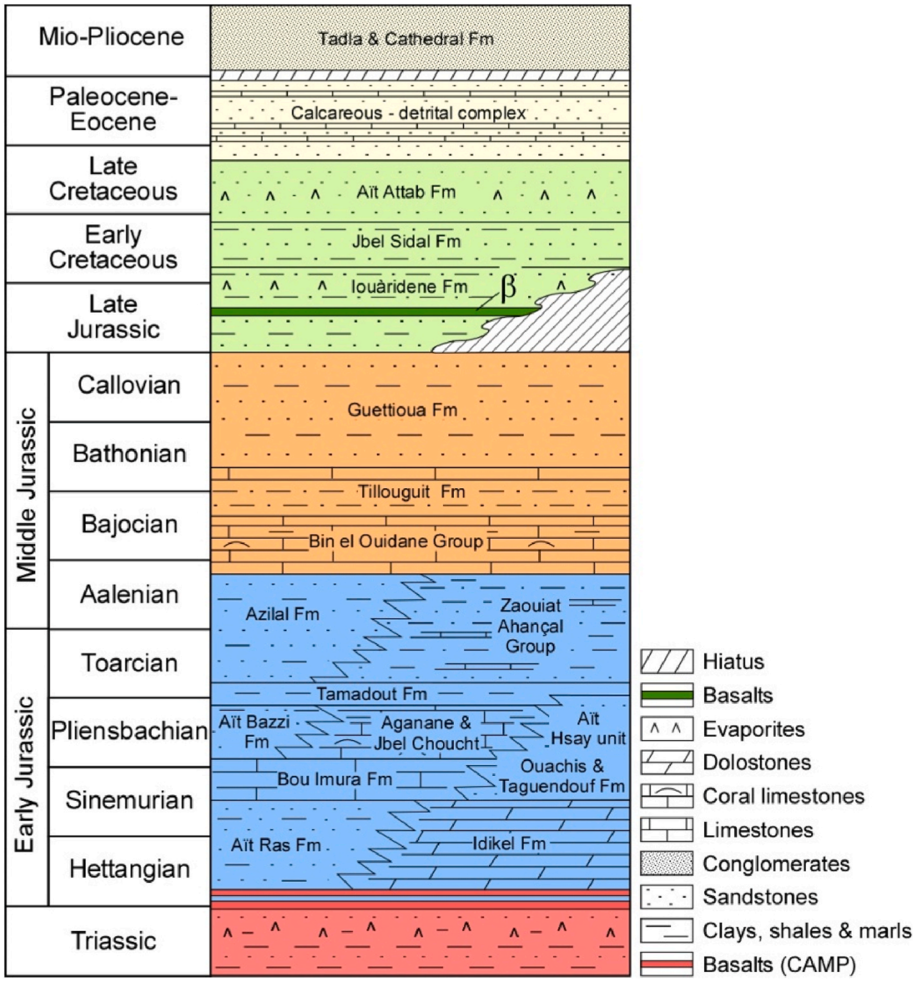

Fig. 3. Synthetic stratigraphic section showing the main characteristics of the mostly Jurassic stratigraphy in the Central High Atlas (compiled after Monbaron, 1985; Fatah et al., 1990; Milhi, 1997, Fadile, 2003; Michard et al., 2011).

(Fig. 3; Lhachmi et al., 2001; Haddoumi et al., 2010). The final stage in the evolution of the Central High Atlas corresponds to the Eocene to Quaternary Alpine compression and uplift (e.g., Monbaron, 1985; Tesón and Teixell, 2008; Domènech et al., 2018), the sedimentary record of which is found essentially in the plains bordering the High Atlas.

3. Methods

The regional cross-section of the Central High Atlas (Morocco) studied in this work represents a 120-km long transect that includes five main areas presented in detail in the following section. These areas were initially characterized by remote sensing mapping (RSM) directly in Google Earth, and locally with high resolution satellite imagery, combined with published data (see Milhi, 1997; Tesón and Teixell, 2008; Tesón, 2009; Martín-Martín et al., 2017). Local satellite imagery included high resolution Geoeye (0.5m resolution) and QuickBird (0.6 m resolution) orthorectified satellite imagery and derived digital elevation models (DEM). QuickBird derived DEM has a spot resolution of 20m × 20 m, and Geoeye derived DEM a spot resolution of 2*2 m. Remote sensing mapping has been performed directly onto DEM data using ArcGis software, and the collection of RSM-derived strike and dip data is included. The RSM was subsequently quality controlled and improved through extensive fieldwork campaigns carried out during the time interval between the years 2011 and 2017. Field work included the systematic collection of structural (strike and dip), stratigraphic (lithology and thickness), and sedimentological (depositional facies) datasets. Field panoramas were used to further map stratal relationships and geometries to support RSM and field mapping.

Structural balanced and restored cross-section construction techniques were applied for the construction of the regional transect, constrained by own and published geological maps and field data. Local complementary cross-sections were built to better understand and illustrate complex 3D geometry of some of the described structures. The cross-sections were built and restored making use of the modelling software Move from Petroleum. Line length and thickness preservation assumption was made at the cover level (e.g. Rowan and Ratliff, 2012; Najafi et al., 2018), together with the preservation of the halokinetic depositional geometries (e.g. Casini et al., 2023), whereas area balancing was used at the basement level.

4. Results

4.1. Central High Atlas rift basin reconstruction

The regional cross-section is divided in five areas as follows: i) The northern Atlassic front, ii) The Abbadine diapiric complex, iii) The Amezraï minibasins and flanking Tazoult and Jbel Azourki salt walls, iv) The Ikerzi diapir and the Msemrir minibasin, and v) The southern Atlassic front.

4.1.1. The northern Atlassic front

The northern Atlassic front in the studied area is located at the confluence between the NE-trending Middle Atlas and the ENE-trending High Atlas (Fig. 4A). This portion of the transect is characterized by the

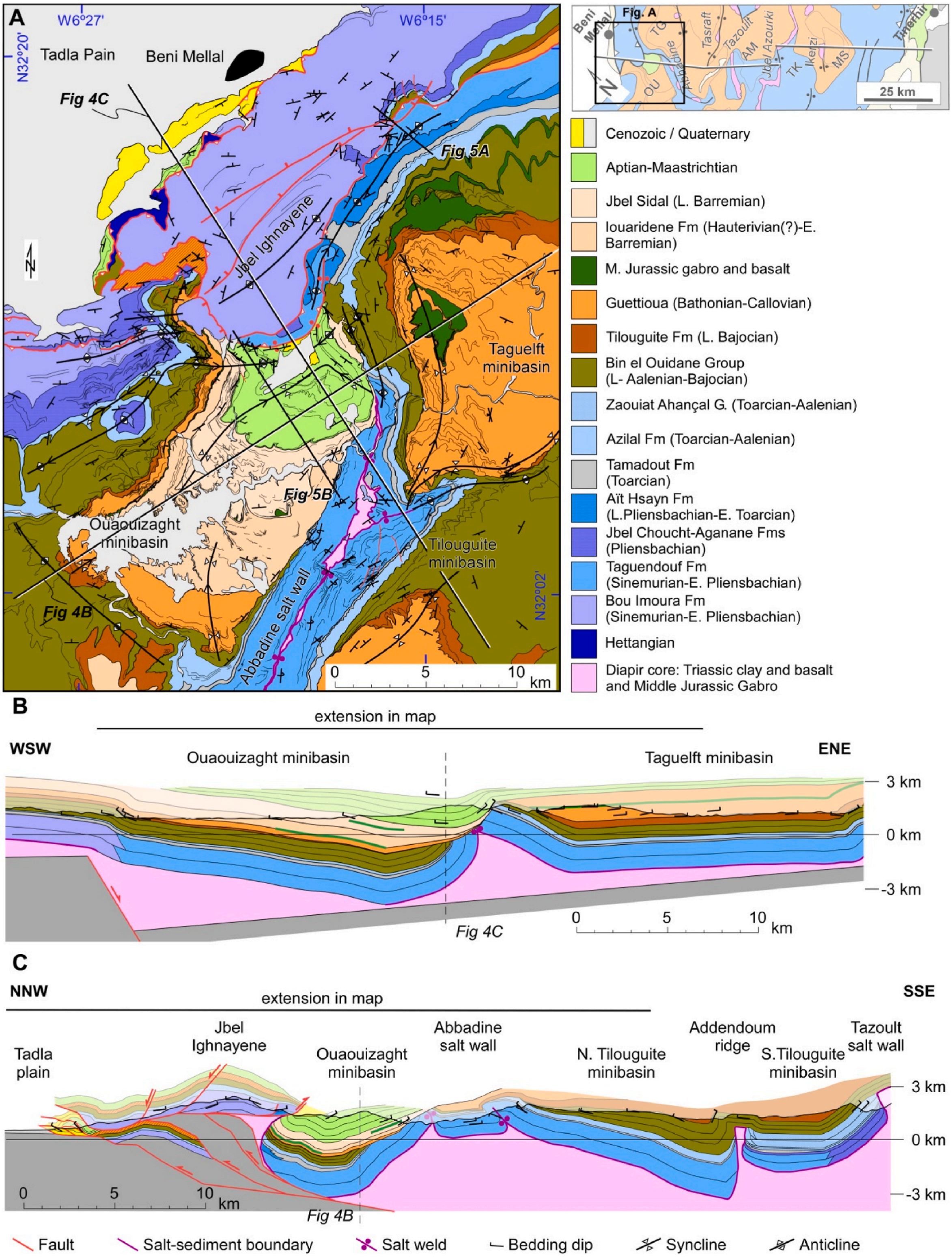

Fig. 4. A) Geological map of the Northern Atlas front in the Beni Mellal area, the Ouaouizaght, Taguelft and Tilouguite minibasins and the Abbadine salt wall based on own field data, remote sense mapping and published data (Monbaron, 1985; Löwner, 2009; Haddoumi et al., 2010). B) WSW-ENW axial cross-section across the Ouaouizaght and Taguelft minibasins. C) Cross-section from the Tilouguite minibasin to the Atlas front.

foreland basin (Tadla Plain), the Jbel Ighnayene culmination, and the Ouaouizaght and Taguelft basins. Two local cross-sections have been constructed to illustrate the geometry of the area (Fig. 4B–C).

The northern foreland basin consists of about 1000 m thick Cenomanian to Quaternary succession directly on top of a thin Triassic cover above the basement (Fig. 4C) (Bouchaou et al., 1997; Frizon de Lamotte et al., 2008). A steep topographic relief of around 1800 m marks the transition from the northern Atlas foreland basin to the Jbel Ighnayene culmination. Its northern front is characterized by thin Jurassic (~850 m of thickness), Cretaceous (~400 m of thickness) and Paleocene-Eocene

(∼350 m of thickness) successions tectonically repeated by a north directed thrust system, and by two north dipping and high angle normal faults that often define a step in the landscape (Figs. 4A and 5A). The highest part of the Jbel Ighnayene culmination is mainly constituted by a thick Sinemurian to Pliensbachian shallow marine carbonate platform succession, including the Bou Imoura (∼1100 m of thickness), and the Aganane and Jbel Choucht formations (∼100 m of thickness) (Figs. 4A and 5A). Towards the south of the Jbel Ighnayene culmination, this Sinemurian-Pliensbachian succession changes to basinal facies of the Taguendouf (∼1400 m of thickness), Tamadout (∼175 m of thickness) and Aït Hsayn (∼150 m of thickness) formations. The boundary between these two domains is defined by a fault with thicker successions and deeper facies on its southern wall interpreted as a normal fault by Monbaron (1985) (Fig. 4A) that currently displays reverse offsets (Fig. 5A), indicating late compressional inversion. The Toarcian continental Azilal Formation overlies older formations on both sides of the inverted fault, with a maximum thickness of 250 m on the southern slope of Jbel Ighnayene culmination and a rather homogeneous facies distribution. The Azilal Formation is conformably overlain by a shallowing upwards succession including the late Aalenian-Bajocian Bin el Ouidane carbonates and clastics (up to 600 m in thickness), the late Bajocian-Albian Tilouguite, Guettioua, Iouaridene and Jbel Sidal red bed formations (up to 800 m in thickness), and a mixed carbonate-clastic Cenomanian-Paleocene succession (up to 1500 m in thickness).

South of the Jbel Ighnayene culmination, the structural relief decreases about 4 km in Ouaouizaght and Taguelft area, where a ∼4500 m-thick Lias to Paleocene succession crops out (Figs. 4 and 5B). These Ouaouizaght and Taguelft structures were originally interpreted as simple synclines (Brede, 1992) but are interpreted as minibasins in the present study in agreement with the model by Moussaid et al. (2024). The Jbel Ighnayene high and the Ouaouizaght minibasin are separated by a north dipping structural contact, the Ouaouizaght thrust weld.

4.1.2. The Abbadine diapiric complex

South of the northern Atlassic front, the Abbadine diapiric complex is characterized, from N to S, by the following structures: a) the Ouaouizaght minibasin; b) the Taguelft minibasin, c) the two branches of the Abbadine salt wall; d) the Northern Tilouguite minibasin; e) the Addendoum salt wall; and f) the Southern Tilouguite minibasin, which borders the Tazoult salt wall to the SSE (Fig. 4C).

This area is mostly characterized by the discontinuously welded Abbadine salt wall, defined by a triple junction, with a northern branch separating the Ouaouizaght and the Taguelft minibasins, a western branch separating the Ouaouizaght and the Tilouguite minibasins, and an eastern branch separating the Taguelft and Tilouguite minibasins (Fig. 4A). The Ouaouizaght minibasin is about 200 km^2 topographic low filled by a sedimentary succession that displays a fanning attitude, from steeply-dipping (∼60°) beds of the Late Pliensbachian-Toarcian Tamadout Formation to subhorizontal Paleocene beds (Figs. 4 and 5B). In the north, this succession abuts against the Ouaouizaght thrust weld, displaying a short wavelength syncline rimming the whole weld. Towards the east, the Ouaouizaght minibasin is bounded by the northern branch of the Abbadine salt wall (Fig. 4C). The southern part of the Ouaouizaght minibasin, on the northern flank of the western Abbadine salt wall, is characterized by the onlap and eastward pinch-out of the upper Toarcian to lower Barremian succession and the final erosive truncation of the whole succession by the upper Barremian Jbel Sidal red bed formation (Fig. 4A). Below this truncation, the Sinemurian basinal carbonates of the Taguendouf Formation are mostly overturned along the whole structure down to the Triassic outcrops in the Abbadine core (Fig. 4A). Similarly, the succession filling the Taguelft minibasin shows a significant thickness increase away from the Abbadine salt wall, although the exposed sedimentary pile represents a shorter time span than in Ouaouizaght, from the Sinemurian to the Callovian (Monbaron, 1980; Bensalah et al., 2013). Both Ouaouizaght and Taguelft minibasins are comparable to the Aït Attab minibasin, located 20 km westward (Fig. 2), where thickness variations also affect at least the Sinemurian to Barremian succession (Jenny, 1984; Monbaron, 1985; Beauchamp et al., 1999; Haddoumi et al., 2010).

The northern limit of the Tilouguite minibasin, on the southern limb of the Abbadine salt weld, is characterized by a thinning of the sedimentary units close to the salt wall (Fig. 4C). In this minibasin, the Bin el Ouidane Formation has a thickness of about 1000 m and the Tilouguite Formation may reach 800 m of thickness, both notably thicker than in the northern Ouaouizaght and Taguelft minibasins. In this minibasin, the Late Bajocian-Callovian Tilouguite and Guettioua red beds formations wedge out westwards truncating the Bin el Ouidane Formation and resting on top of Azilal and Taguendouf formations (Fig. 4 A). The western termination of the Tilouguite minibasin is characterized by a N-S structure, linked to the Abbadine salt wall (Figs. 2 and 4A), cored by Triassic rocks, and flanked by thick steeply dipping Sinemurian-Pliensbachian basinal successions (Monbaron, 1985). These Lower Jurassic deposits show opposite polarity on both sides of the structure and are unconformably overlain by Bathonian red beds (Jossen, 1990), which implies a sedimentary hiatus of about 15 Myr, encompassing the Toarcian, Aalenian and Bajocian periods.

The minor E-W trending Addendoum ridge can be recognized in the central part of the Tilouguite minibasin, characterized by a north-dipping monocline defined by the Aalenian Bin el Ouidane platform carbonates along the transect (Fig. 4C) but exposing Triassic rocks ∼8.5

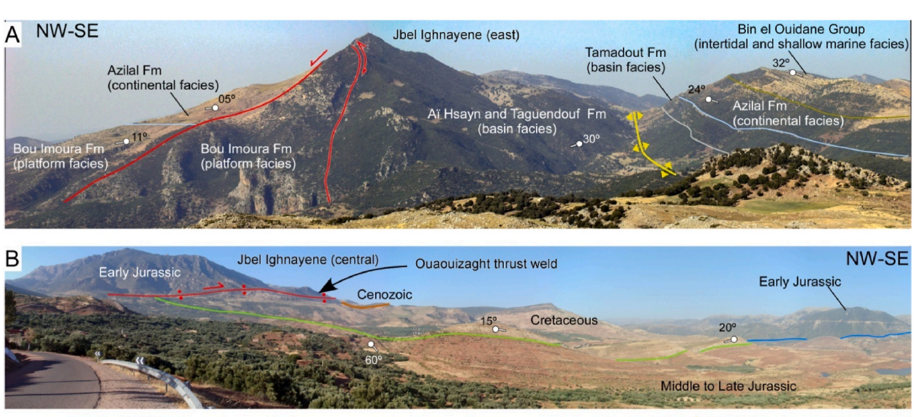

Fig. 5. A) Field panorama from the eastern sector of the Jbel Ighnayene culmination showing the location of a major inverted normal fault that marks the boundary between the Early Jurassic shallow marine and basin domains. On the SE part, the lower members of the infill of the Taguelft minibasin can be observed. B) Field panorama of the Ouaouizaght minibasin filled by continental deposits ranging from Middle Jurassic to Cretaceous ages. The north boundary of the minibasin corresponds to the Ouaouizaght thrust weld.

km to the East (Fig. 2). In this area, the Triassic rocks are unconformably overlain by the Toarcian Azilal Formation with a thickness of about 400 m (Monbaron, 1985). Towards the south, near the Tazoult salt wall, the exposed sedimentary succession is thicker, with >700 m of mixed carbonate-clastic platform sediments of the Toarcian Zaouiat Ahançal Group, and characterized by deeper-water facies. In the intervening depocenter, the uppermost members of the Bin el Ouidane Group are truncated by the beds of the Tilouguite formation (Jossen, 1990). This formation, which is very thin in this area, is on its turn truncated by the basal beds of the Bathonian Guettioua red beds, which unconformably overlay the lower member of the Bin el Ouidane Group. This area is notable for its preserved, horizontally layered La Cathédrale alluvial fan conglomerates, Miocene-Pliocene in age, overlying the northern flank of the Tazoult salt wall (Fig. 6A)(Martín-Martín et al., 2016).

4.1.3. The Amezraï minibasin and the Tazoult and Jbel Azourki salt walls

The Tazoult salt wall, on the southern border of the Tilouguite minibasin, shows an outstanding diapiric signature on both flanks (Bouchouata et al., 1995; Martín-Martín et al., 2016). The Tazoult salt wall is an elongated four-closure 19 km long and 3 km wide NNE-SSW-trending salt wall cored by Upper Triassic red beds, CAMP basalts and Middle Jurassic intrusions. The sedimentary succession flanking the salt wall ranges in age from Hettangian to Bajocian and displays large-scale halokinetic depositional sequences on both the SE and NW flanks. The diapir walls are formed by steep subvertical Pliensbachian platform carbonates of the Jbel Choucht Formation arranged in hook sequences along both flanks within a spatial range of hundreds to thousands of meters. The overlying late Pliensbachian-Aalenian mixed carbonate/siliciclastic deposits of the Zaouiat Ahançal Group form small-scale (ten to few hundred meters thick) wedge and hook halokinetic sequences recording the passive growth of the Tazoult salt wall, and the lateral extrusion of the evaporite-bearing rocks to form an allochthonous salt sheet towards the adjacent SE Amezraï minibasin. The Bajocian platform carbonates of the Bin el Ouidane Group fossilized the Tazoult salt wall. Cross-section restoration indicates that syn-depositional halokinetic deformation is significantly higher than that related to shortening (Martín-Martín et al., 2017).

The Amezraï minibasin with a width of ∼17 km is located between the Tazoult and Jbel Azourki salt walls (Figs. 2B and 6). The Amezraï minibasin, on the southern flank of the Tazoult salt wall, exposes Pliensbachian shallow marine carbonates unconformably overlain by

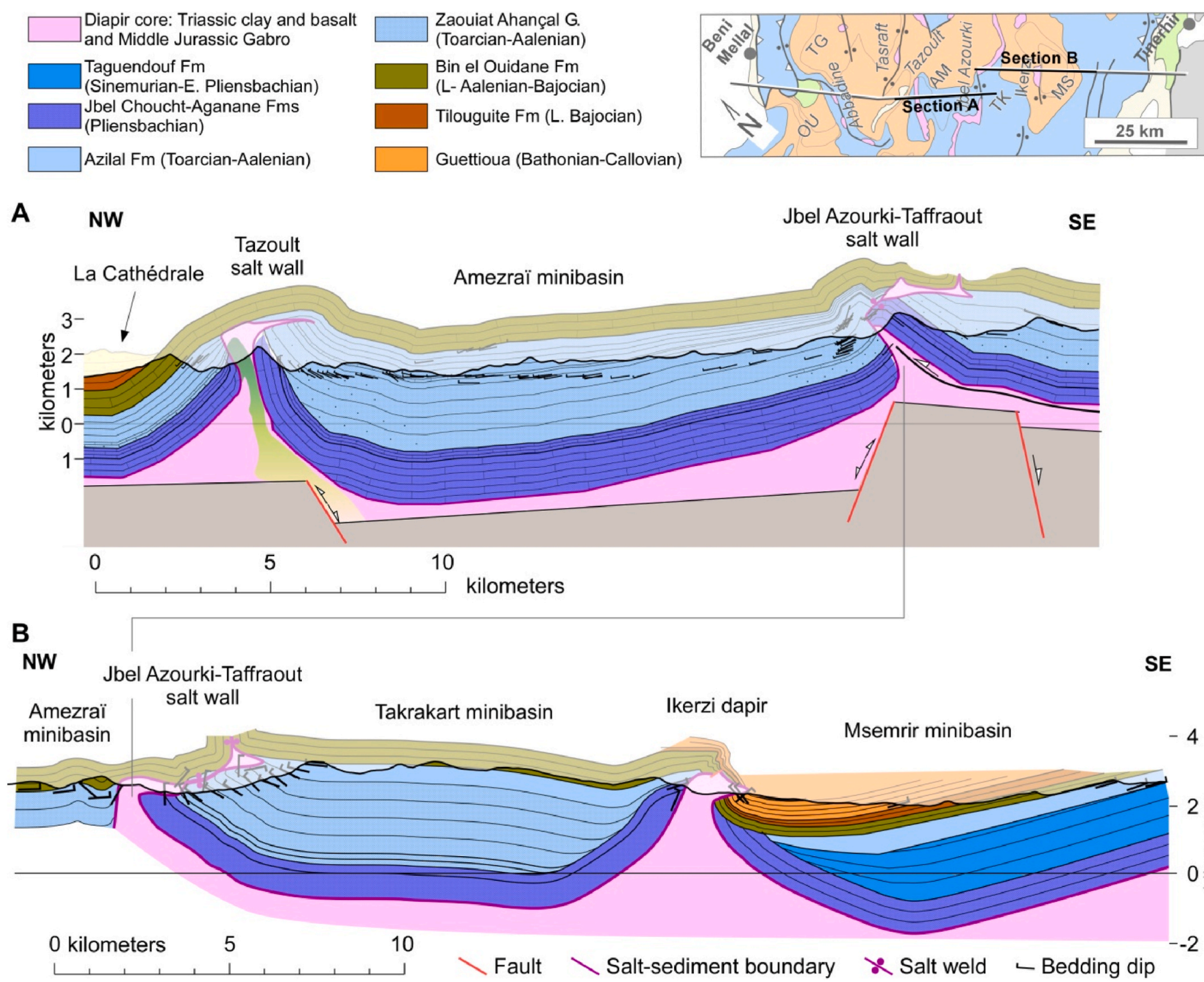

Fig. 6. Cross-section from the Tilouguite minibasin to the Msemrir minibasin, across the Tazoult salt wall, the Amezraï minibasin, the Jbel Azourki salt wall, the Takrakart minibasin and the Ikerzi diapir. Transect A has been modified after Martín-Martín et al. (2016) based in the new observations detailed in the text. Transect B show the large-scale southward extrusion of a salt sheet in a south direction in the Jbel Azourki-Taffraout salt wall.

the Toarcian mixed platform sediments of the Zaouiat Ahançal Group and Aalenian-Bajocian shallow carbonates of the Bin el Ouidane Group (Martín-Martín et al., 2016). Besides, Pliensbachian outcrops on the southern part of the minibasin show a complete platform to basin transition with the development of a large slope breccia (Malaval, 2016). This implies that a platform to basin transition needs to be placed between both flanks of the Amezraï minibasins, below the approximately 2.7 km thick Toarcian infill, although the precise location of this transition remains elusive due to limited outcrop exposure.

The Aalenian-Bajocian carbonates of the Bin el Ouidane Group represent the youngest preserved sediments of the Amezraï minibasin. These carbonates form a 2500-m-high plateau, bounded on its northern edge at the location of the Tazoult salt wall by a 3-km lowering of the structural level. To the south, the plateau, the Bin el Ouidane Group beds are directly in contact with the Pliensbachian successions of the southern flank of the Jbel Azourki salt wall, which is welded in the cross-section transect (Fig. 6).

The welded Jbel Azourki salt wall (Jbel Azourki salt weld), more than 100 km long, is one of the longest tectonic structures of the Central High Atlas (Fig. 2), associated with the highest topographic reliefs

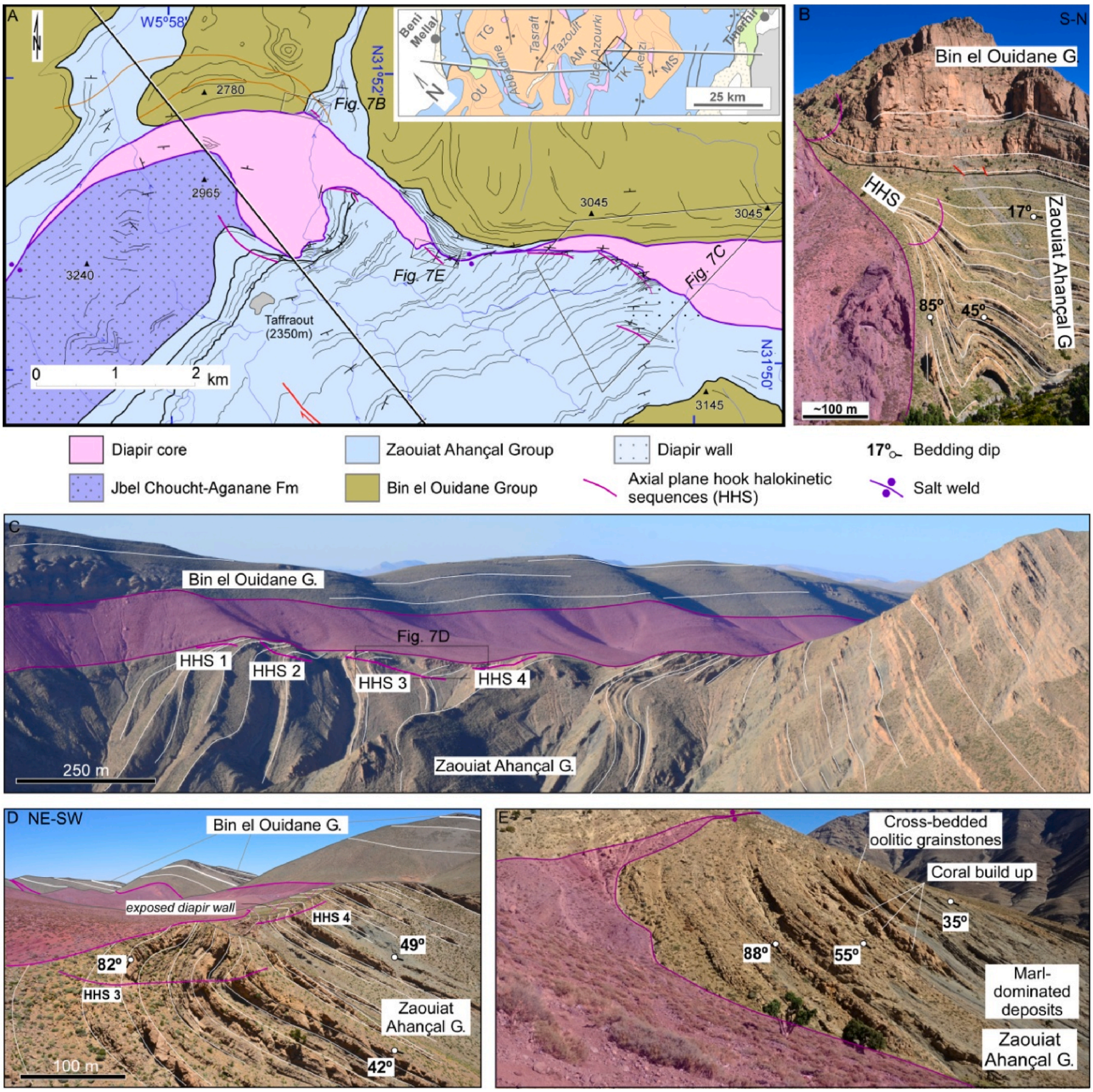

Fig. 7. A) Geological map of the Taffraout area showing the distribution of halokinetic sequences, predominantly hook type (HHS) along the Taffraout salt sheet. B) Field picture showing the characteristics of hook halokinetic sequences (HHS) with rapid thinning of the Toarcian succession close to the diapir (~100 m). C and D) Panorama and zoom in field picture showing the superposition of several hook halokinetic sequences (HHS) in the contact between the Taffraout diapir and the Toarcian sedimentary succession. E) Rapid facies change interpreted to be related to the growing of the diapiric structure. Corals and cross-bedded oolitic grainstone deposited in high energy, shallow settings near the diapir change to marl-dominated facies associated to low energy settings away of the diapir.

forming part the of the North Atlassic fault (Roch, 1939). It is composed of several segments separated by relay zones. The geometry of the diapiric ridges along this structure varies along strike from large salt sheets to subvertical segments. The westernmost outcrops of the Jbel Azourki salt wall are the structurally lowest outcrops of the studied area, which allows determining the geometry at depth of the diapiric structure (Fig. 6B). The structural lows show the salt pedestals containing Triassic igneous and fine-grained sedimentary rocks below the liassic halokinetic depositional units (Vergés et al., 2017). The salt pedestals are separated by structurally high domains where the ridge walls are welded and

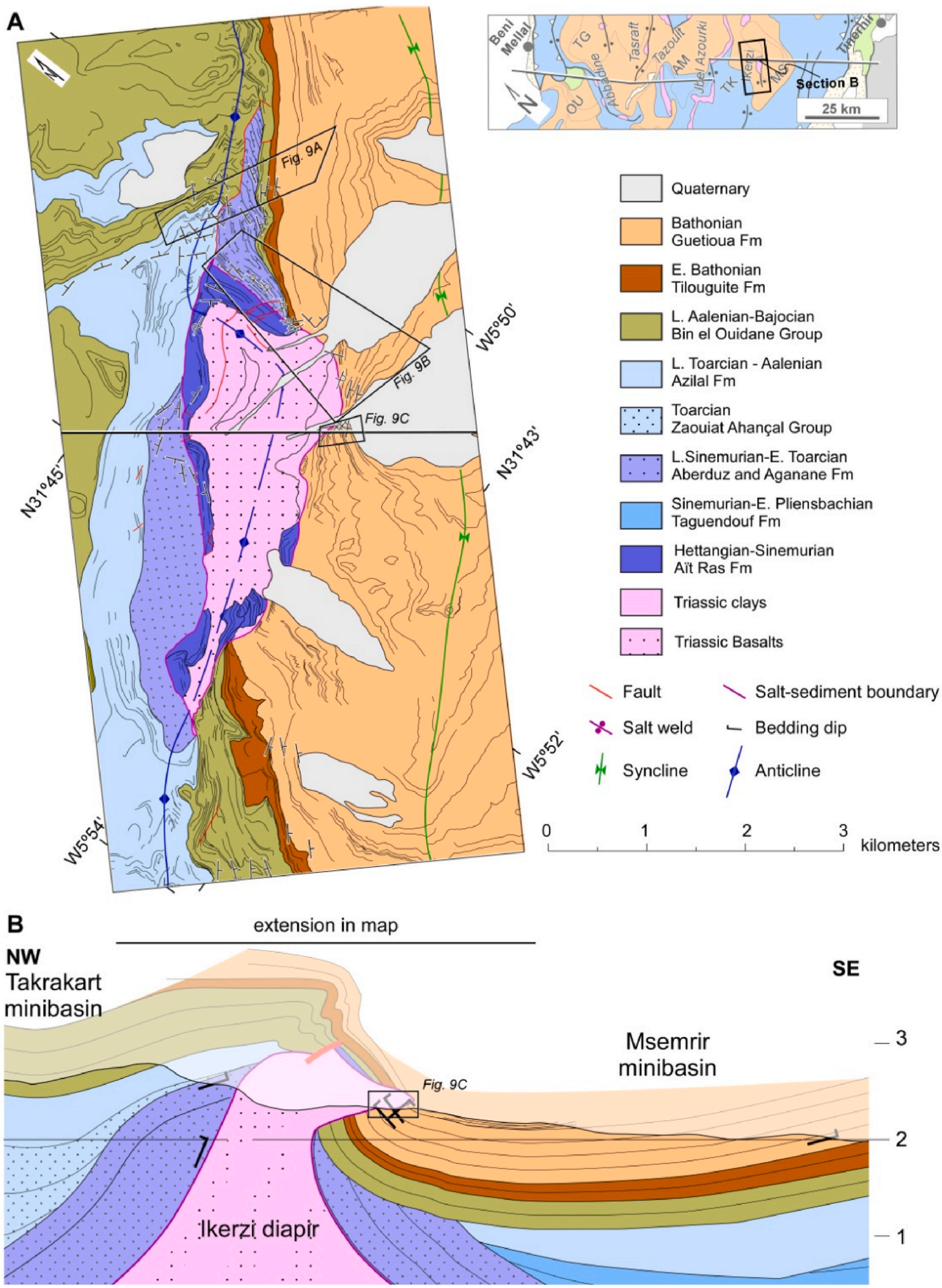

Fig. 8. A) Geological map of the Ikerzi diapir and the Msemrir minibasin. Location of field pictures in Fig. 9 are shown. B) Cross-section showing thickness variations across the diapir structures and interpreted salt-related geometries at depth.

juxtapose liassic sediments with opposite polarity on both sides. In the central part, the Jbel Azourki salt wall is characterized by an oblique segment of the structure, the 6 km long Taghia relay zone (Fig. 2), characterized by the collapse of its roof and very narrow highly subsiding rim minibasins (Saura et al., 2014; Malaval, 2016).

The segment of the Jbel Azourki salt wall located east of the Taghia relay zone is characterized by an 11 km-long, very tight to welded salt wall with a southward dipping attitude (Fig. 2). The southern limb of the Jbel Azourki salt weld contains Pliensbachian carbonate platform rocks of the Jbel Choucht and Aganane formations, which lay at very low angle on top of the Triassic materials (Fig. 6). Besides, its northern wall is characterized by the eastwards onlap and progressive pinch-out of the liassic platforms and the different members of the younger Zaouiat Ahançal Group.

The eastern termination of the Jbel Azourki salt weld corresponds to the Taffraout diapir exposing Triassic clay and basalts (Fig. 7). The structure of the northern flank of the Jbel Azourki salt wall in the Taffraout area is characterized by a gently north-dipping succession involving the highest interval of the Zaouiat Ahançal Group and the Bin el Ouidane Formation. These successions display a very rapid thinning close to the diapir, associated with a system of diapiric-related folds with increasing interlimb angle upsequence and a close to 90°, very short length (~100 m) fanning attitude associated with a thickness decrease of at least 250 m (Fig. 7). These characteristics fit with the definition of hook halokinetic sequences (HHS) defined in la Popa Basin by Giles and Rowan (2012). Besides, the southern flank of the structure involves the Pliensbachian Aganane Formation, the Toarcian-Aalenian Zaouiat Ahançal Group, and the Aalenian-Bajocian Bin el Ouidane Formation. This succession displays an overall fanning attitude, from subvertical at the base to gently south-dipping at the top although along a much longer distance than on the northern flank (~3-km) (Figs. 6 and 7), suggesting ongoing halokinesis during the deposition of the whole succession. Additionally, the contact of the mixed platform of the Zaouiat Ahançal Group with the Triassic rocks of the diapir core is characterized by the superposition of several, small scale (<100 m) hook and wedge sequences (Fig. 7), also recording the salt activity of the Jbel Azourki salt wall during their deposition. The subvertical attitude of these stacked hook and wedge sequences results in very gently north dipping salt-sediment interface, with the low dipping uppermost Zaouiat Ahançal Group and Bin el Ouidane beds of the northern flank resting on top of the diapir and, locally, even on the southern flank (Figs. 6 and 7). The easternmost studied outcrops of the Jbel Azourki-Taffraout salt weld juxtapose the base of the Bin el Ouidane Group of both limbs with subvertical attitude and opposite polarity.

Diapiric activity during the early to middle Jurassic resulted in the deposition of halokinetic sequences characterized by rapid facies shifts from shallow to deep-water environments on the flanks of the Taffraout structure (Fig. 7). These sequences also exhibit evidence of local bathymetric highs, as indicated by coral buildups and cross-bedded oolitic grainstones that prograded away from the structure (Malaval, 2016).

4.1.4. The Ikerzi diapir and the Msemrir minibasin

The Ikerzi diapir is located 15 km to the south of the Jbel Azourki salt wall, flanked by the Takrakart and Msemrir minibasins respectively to the north and south (Figs. 2 and 8). The Takrakart minibasin mostly exposes, in the studied transect, the mixed carbonate-siliciclastic marine beds of the Toarcian-Aalenian Zaouiat Ahançal Group, their equivalent intertidal beds of the Azilal Formation, and the shallow marine carbonate beds of the Bin el Ouidane Group, which nicely define a very gentle monocline.

Older sedimentary units are exclusively exposed along the margins of adjacent salt structures, where a ~4 km thick Pliensbachian to Bathonian succession on its northern flank contrasts with a much thinner ~2.5 km thick equivalent succession on its southern flank. These lateral facies variations are further emphasized by the presence of intertidal Toarcian Azilal Formation sediments on the southern flank, contrasting with the predominantly subtidal Zaouiat Ahançal Group on the northern flank (Fatah et al., 1990). The southern flank is also characterized by a truncated Aganane, about 200 m thick, inner platform carbonate succession, pinching out against the northern wall of the Ikerzi diapir (Fig. 8). This diapir exposes Triassic clay and basalt in its ~5 km long, ~1.5 km wide core and is located along a 20-km long NE-trending monocline. Its southern limb, steeply inclined and defined by Aalenian-Bajocian Bin el Ouidane Group, constitutes the northern flank of the Msemrir minibasin. The diapiric nature of the Ikerzi diapir has been previously discussed by Ettaki et al. (2007b).

The northern flank of the Ikerzi diapir is characterized by the wedging of the whole Toarcian-Bajocian succession, onlapping on the Hettangian-Pliensbachian carbonate beds defining the northern wall of the diapir (Fig. 8). The sedimentary wedging above the Ikerzi diapir is associated with the North-dipping Ikerzi normal fault, which separates the thick Aalenian strata on the northern flank of the diapir from a significantly thinner equivalent sequence on its southern side, where they unconformably overlay much older Sinemurian to early Toarcian shelf carbonates of the Aberdouz Formation (Fig. 9A and B). The younger beds of the Bin el Ouidane Formation overlap the Ikerzi normal fault and thus fossilize it (Fig. 9A). Short wavelength kink folds are conspicuous of the well bedded Toarcian-Bajocian succession of the northern flank of the Ikerzi diapir (Fig. 8B and A).

The Msemrir minibasin, on the southern flank of the Ikerzi diapir, includes a ~1000 m thick sedimentary succession encompassing the late Aalenian–Bajocian Bin el Ouidane Group, the early Bathonian Tilouguite Formation and the Bathonian Guettioua Formation. In this minibasin, the Bin el Ouidane Group unconformably overlays the Aberdouz Formation, with a contact that entails a sedimentary hiatus encompassing most of the Toarcian and Aalenian periods (green line in Fig. 9A), which is not observed on the northern limb, where the succession is fairly continuous.

A subvertical stack of hook and wedge depositional sequences constitutes the northern flank of the Msemrir minibasin, where the salt diapir-sediment interface is subhorizontal at surface suggesting a potential salt extrusion during Bajocian and Bathonian times (Fig. 9B and C). The Msemrir minibasin has a semicircular shape in map view, especially well depicted by the late Aalenian-Bathonian sequence. This geometry is attributed to the asymmetric attitude of this succession on both sides of the minibasin, subvertical in the north and gently dipping north in the south, with a significant stratigraphic thickness reduction of approximately 3 between the southern and northern limbs. The most significant feature of this northern flank of the Msemrir minibasin is the lack of the Ouchbis and Tagoudit formations amounting 1500 m on the southern flank of the minibasins (Fig. 10).

4.1.5. The Southern Atlassic front

The southern part of the cross-section extends from the southern boundary of the Msemrir minibasin to the exposed undeformed Paleozoic basement of the southern foreland region (Fig. 10). The northern domain of this part of the cross-section is characterized by exposed lower Jurassic thick successions, corresponding to the southern margin of the salt-related Jurassic rift basin. Besides, the southern domain is constituted by relatively thin succession encompassing a lower Jurassic, Cretaceous and Cenozoic depositional succession, which appears tectonically repeated as part of the south directed thrust sheets that define the southern fold and thrust belt (Fig. 10).

The southern margin of the salt-related Jurassic rifted basin is distinguished by hectometer-to kilometer -scale folds, mostly involving Hettangian to Pliensbachian deposits defining a northwards prograding system. The post-Pliensbachian sediments filling the Msemrir minibasin pinch-out southward against the Jbel Taouya anticline (Fig. 10), with >700 m of thickness decrease between its northern and southern flanks (Milhi, 1997) (Fig. 10A). Another interesting feature of the Southern Atlassic front is the changing nature of the Hettangian-Pliensbachian

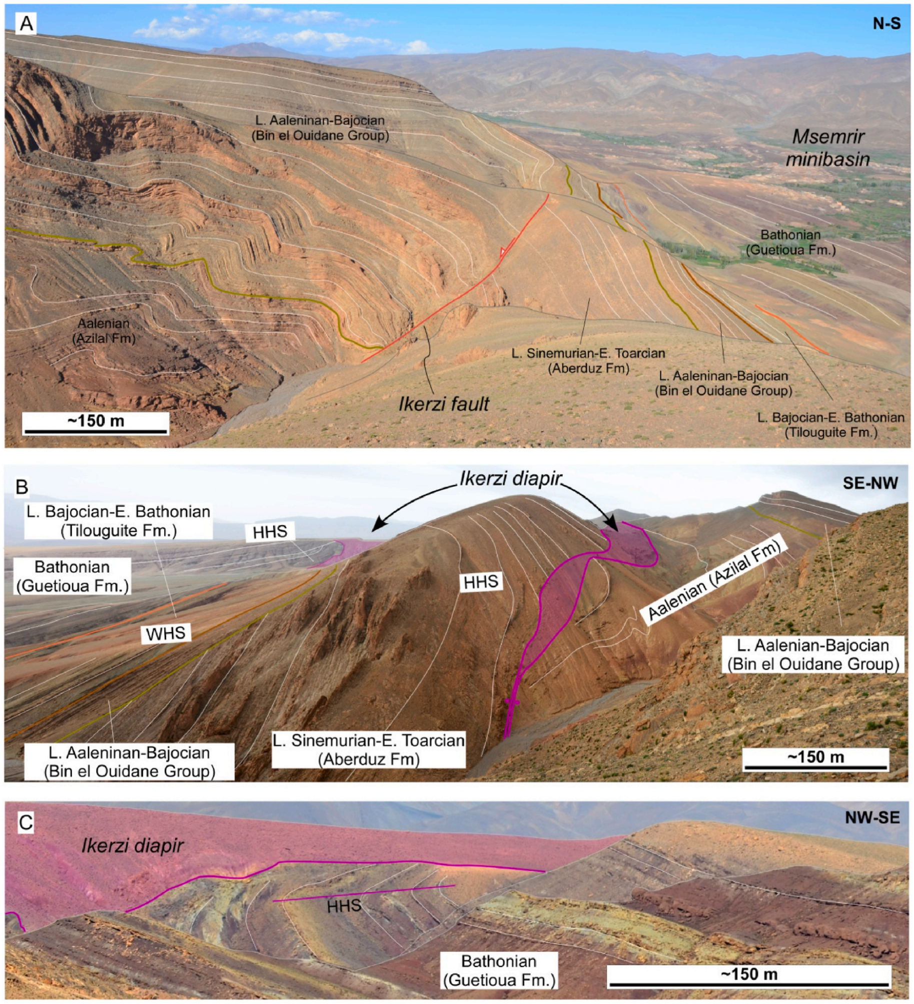

Fig. 9. A) Northern limb of the eastern termination of the Ikerzi diapir showing the location of the Ikerzi fault. On the northern hanging wall, the Aalenian Azilal Formation and the Late Aalenian—Bajocian succession abut the Ikerzi fault and show a thickness increase northward. On the Southern footwall a significant reduction of the Bin el Ouidane succession is evident. On the background, the Msemrir minibasin can be observed filled by the youngest sediments of the area. B) Eastern segment of the Ikerzi diapir. On the northern limb, the Aalenian-Bajocian succession laps on the Hettangian rocks within the Ikerzi diapir. On the southern limb, the basal part of the Pliensbachian-Toarcian Aberdouz Formation laps at high angle on the diapir wall. Upsequence, this succession is truncated by the Late Aalenian-Bajocian Bin el Ouidane Formation, revealing a sedimentary hiatus involving most of the Toarcian and Aalenian. HHS- Hook halokinetic sequences; WHS- Wedge halokinetic sequences. C) Detail of a halokinetic hooks within the Bathonian Guettioua Formation, on top of the Ikerzi diapir in its central part. The graphical scale corresponds to the hooks.

succession across the Jbel Taouya anticline. Whereas its northern flank shows a 1200 m thick Sinemurian-Pliensbachian distal platform succession (Aberdouz Formation) conformably overlain by 1200 m of basinal marls (Ouchbis Formation), its southern flank only shows the Aberdouz Formation followed by about 1000 m of platform carbonates of the Jbel Choucht Formation as documented by Ettaki et al. (2007a). On the northern flank of the Jbel Taouya anticline, the Ouchbis Formation is conformably overlain by the Tagoudit Formation, a turbiditic depositional sequence that has been correlated with a regional drowning event defining the passage from Pliensbachian to Toarcian (Wilmsen and Neuweiler, 2008; Lachkar et al., 2009) (Fig. 10B).

The southerly adjacent anticline is characterized by the occurrence of a Sinemurian slope megabreccia labeled as Todrha Formation that indicates the location of the platform-to-basin boundary at that stage. The Todrha Formation overlies the Sinemurian platform carbonates and pinches-out below the platform carbonates of the Pliensbachian Jbel Choucht Formation to the south (Milhi, 1997)(Fig. 10).

The Sinemurian–Pliensbachian successions to the south of the Todrha Formation outcrop define a ~3 km wide anticline truncated by a steep fault separating the Jurassic-dominated area from the southern fold and thrust belt, which we interpret as the inverted southern bordering fault of the Atlas Jurassic rift basin (Fig. 10). This fault incorporates a ~1100 m thick Sinemurian-Pliensbachian succession on its hangingwall, showing inner platform, platform margin and slope facies and grouped in hook depositional sequences close to the fault (Fig. 10D). On its footwall, a ~450 m thick Hettangian-Sinemurian limestone, dolomite, and marl succession showing pervasive karstic features at its basal part, and abundant pisolites in its upper part, deposited in a shallow depositional environment forming an upsequence deepening. This Hettangian-Sinemurian succession is unconformably overlain by ~250 m-thick Albian red beds followed by a 50 m-thick Cenomanian-Turonian limestone unit and by 150 m of Upper Cretaceous-Paleogene red beds. This young succession is conformably overlain by a >50 m-thick Eocene carbonate sequence (Fig. 10C). The youngest exposed sediments in this area correspond to thin Miocene-Pliocene conglomerates (Tesón, 2009).

The southernmost area is characterized by a SE-verging imbricated thrust system only involving the Albian-Miocene succession (Tesón, 2009). The frontalmost thrust juxtaposes the Cenomanian–Turonian limestone on top of the youngest conglomeratic unit of the Ouarzazate

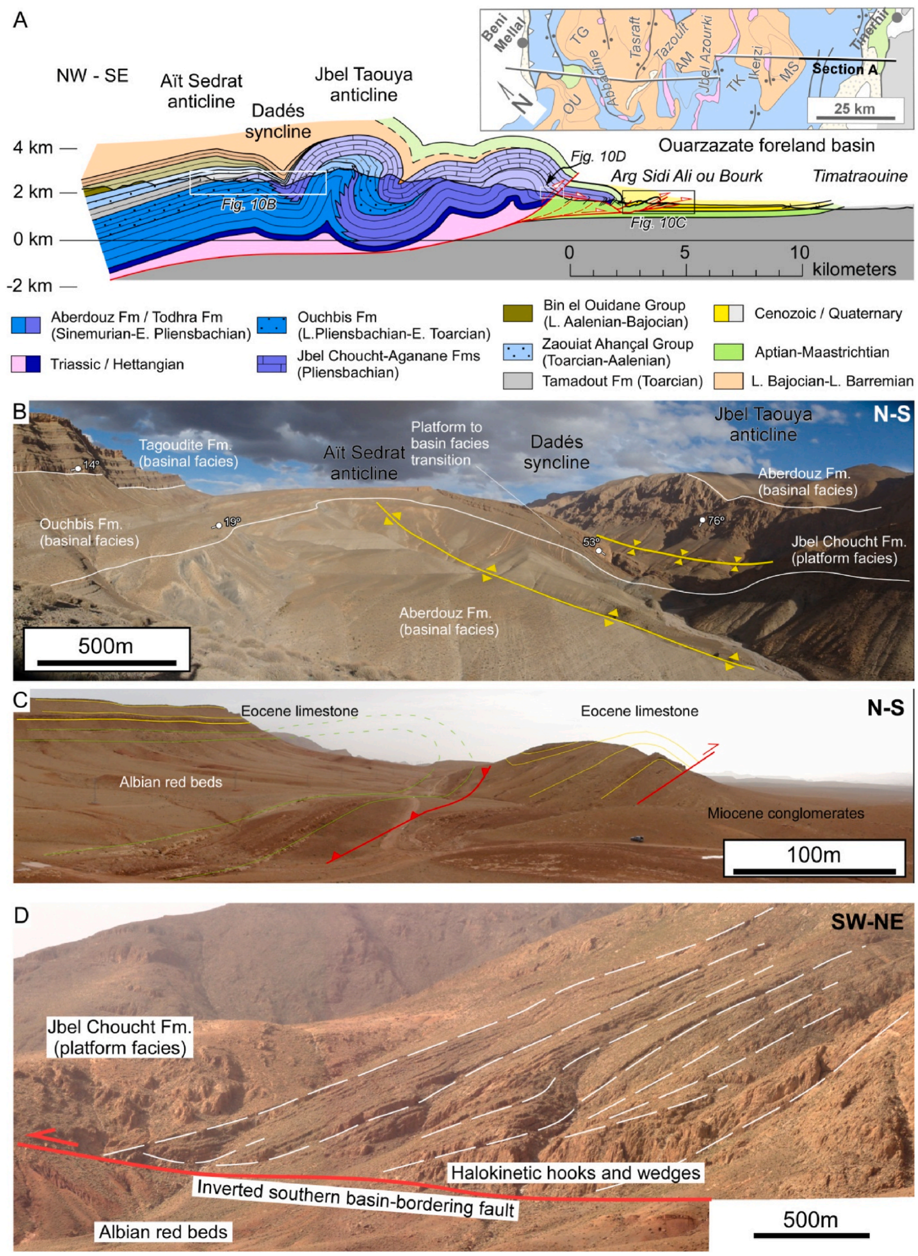

Fig. 10. A) Balanced cross-sections across the Southern Atlassic Front based on field, remote sensing, and published data. B) Interpreted field panorama showing the succession of folds developed in the southern Talas front area: Aït Sedrat anticline, Dadés syncline and Jbel Taouya anticline. Pliensbachian platform to basin transition occurs across the Aït Sedrat anticline. C) Interpreted field picture showing characteristic thrust systems from the southernmost part of the fold and thrust system, where Cretaceous deposits are emplaced above Eocene limestones.

foreland basin, and thus implying a young age of thrusting (Fig. 10).

The Ouarzazate foreland basin is at an average altitude of 1400 m, 900 m higher than the northern Tadla foreland basin, which points to a dynamic topography probably related to deep seated processes.

4.2. Synthesis of the diapiric structure of the central High Atlas

The compiled data and observations along the presented transect lead us to the identification of different structural domains, mostly related to the role of salt tectonics on their evolution (Fig. 11). The northern Atlassic front corresponds to the northern margin of the Jurassic rift basin, displaying the transition between a fault-controlled northern domain (Jbel Ighnayene area) and a southern domain where diapiric activity was dominant in the basin architecture (Aït Attab, Ouaouizaght and Taguelft minibasins). Fault activity seems to control the deposition of the early Jurassic carbonate systems, with shallow carbonate platforms developed in basement highs (Bou Imoura and Jbel Choucht Fm) that transition to basinal deposition towards the south (Taguendouf and Aït Hsayn Fm). The homogeneous thickness and facies distribution of Azilal Formation across this domain records the ceasing of the normal fault activity around Toarcian times. Besides, the variation in the stratigraphic succession observed south and north of the Ouaouizaght thrust weld suggests a long-lived, syn-depositional activity throughout Jurassic, Cretaceous and Paleocene.

The Abbadine diapiric complex shows a completely different tectonic regime than that interpreted in the northern Atlassic front. This area, located south of the northern Atlassic front, was clearly dominated by salt tectonics with the development of several minibasins (e.g., Ouaouizaght, Taguelft and Tilouguite) and salt walls distributed in a polygonal array, active at least up to Late Cretaceous (Fig. 4). The salt

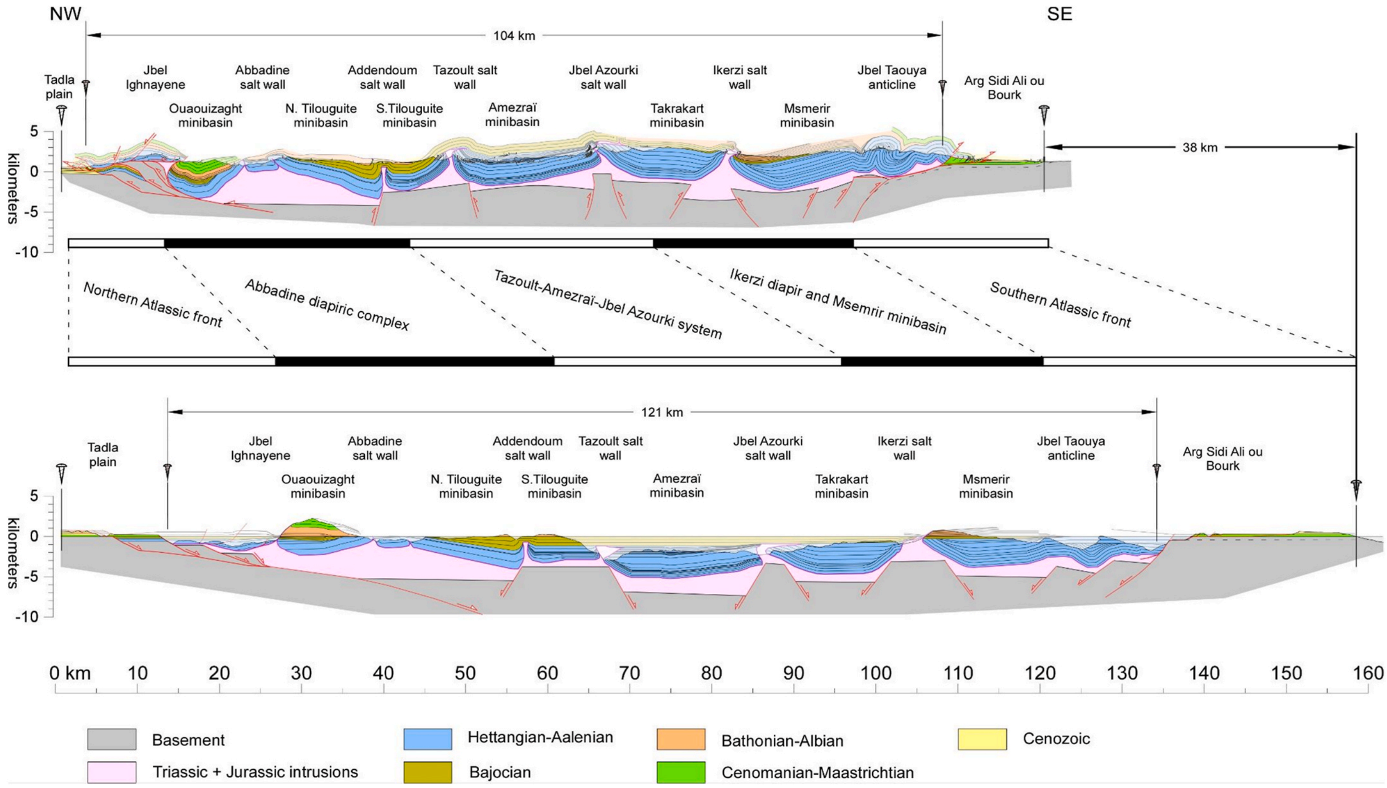

Fig. 11. Balanced and restored cross-sections (top Bajocian).

walls were squeezed and finally welded most probably during the Late Cretaceous – Cenozoic compression related to the Alpine orogeny.

The Tazoult-Amezraï-Jbel Azourki system, widely studied by Martín-Martín et al. (2017), Moragas et al. (2017) and Vergés et al. (2017), depicts a central minibasin with a thick liassic succession flanked by two salt walls associated with south directed salt sheets fossilized by the Dogger deposits. The liassic succession displays a similar thickness in the Takrakart minibasin, south of the Jbel Azourki salt wall, whereas it is significantly reduced north of the Tazoult salt wall, in the Tilouguite minibasin. Late Alpine compression resulted in welding of the salt walls and folding of the Dogger beds deposited on their roofs.

The geometric characteristics described above lead us to interpret the Taffraout structure as a south-directed thrust-weld, which results from the welding of an initial salt sheet developed above a basement normal fault, which we have interpreted to be north-dipping (Fig. 6). These features, together with the fanning attitude of the adjoining successions allow us to propose a sequence of development characterized by an initial stage of diapir growth, corresponding to the onset of extension, associated with the development of the Jbel Choucht platform as suggested by the high cut-off angle of this formation against the diapir. Subsequently, the development of stacked hooks on both sides of the structure record diapir exposure and suggests a potential drop in the sedimentation rate (Fig. 7). This stage was followed by the southward extrusion of the Triassic rocks and the development of a salt sheet during the deposition of the Zaouiat Ahançal Group, as recorded by the fanning attitude of its beds. Extensive deposition of the Bin el Ouidane Formation on top of the salt extrusion records the decrease and eventual end of halokinetic activity in the area (Fig. 6). Finally, Cenozoic shortening resulted in squeezing of the diapir and southward thrusting of the northern wall. The Taffraout structure could form at any stage from the deposition of the Bin el Ouidane Formation to compression; available evidence does not allow a more precise dating.

The structural and stratigraphic relationships observed around the Ikerzi diapir evidence halokinetic activity at least from Late Sinemurian to Bathonian, with an initial stage with higher subsidence in the north swapping to a faster subsidence in the south during the deposition of the Bin el Ouidane Formation. This final stage was associated with a south directed salt sheet overtopping the basal part of the Bathonian succession, as evidenced by the subvertical stack of hooks described in the area. Observed facies indicate that this structure defined a paleohigh during most of the Jurassic.

The characteristics observed in the southern Atlassic front led us to interpret two distinctive tectonic domains in this part of the High Atlas Basin. The major inverted normal fault identified in this part of the regional transect corresponds to the southern margin of the Jurassic rift basin (Fig. 10). North of this fault the Early Jurassic deposition was dominant, with the development of very thick carbonate platforms that transitioned to basin realm under the influence of both extensional and salt tectonics. Contrarily, south of this fault accommodation was very limited, resulting in very condensed sedimentary succession (Fig. 10), which was later deformed and duplicated in the formation of the fold and thrust belt during the Alpine orogeny (Tesón et al., 2010; Tesón and Teixell, 2008).

5. Discussion

5.1. Reconstruction of the central High Atlas rift basin

The structural analysis of combined studied areas results in balanced and restored cross-sections across the Central High Atlas diapiric province of Morocco from the Tadla foreland basin in the north to the Ouarzazate foreland basin in the south (Fig. 11). The present-day cross-section is characterized by two thin-skinned fold and thrust belts on both Atlassic fronts, duplicating the thin Mesozoic to Paleogene stratigraphic succession deposited on the shoulders of the Central High Atlas Basin during the post-rift stage. Moreover, this basin is characterized by thick Jurassic sedimentary successions defining large minibasins, separated by narrow ridges, corresponding to welded salt walls at surface. The central most part of the Central High Atlas Basin corresponds to the topographic and structurally highest area, where thick Early Jurassic successions of the Amezraï and Takrakart minibasins are conformably overlain by gently dipping Middle Jurassic carbonate platforms defining extensive plateaus (Fig. 11). On the flanking Tilouguite and Msemrir minibasins, respectively to the North and South, the Middle Jurassic successions are extensively exposed, displaying unambiguous patterns of halokinetic depositional sequences. Finally, north of the Tilouguite minibasin, the Ouaouizaght minibasin exposes a relatively thick Cretaceous succession, also depicting halokinetic patterns, evidencing diapiric growth during its deposition. Finally, the constructed cross-section across the Central High Atlas Basin shows a conservative approach, in which the maximum observed thicknesses are preserved at depth, towards the centre of the basin. However, salt-related basins exhibit a distinctive thickening of the halokinetic depositional sequences, often exceeding 200% towards the centre of minibasins. This pattern was identified in other field areas as for example in the Sivas Basin (Ribes et al., 2015), in the Sopeira Basin (Saura et al., 2016), and in seismic data from North Sea (Jackson et al., 2020; Jackson and Lewis, 2016) Gulf of Mexico (Rowan et al., 1999, 2016), and Glückstadt Graben in NW Germany (Warsitzka et al., 2017). In the studied area, this halokinetic wedge pattern is also corroborated by sandbox models (e.g., Moragas et al., 2017; Dooley and Hudec, 2020; among many others). Summarizing, the presented cross-section recognizes at least 7 major linear diapir systems that can be demonstrated to have controlled deposition. This is likely the minimum of structures that were present, and that as seen from the presented maps several of these diapirs bifurcate or amalgamate along strike, so the number of major structures varies depending on where a transect is made (Fig. 2). Significantly not all diapir walls follow the main rift trend; some such as the Abbadine salt wall are near orthogonal to the main rift trend (Fig. 4). It is anticipated that further work will reveal more, smaller salt-related structures within this basin.

The difference in length between the balanced and restored cross-sections entails a total shortening at the cover level of about 38 km (24%). From those, 21 km are accumulated in the northern and southern external fold and thrust domains, and only 17 km within the Jurassic rift basin (Fig. 11). This amount of shortening is similar to those previously reported in this region by Frizon de Lamotte et al. (2008), proposing between 10 and 35 km, Teixell et al. (2003) indicating 20 km of shortening across the Marrakech-Ouarzazate transect and up to 30 km across the Midelt-Errachidia transect, and Casas-Sainz et al. (2023) calculating shortening values between 20 and 50 km across the Central High Atlas. Notably, our calculated shortening in the studied transect exceeds previous estimates, but this discrepancy is attributed to larger shortening values within the northern thrust system, compensated by lower shortening in the High Atlas Basin, which contributes only 14% to the total. Previous shortening estimations in the Central High Atlas did not consider the initial diapiric geometry in minibasins and salt walls, even though there were already published works tentatively discussing the Jurassic halokinetic contribution (e.g., Laville, 1988; Laville, 1988; Poisson et al., 1998).

The construction of the balanced and restored cross-sections across the Central High Atlas is hindered by the difficulty in defining the basement structure beneath the Upper Triassic evaporites, which despite extensive surface and subsurface investigations remains poorly constrained. The interpretation of the basement structure beneath the Permo-Triassic units in this work is based on a set of assumptions supported by geological observations. Poisson et al. (1998) proposed a weak decoupling between Triassic and Paleozoic units arguing that folding in the cover occurred as a response to thrusting in the substratum, where thrust faults display a low-angle attitude and merge on a crustal detachment. According to Teixell et al. (2003) and Babault et al. (2013), the pre-Mesozoic series are mostly folded together with the cover with a mild diapiric imprint, and form wide folds associated with deep faults detached along the upper-lower crust boundary (Ayarza et al., 2005). Michard et al. (2011) depict a practically flat top basement, implying the inversion of subvertical rift faults to its null point. The apparent basement-cover coupling in the central part of the High Atlas Basin contrasts with largely decoupled thrust systems on both foreland belts. Casas-Sainz et al. (2023) proposed a doubly verging basement wedge, with partially inverted rift-related faults below the Jurassic depocenters. According to Domènech et al. (2016), structural observations and thermochronology suggest that most rift-related faults were not reactivated during the Paleogene compression stage, whereas Fekkak et al. (2018) infer a mixed thin-skinned model with newly formed shallow-dipping thrusts on the chain margins and inversion of the Mesozoic normal faults in the Atlas Axial Zone. Our own observations in the basement outcrops in the Marrakech Atlas (>130 km west of the transect) suggest that some of the basement faults were at least partially inverted and verticalized. Additionally, the Cenozoic La Cathédrale alluvial fan, unconformably above the northern flank of the Tazoult ridge, with thicker Jurassic successions on the southern limb (Fig. 6), attests for the late inversion of this structure which we interpret as associated with a basement normal fault (see Martín-Martín et al., 2017; Moragas et al., 2017). Based on these observations, we propose a basement configuration in which most Permo-Triassic and Jurassic normal faults are inverted and verticalized (Fig. 11). Additionally, the depicted folding of the top of the basement implies that the underlying rocks must have undergone some penetrative shortening. The proposed distribution of the basement highs and faults below the Central High Atlas Basin assumes that diapirs typically form on the footwall domain of basement normal faults during extension as observed both in salt-related rift basins and analogue models (Nalpas and Brun, 1993; Jackson and Vendeville, 1994; Vendeville et al., 1995; Dooley et al., 2003; Dooley et al., 2005; Loncke et al., 2010; Moragas et al., 2017; Dooley and Hudec, 2020).

The proposed basement Early Jurassic reconstruction beneath the High Atlas Basin implies a total extension of about 33 km (~36%) during the Permo–Triassic and Jurassic rifting, by comparison with the original length of the top basement, which although speculative, supplies an approximation enhancing the qualitative analysis of the extensional stage.

5.2. *Diapir activity, timing and associated facies distribution in the central High Atlas*

The facies distribution across the Central High Atlas Basin was already addressed by previous authors (Jossen, 1990; Poisson et al., 1998; Piqué et al., 2002; Martín-Martín et al., 2016; Moragas et al., 2016; Malaval, 2016; Joussiaume, 2016). However, this work highlights for the first time the correlation between shallow water marine sediments and diapiric structures at basin scale during the Sinemurian-Pliensbachian period, and especially during the Toarcian-Aalenian period (Fig. 12).

Following the deposition of the Triassic terrigenous and evaporitic succession, a widespread marine transgression occurred during the Early Jurassic in the Central High Atlas (Fig. 12A). Sea level rise resulted in a transition from continental to shallow marine depositional settings and the deposition of Hettangian to lower Sinemurian peritidal carbonates (Souhel et al., 2000)). Regional paleogeographic reconstructions (Frizon de Lamotte et al., 2009; Charton et al., 2021; Skikra et al., 2021) indicate that during Early Jurassic times, the Atlas rift basin deepened eastwards where fully marine environments occurred in the Algerian and Tunisian Atlas regions. Contrarily, towards the west the basin was bounded by a very high relief region located south of Marrakech, which conformed its boundary with the Western Moroccan Atlas and the Atlantic domain (Domènech et al., 2015; Charton et al., 2021).

After a period of tectonic quiescence during the earliest Jurassic, tectonic extension was characterized by the activity of normal faults from Sinemurian to Pliensbachian (Ellouz et al., 2003; Frizon de Lamotte et al., 2009; Lachkar et al., 2009), which triggered the onset of salt mobilization and diapir growth across the Central High Atlas Basin (Ettaki et al., 2007b; Saura et al., 2014; Vergés et al., 2017; Moragas et al., 2018) (Fig. 12B). This is due to displacement loading (Hudec and

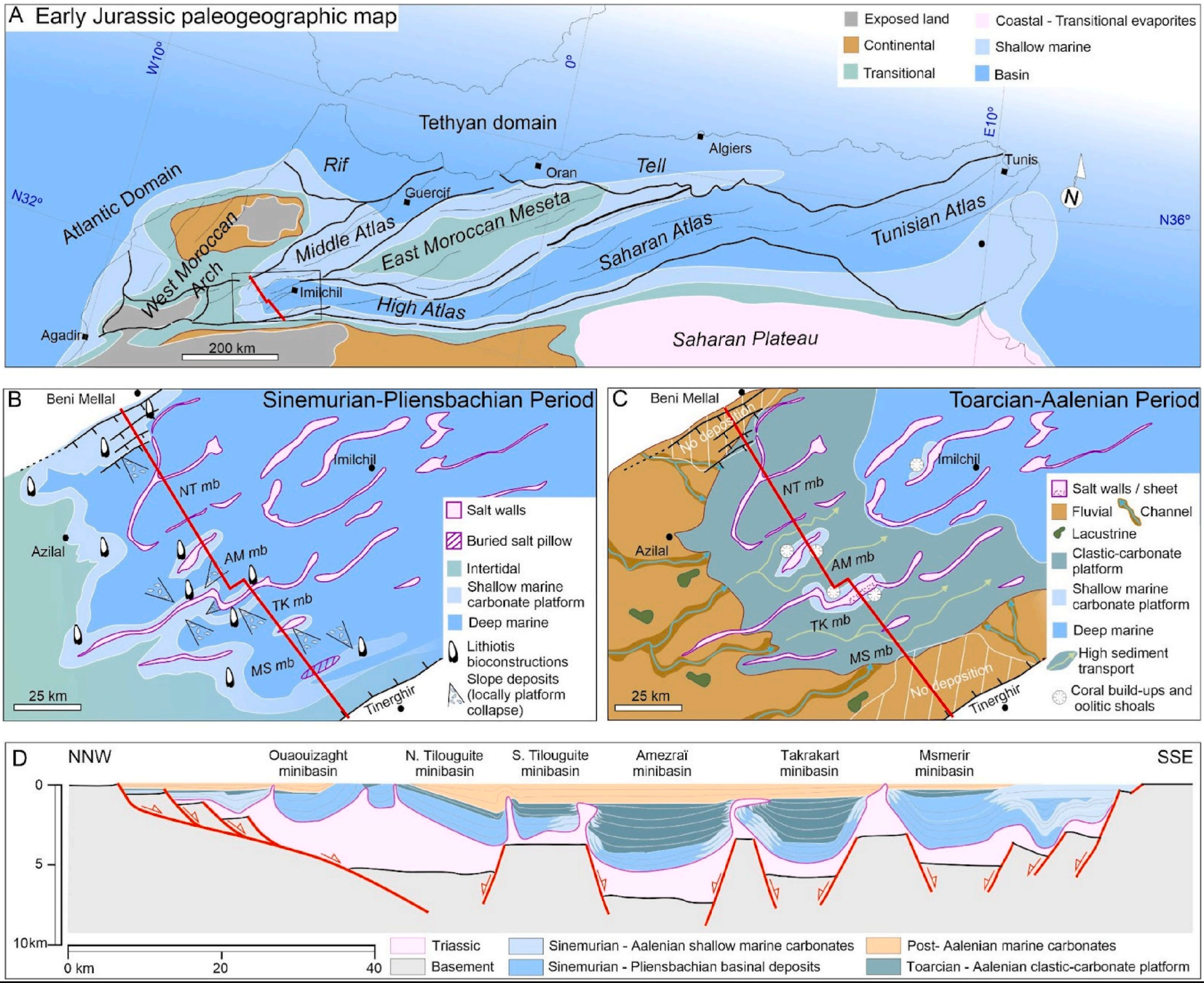

Fig. 12. A) Regional Early Jurassic paleogeographic map of the Atlas System compiled from Bosence et al. (2009), Charton et al. (2021), Turner et al. (2023), and Skikra et al. (2021). B) Sinemurian-Pliensbachian and C) Toarcian-Aalenian paleogeographic maps of the Central High Atlas. These maps are based on field observation and compiled data from published geological maps (Jenny and Couvreur, 1985; Jossen, 1990; Monbaron, 1985; Fadile, 2003; Hadri, M, 1997; Milhi, 1997; Fatah et al., 1990). D) Restored cross-section across the Beni Mellal-Tinerhir transect showing lower Jurassic facies distribution.

Jackson, 2007), implying that regional extension mobilizes the salt units. In this scenario necking of post-salt units generates lateral gradients in vertical loading, enhancing reactive diapirism. During this stage, the Central High Atlas Basin was characterized by shallow carbonate platforms along its northern and southern margins, while the central part featured deep marine deposits with isolated shallow marine carbonate platforms (Fig. 12). Along the basin margins, the transition from platform to slope or basinal deposits is interpreted to be controlled by active normal faults (Fig. 12). This link is especially evident in the northern margin, around the Jbel Ighnayene culmination, where an inverted normal fault shows the position of the platform margin (Fig. 5 A). Conversely, the transition to deep marine deposits occurs gradually in the southern margin of the High Atlas Basin, in the Aït Sedrat-Jbel Taoya (Fig. 10). This more gradual change in the southern margin might indicate that normal faults were partly concealed by thicker Upper Triassic evaporites (Fig. 11).

The complex facies distribution during the Sinemurian and Pliensbachian, with intervening shallow marine carbonate platforms, slope and deep marine carbonates frequently defining facies belts around diapiric structures suggest a strong interaction between halokinesis and depositional processes (Fig. 12B). While diapir activity in the northern region of the basin is primarily indicated by variations in thickness and syn-depositional deformation of deep marine deposits (Ouaouizaght and Tilouguite minibasins), in the central and southern regions diapir structures appear associated with shallow carbonate platforms (Tilouguite, Amezraï, Takrakart and Msemrir minibasins) (Fig. 12). The Pliensbachian carbonate platforms are characterized by the prevalence of lithiothis bivalves, which represent shallow near-shore tropical waters environments (Fraser et al., 2004). In these shallow environments, the growth of salt walls promoted subaerial exposure of the Pliensbachian carbonate platforms, resulting in the development of karst (Martín-Martín et al., 2017; Moragas et al., 2020). Additionally, sedimentological analysis of the Jbel Azourki salt wall show that Pliensbachian carbonate platforms transitioned to hemipelagic and gravity-flow deposits in small scale rim minibasins associated with diapirs (Malaval, 2016) (Fig. 12B). Thus, we interpret that the growth of diapiric structures influenced the development of carbonate platforms in two ways: *i)* creating bathymetric highs that allowed the proliferation of bivalve and other organism colonies; and *ii)* causing the collapse of platform margins due to instabilities associated with the growing diapirs. Besides, salt withdrawal below the minibasins enhanced the deposition of deeper facies in the thick depocenters between salt walls (Fig. 12).

The Pliensbachian and Toarcian times were marked by a gradual marine regression, particularly pronounced in the western portion of the basin west of Beni-Mellal (Fig. 2). Subsequently, a transgression from mid Toarcian to Aalenian times occurred (Milhi et al., 2002). The Toarcian to Aalenian deposition was characterized by an increase of siliciclastic input into the basin. In combination with eustatic changes and vertical movements, continental depositional systems were predominant in the westernmost regions of the High Atlas Basin, while its central region was characterized by mixed carbonate-siliciclastic marine deposition (Fig. 12C). During Toarcian to Aalenian times, diapir activity is recorded by very well-exposed halokinetic sequences (Figs. 6 and 7). Additionally, coral build ups and oolitic shoals restricted to the vicinity of growing diapir walls rapidly passing to deeper marl-dominated deposits also evidence syn-depositional diapiric activity (Fig. 7). These proximal facies are frequently stacked in thick successions (e.g., >2 km in the Taffraout diapir overhang) attached to the diapiric structures laterally passing to very thick successions in the minibasins (e.g.,>3 km in the Amezraï minibasins). This indicates that salt tectonics reached it maximum expression during Toarcian and Aalenian in the studied transect (Figs. 11 and 12D).

Bajocian to Callovian, or even younger deposits, are scarcely preserved in the studied transect, and thus diapiric activity and its impact into depositional patterns are difficult to assess, especially in the central region of the High Atlas Basin. However, diapiric activity continues from Middle Jurassic onward as it is recorded in the Ouaouizaght minibasin.

The evolution of the Zaouiat transect significantly differs in terms of subsidence patterns and timing of maximum salt activity towards the east. In the minibasins of the Imilchil area and in the Azag minibasins km-thick Bajocian to Callovian successions have clear halokinetic character, indicating a much longer diapiric activity (Saura et al., 2014; Teixell et al., 2017). Despite diachronicity of salt tectonics, the relationship between facies distribution and salt structures reported in the studied transect is also observed in the eastern part of the basin. This is evident in examples such as the Tassent and Ikkou salt walls in the Imilchil area, and the salt walls bounding the Azag minibasin, where coral reefs location and oolitic grainstone progradation are controlled by the growth of salt structures (Joussiaume, 2016; Teixell et al., 2003).

Variations in thickness and geometry of halokinetic sequences within the High Atlas Basin recorded the migration of minibasins depocenters though time across and along the basin axis. Across the studied transect, minibasins depocenters migrated northwards from Jurassic to Paleogene evolution (Fig. 11) and towards the basin centre in the Imilchil transect (Michard et al., 2011; Saura et al., 2014). The migration of minibasin depocenter is likely attributed to salt migration from minibasins to salt walls and salt depletion and welding at the bottom of minibasins both along and across their direction (Moragas et al., 2017). Concurrently, the progradation of deltaic deposits over the salt body may trigger the migration of salt in the same direction, leading to the development of a syn-sedimentary salt wall that can grow at a sharp angle to the regional faulting at depth (Saura et al., 2014; Moragas et al., 2017).

5.3. The early stages of rift basins and passive margins associated with syn-rift salt diapiric systems

The proposed geometry for the Early to Middle Jurassic Central High Atlas Basin is consistent with the structural complexity of diapiric rift margins associated with syn-rift salt as described by Tari et al. (2003) (Fig. 1). A similar scenario has been described for the nearby Atlantic Moroccan margin (Tari et al., 2003; Uranga et al., 2024), and in the Gulf of Cadiz and the Algarve Basin (Ramos et al., 2014, 2017). Although the diapirism is slightly younger in the Gulf of Cadiz and significantly longer in offshore Morocco due to ongoing extension and ocean formation, the lower Jurassic part of the successions displays astonishingly similar halokinetic geometries, which indicates that the Central High Atlas can be a good analogue for the Atlantic Moroccan margin and the Gulf of Cadiz-Algarve basin. In the three cases (Central High Atlas, offshore Morocco, and Gulf of Cadiz), irregular distribution of syn-rift salt had a major impact in salt tectonics. Large, disconnected salt structures develop on top of basement faults, salt sheets are common and compressional folding is frequent around the salt structures. Secondary vertical welds closing the connection between the lower and upper part of the diapirs are also frequent, which suggest that some of the Atlassic structures could be, at least in part, already closed during the Middle Jurassic. Besides, basal welds are also frequent in the offshore cases whereas they have not been depicted in the presented Central High Atlas model. This could be due to either an overestimation of the salt at depth in the Central High Atlas (as discussed above) or the long-lived nature of the offshore cases. The Central High Atlas Basin, the Atlantic Moroccan margin and the Gulf of Cadiz and Algarve formed at the onset of Pangea break up and the subsequent formation of the Central Atlantic Ocean. Therefore, they provide a first-class example for buried margins and rift basins with syn-rift salt worldwide, such us the rift system offshore Nova Scotia or the currently active Red Sea (Fig. 1).

Additionally, the link between diapir growth and carbonate facies distribution already proved for particular structures in Cenozoic/present-day salt-basins as the Red Sea and the Gulf of Mexico (Bosence, 2005) or in Upper Cretaceous systems of the la Popa Basin (Giles et al., 2008) is here also presented at a basin-scale. Our results show that in carbonate-dominated salt basins, if diapir uplift is enough to keep the basin floor at shallow depths, carbonate production may be enhanced, and platforms facies can be found at any point of the basin. These observations are to be considered when studying similar scenarios worldwide and might be used to define geological models in initial phases of the exploration processes enhancing a better interpretation of seismic data.

6. Conclusions

The study of the shoulder-to-shoulder structure of the inverted Atlas rift basin (High Atlas of Morocco) allows establishing the following conclusions:

For the first time, regional balanced and restored cross-sections of the Central High Atlas showing the diapiric nature of the basin and the role of salt tectonics during its evolution are presented. The constructed cross-sections across the Central High Atlas include seven salt walls and six intervening minibasins with associated halokinetic strata, providing evidence of diachronous diapiric growth from Early Jurassic to Cenozoic times. Several of these diapirs bifurcate or amalgamate along strike, so the number of major structures varies laterally. The comparison of the restored and balanced cross-sections allows estimating a shortening of about 38 km, 21 km accumulated in the external Atlassic fold and thrust belt domains, and 17 within the Jurassic rift basin.

During the Early Jurassic rifting, shallow water carbonate platforms nucleated both along the margins of the High Atlas Basin and around many salt walls (i.e., highs) within the basin, while intervening minibasins underwent higher subsidence rates and were filled with deep-water limestones and marls. Subsequently, a longitudinal mixed clastic carbonate deltaic system prograded eastwards filling the minibasins between the long rising salt walls. During this stage, shallow marine shoals and reef patches developed attached to the diapiric walls, evidencing continuous diapir rise.

Throughout the whole rift basin, where local diapir uplift rate is similar to regional subsidence rate, shallow deposition environments or even local subaerial conditions occurred. Thus, platform development was enhanced and karstic processes could develop around salt structures in central parts of the basin. The lessons learnt in the Central High Atlas serve as a valuable analog and provide insights for understanding the early stages of rifting, salt tectonics, and the evolution of passive margins on a worldwide scale.

CRediT authorship contribution statement

Saura Eduard: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martín-Martín Juan Diego:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vergés Jaume:** Writing – review & editing, Project administration, Funding acquisition, Data curation, Conceptualization. **Moragas Mar:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Razin Philippe:** Writing – review & editing, Investigation, Data curation. **Grélaud Carine:** Writing – review & editing, Investigation, Data curation. **Messager Gregoire:** Writing – review & editing, Investigation, Funding acquisition, Data curation. **Hunt David:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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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Data availability

Data will be made available on request.

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