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3D variation of shortened salt walls from the Moroccan Atlas: Influence of salt inclusions and suprasalt sedimentary wedges

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ABSTRACT

We present a field study of salt ridges and minibasins of the Moroccan High Atlas near Rich that shows the along- and across-strike variability of such structures. Salt walls evolved from halokinesis during Jurassic rifting, to shortening during Cenozoic orogeny. Salt wall segments exhibit variable degrees of welding due primarily to the local presence of intrasalt inclusions (basalt and gabbro) rather than orientation with respect to the shortening or position along the ridge. Flanking Jurassic minibasins may be upright and symmetric or tilted; tilting may have started during halokinesis but was largely acquired during shortening. Minibasins tilt away from welded diapiric segments towards inclusion-rich segments, indicating differential diapir rise. The structure of the central parts of the salt walls differs from the lateral terminations. While the central parts are relatively simple with aperture or welding governed by the inclusions, many salt walls end buried by suprasalt sedimentary wedges. These perched wedges were not arched upward during diapir squeezing but were unexpectedly folded into synclines. The folding was formed by the flanking minibasin tilting in one limb and by inhomogeneous diapir rise and lateral salt escape in the other, thus defining a new modality of roof and shoulder folding above salt diapirs.

1. Introduction

The role of salt as responsible for diapirism forming heterogeneities in layered stratigraphic successions is increasingly being recognized in salt-involved fold and thrust belts. Several deformed belts derive from the contraction of salt-bearing basins where the distribution of pre-shortening diapirs largely controlled the final structure. This has been reported in orogenic belts and foreland basins such as the Alps, the Pyrenees, the Flinders ranges, the Zagros, the northern Andes, and the Atlas Mountains (e.g. Burrel and Teixell, 2021; Callot et al., 2007, 2012; Célini et al., 2020; Graham et al., 2012; Granado et al., 2019; Hudec et al., 2021; Labaume and Teixell, 2020; Letouzey et al., 1995; Martín-Martín et al., 2016; Parravano et al., 2015; Rowan and Vendeville, 2006; Santolaria et al., 2022; Saura et al., 2014, 2016; Teixell et al., 2015, 2017, and others). Synsedimentary shortening during and after diapirism has also been documented in seismic studies of detached continental slopes (e.g. Brun and Fort, 2004; Rowan et al., 2004).

Marked structural differences have been noted between contractional belts with precursor salt diapirs and those without (Rowan and Vendeville, 2006; Callot et al., 2007; Jackson and Hudec, 2017). As expected, weak salt diapirs concentrate shortening in preference to intervening sedimentary sequences. Shortening of preexisting diapirs localizes folds and thrusts, and produces diagnostic structures such as squeezed diapirs, secondary welds and salt sheets (Fig. 1). In the adjacent overburden we see roof arching, megaflap steepening, and shortcut thrusting (Fig. 1) (e.g. Jackson and Hudec, 2017, and references therein). While most documented examples from natural and experimental studies focused on the behavior of diapir stocks (e.g. Dooley et al., 2009a; Dooley and Hudec 2020; Duffy et al., 2018), the 3D nature of shortening salt walls has been less investigated (Dooley et al., 2009b; Callot et al., 2012; Rowan et al., 2012; Vidal Royo et al., 2021).

In addition, diapir interiors often contain large inclusions of rigid and dense rock bodies embedded in the salt (Lotze, 1955; Kent, 1958; Pflug, 1967; Jackson et al., 1990; Gansser, 1992; Jackson et al., 2014; Fernandez et al., 2017). A few studies addressed the mechanics of the ascent or sinking of such inclusions or stringers within salt (e.g. Weinberg, 1993; Koyi, 2001; Chemia et al., 2008; Burchardt et al., 2011). Owing to difficulties in imaging intrasalt structure with seismic methods

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and scarce field studies, there is little documentation of the role of such intrasalt complexities in shortening. Similarly, diapir tops often contain perched sedimentary bodies that form diapir roofs, shoulders, or secondary minibasins (Jackson and Hudec, 2017; Giles et al., 2018; Célini et al., 2021, 2022) (Fig. 1). Upon shortening, intrasalt or suprasalt features may form buttresses that can condition the squeezing of a diapiric ensemble, resulting in complex patterns of salt-wall persistence or closure (Fig. 1). This exerts a control on shortening in addition to those related to salt wall orientation or to the strain gradients observed in relation to the position within an individual salt wall and its terminations (e.g. Rowan et al., 2012; Duffy et al., 2018) (Fig. 1).

The purpose of this paper is to provide further documentation on the products of shortening of salt wall provinces, based on a case from the High Atlas mountain belt in Morocco that departs from the most commonly described structures. We illustrate along-strike variations in salt-wall structure and flanking minibasin rotation, addressing the role of rigid-body inclusions within salt bodies, the behavior of suprasalt overburden layers perched on top of diapirs, and the shortening interactions between adjacent salt walls and their terminations. This study describes examples from a well-exposed terrain that can provide analogs for the interpretation of subsurface salt walls where seismic data fail to image the wide range of three-dimensional salt-tectonic complexities.

2. Geological setting of the Moroccan High Atlas

The Atlas chains of Morocco are intracontinental mountain belts that formed during the late Cretaceous-Cenozoic by N–S shortening in the northern African plate. The High and Middle Atlas Mountains developed as fold-thrust belts by the tectonic inversion of former orthogonal or oblique rift troughs that opened in Triassic-Jurassic times (Choubert and Faure-Muret, 1962; Mattauer et al., 1977; Laville and Piqué, 1992; Arboleya et al., 2004) (Fig. 2). Regional extension during the Triassic and Jurassic was oriented NE-SW, with respect to the frame of the present-day African plate (Mattauer et al., 1977; Ait Brahim et al., 2002; El Kochri and Chorowicz, 1996; Frizon de Lamotte et al., 2009; Domènech et al., 2015). The dominant shortening direction during the late Cretaceous and Cenozoic was NNE-SSW, almost coincident with the previous extension direction (Fig. 3). The inversion and shortening strain experienced during the Atlas orogeny was moderate (15–24%; Teixell et al., 2003); much of the high topographic elevation of the Atlas Mountains is due to recent long-wavelength mantle uplift (Teixell et al., 2005; Missenard et al., 2006; Babault et al., 2008), by which the internal structural attributes of the Jurassic basin are often preserved and recognizable.

The Triassic rift is exposed in the western High Atlas south of Marrakech (Fig. 2, inset), represented by red beds accumulated in relatively small basins bounded by steep extensional faults, occasionally reactivated as, or shortcut by, thrusts (Qarbous et al., 2003; Domènech et al., 2015; Perez et al., 2019). Jurassic deposits are expansive and largely marine in origin but still confined in an elongated rift coincident with the extent of the present-day High Atlas belt (Fig. 2). Atlas rift evolution was accompanied by the intrusion of late Jurassic alkaline igneous rocks (gabbro, syenite and doleritic dykes; Hailwood and Mitchell, 1971; Laville and Piqué, 1992). Cretaceous post-rift and Cenozoic synorogenic deposits are today mostly confined to the peripheral plains bordering the High Atlas (Fig. 2).

The present tectonic structure of the inverted Jurassic basin consists of narrow deformation zones consisting of tight antiforms or thrust

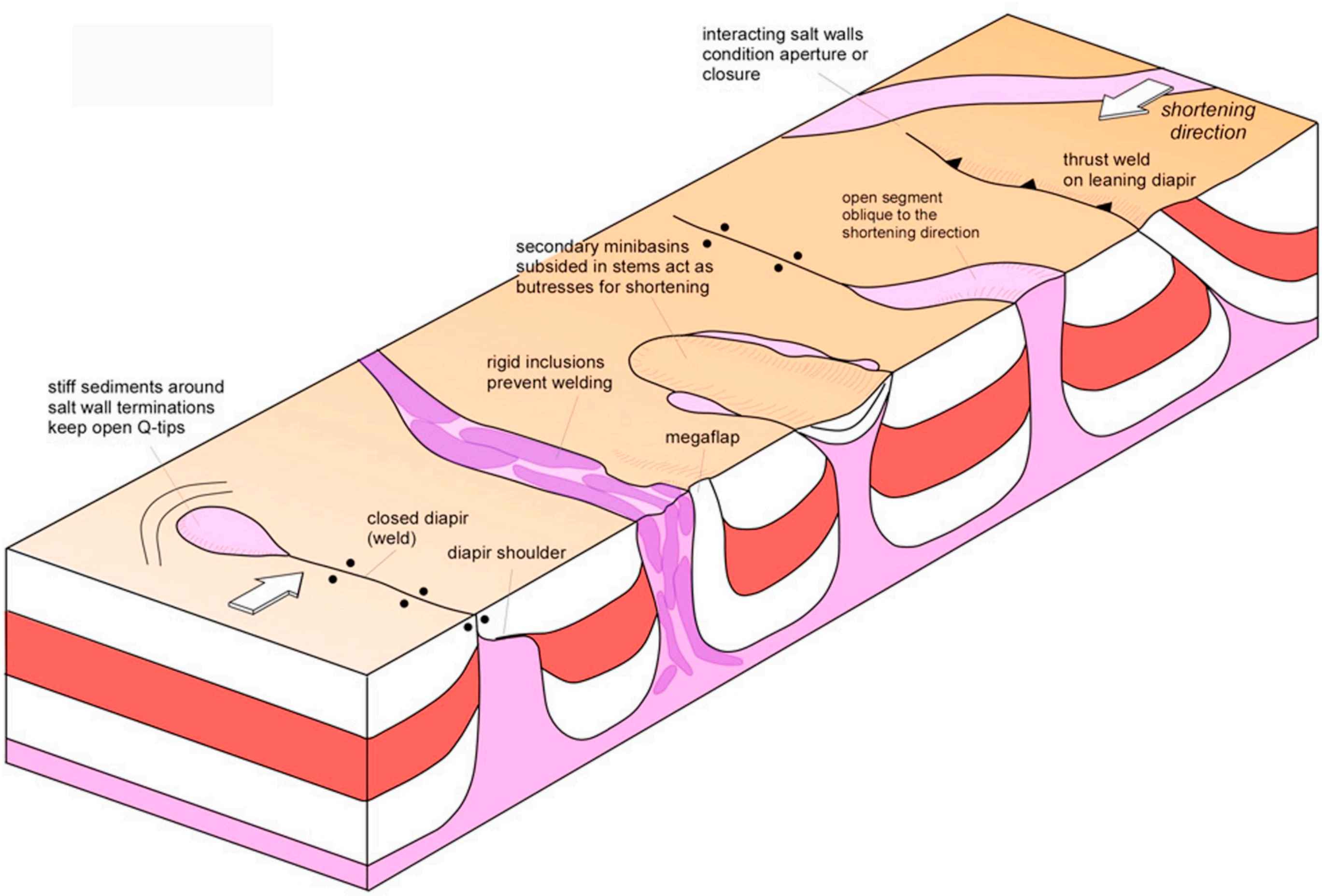

Fig. 1. Conceptual diagram showing potential features that may affect the behavior of preexisting salt walls during shortening.

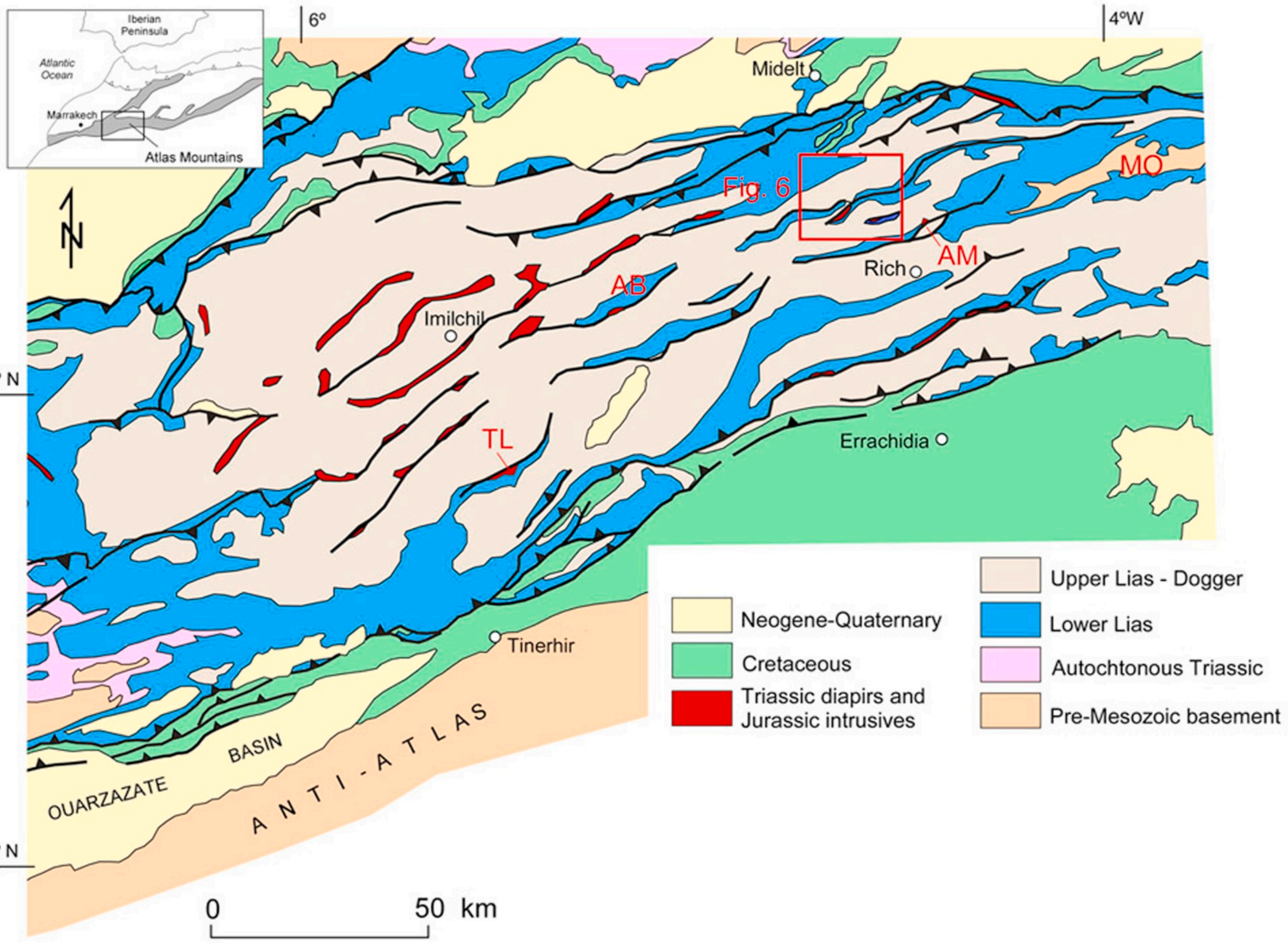

Fig. 2. General map of the Central High Atlas showing the location of the study area (boxed). TL: Toumliline diapir; AB: Aberdouz salt wall; AM: Azag minibasin; MO: Mougueur basement massif.

faults that form calcareous ridges of Lias carbonates, separated by broad synclines occupied by upper Lias-Dogger shales and upper Jurassic red beds (Schaer, 1987; Teixell et al., 2003) (Fig. 2). The ridges are often cored by the Triassic red shales (Keuper facies), basalt, and occasional evaporites. Ridge folding during the Jurassic basin-opening stage has been in the past years attributed to halokinesis of the Keuper salt, which defines a salt province (Ettaki et al., 2007; Michard et al., 2011; Saura et al., 2014; Moragas et al., 2016; Martín-Martín et al., 2016; Teixell et al., 2017; Vergés et al., 2017). As in other mountain belts of the Tethys domain, salt structures formed during the rifting stage were rejuvenated during the Cenozoic convergence, which often led to diapir squeezing, making them easy to overlook (Michard et al., 2011; Saura et al., 2014; Teixell et al., 2003, 2017).

2.1. Stratigraphy

2.1.1. Triassic

In the Atlas basins, Triassic synrift sedimentation began with detrital red sandstones (Anisian-Carnian), largely outcropping in the Marrakech High Atlas, followed by red to green shales with gypsum, salt, siltstone, and porous dolomite (cargneule) bodies (Keuper facies; Upper Triassic) (Mattis, 1977; Beauchamp, 1988). In the Central High Atlas, basement and Lower Triassic sandstones are rarely exposed, and Keuper rocks crop out in the cores of diapirs and concordant salt anticlines. This Keuper unit is interpreted as the source layer for the Atlas diapirism (Michard et al., 2011), although halite is not observed at the surface in the study area - the sole outcrop is in a small diapir near Toumliline, located 80 km to the SW (Teixell et al., 2003) (Fig. 2).

Keuper rocks are intermingled with basalts belonging to the Central Atlantic Magmatic Province (CAMP) emplaced around the Triassic-Jurassic boundary (Nomade et al., 2007). Since both shales and basalts are exposed mainly in the deformed interior of diapirs, the geometric relationships between them are complex, but observations in the Marrakech High Atlas indicates that the basalts originally overlay the bulk of the Keuper shale and salt (Beauchamp, 1988; Perez et al., 2019).

2.1.2. Lower and middle Jurassic

The stratigraphy of the Jurassic of the Central High Atlas has been extensively documented (Du Dresnay, 1971; Evans et al., 1974; Studer, 1987; Warme, 1988; Milhi et al., 2002; Wilmsen and Neuweiler, 2008; Ait Addi and Chafiki, 2013; Bodin et al., 2011, 2017; Teixell et al., 2017). Specifically, a synthetic log of the study area is presented in Fig. 4, based on observations in the Aouja-Zerkoun ridge and Agounou syncline (Fig. 3). The lowermost Jurassic (Hettangian?-Sinemurian) is composed of shallow-water marine carbonates, consisting of massive and laminated limestones and dolomites in the lower part (Idikel formation; Studer, 1987) and sponge-rich limestone mounds in the upper part, which are not always present (Foum Zidet formation; Neuweiler et al., 2001). The maximum exposed thickness of the Hettangian?-Sinemurian as a cartographic unit in the study area at Jebel Aari Mdourt is about 700 m, although it can be locally reduced to a few tens of m in the vicinity of ridges (Jebel -abbreviated J in Fig. 3 and the

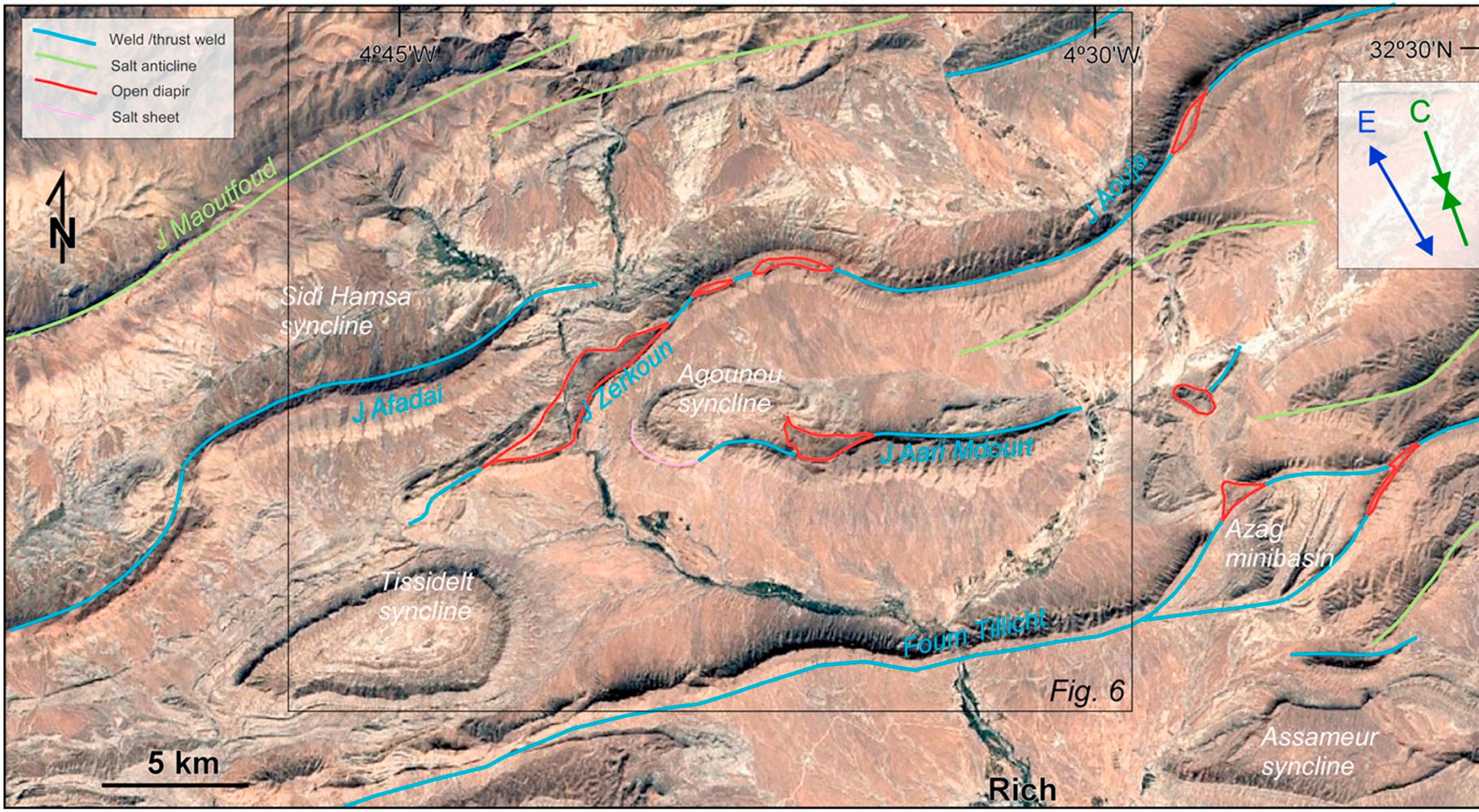

Fig. 3. Interpreted Google Earth satellite image of the High Atlas of Rich showing the system of salt ridges and synclinal minibasins referred in this study. J: Jebel. E and C in inset indicate the inferred mean extension direction during the Jurassic rifting and the compression direction during the Cenozoic orogeny (see text for discussion).

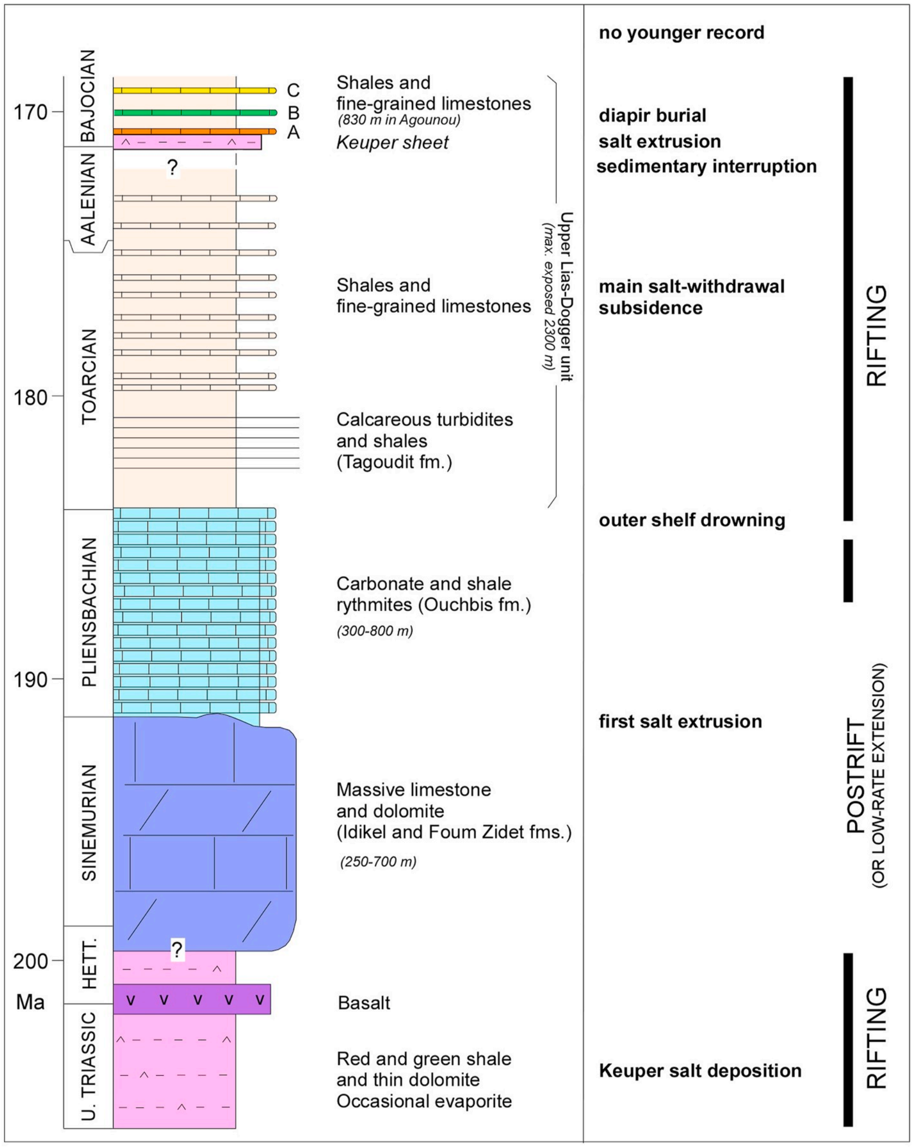

Fig. 4. Synthetic stratigraphic log of the Triassic-Jurassic succession of the Zerkoun ridge-Agounou syncline, in the central part of the mapped area in Fig. 6. Thickness ranges refer to the entire study area.

following-means *mountain* in Arabic). The Sinemurian is followed by carbonate rhythmites of distal platform/slope origin and Pliensbachian age (Ouchbis formation; Studer, 1987), up to 800 m thick near the surface in the study area. Laville et al. (2004) interpreted that those lower Lias marine carbonates sealed the Atlas Triassic rifts. Accommodation by renewed rifting increased in the mid Liassic in the Central High Atlas, and the earlier platform carbonates were drowned and disrupted by the formation of subsiding basins where thick successions of shales, limestones and calciturbidites accumulated up to Dogger times. The late Pliensbachian-early Toarcian platform drowning resulted in turbidite sedimentation during the Toarcian (Tagoudit formation, 80–100 m thick; Studer, 1987; Wilmsen and Neuweiler, 2008). The overlying shale-dominated unit (Aalenian to Bajocian-Bathonian?) infills synformal minibasin centers and may be up to 2300 m thick in the study area. Its stratigraphy is less distinctive, dominated by calcareous shale (marl) with fine-grained limestone and calciturbidite interbeds. In the southern limb of the Agounou syncline, the succession is punctuated by a Keuper sheet that is found interbedded in the middle of the succession (Figs. 4–6). Key photogeologic beds A, B and C have been mapped above the Keuper, in a succession that is up to 830 m thick. These beds consist of fine-grained limestones, level A being a condensed faunal interval with belemnites and ammonites and occasional hardground atop. The strata under the Keuper sheet contain ammonites of the mid Aalenian (det. J. Sandoval), whereas marker bed A provided a lower Bajocian fauna (Laeviuscula biozone). The upper part of the succession (above bed A in Fig. 4) is barren.

The Toarcian and younger fine-grained and limestone deposits have been grouped in a single cartographic unit in this work (upper Lias-Dogger in Fig. 6 and the following). Marker beds A, B and C, indicated for the Agounou syncline, have not been identified in the other basins because of the monotony of the succession.

No younger stratigraphic units were preserved in the study area or in the High Atlas of Rich in general, although elsewhere in the High Atlas the Jurassic record ends with Bathonian to Kimmeridgian red beds with numerous discontinuities indicative of a generalized regression (Jenny et al., 1981; Haddoumi et al., 2010).

2.2. *Jurassic gabbro intrusions and dolerite dykes*

Jurassic gabbro intrusions in the Central High Atlas are typically observed within Triassic salt walls (Michard et al., 2011; Martín-Martín et al., 2016; Calvín et al., 2017). In the study area, three small gabbro

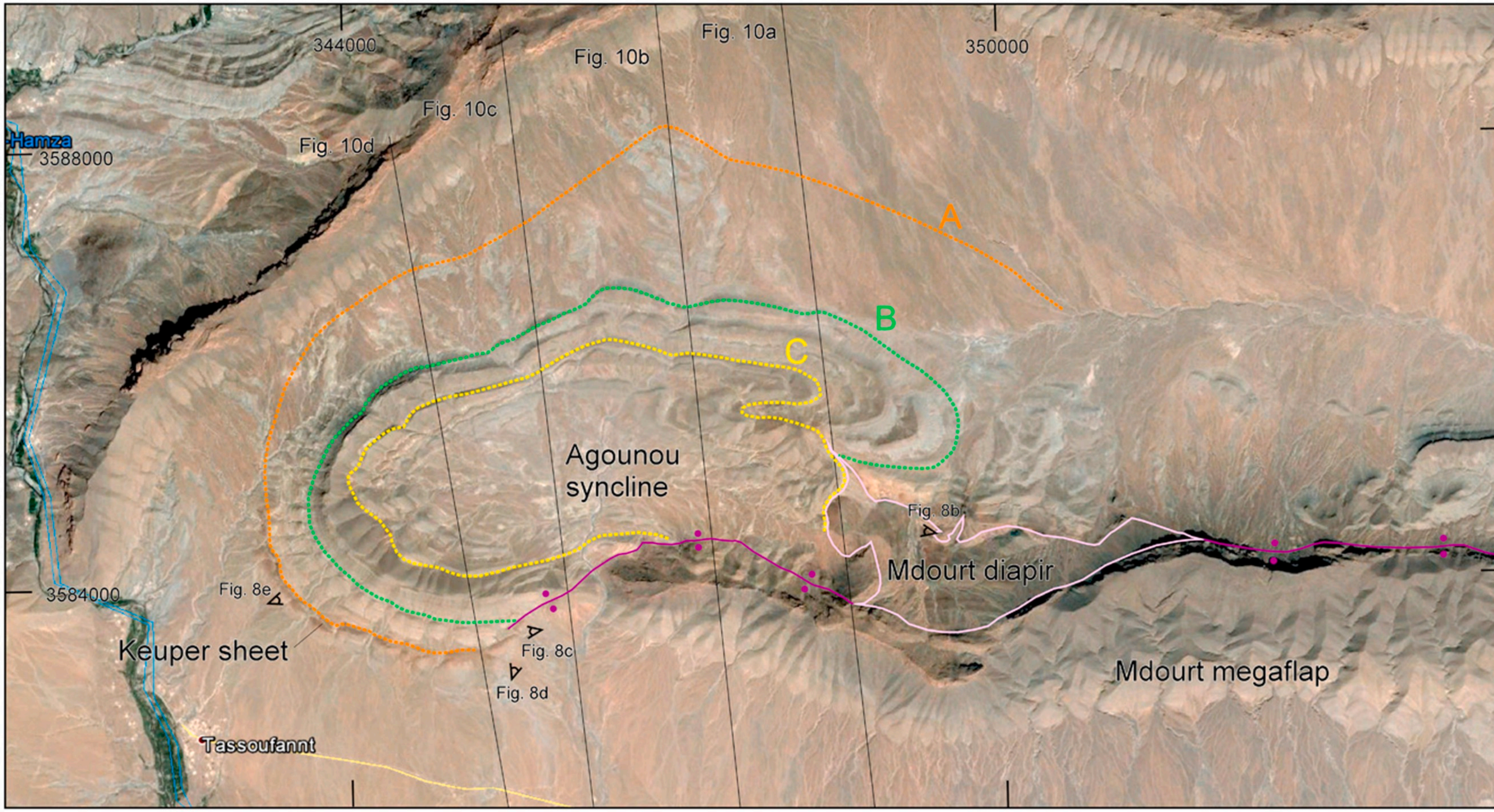

Fig. 5. Google Earth satellite image of the Agounou syncline and Mdourt diapir (compare with the central part of the geologic map in Fig. 6). UTM coordinates, zone 30. A, B and C are photogeologic maker beds within the upper Lias-Dogger succession (see the text for explanation). Also indicated are the traces of the cross-sections of Fig. 10, and the location of the field photographs in Fig. 9b–e. Picture 9a is from the Zerkoun diapir west of the image area.

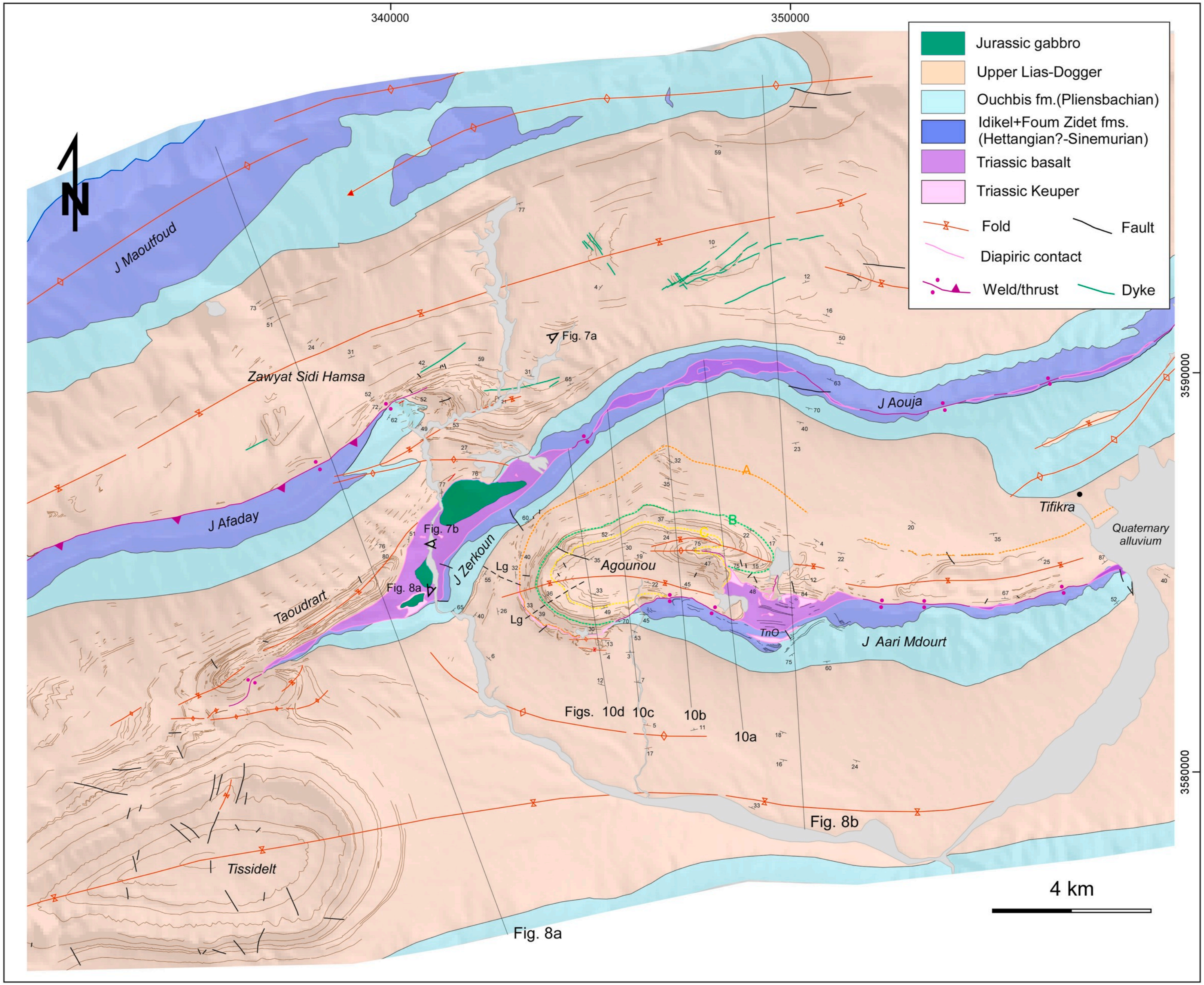

Fig. 6. Geological map of the Agounou-Sidi Hamsa area (location in Figs. 2 and 3) showing the stratigraphic units distinguished with internal bed traces, the main structures, and the location of the cross-sections of Figs. 8 and 10 as well as the field photographs of Figs. 7 and 9a. J: Jebel, TnO: Tizi n'Ourhioul pass. Lg indicates the approximate position of the stratigraphic log in Fig. 4. UTM coordinates, zone 30.

plutons are hosted by Keuper shale and basalt in the core of the Zerkoun diapir (Fig. 6). The Zerkoun gabbros are formed predominantly by plagioclase and pyroxene, with minor olivine, and appear internally undeformed. They have not been dated in the area, but comparable intrusions in the Imilchil area (Fig. 2) have been dated by the K–Ar and Ar–Ar methods as late Jurassic (Oxfordian to Tithonian, 160-145 Ma) (Hailwood and Mitchell, 1971; Armando, 1999). Dolerite dykes, probably related to the same magmatic event, are seen cutting the upper Lias-Dogger sediments in the core of the Sidi Hamsa syncline (Fig. 6). Their main orientation is NE-SW, approximately perpendicular to the inferred Jurassic extension direction, although a few NW-SW-oriented dykes are also found.

3. Salt tectonics in the High Atlas of rich

The Central High Atlas near the locality of Rich shows a characteristic pattern of antiformal and faulted calcareous ridges of varying E-W to NE-SW trends, with wider synclines between them (Dubar, 1939) (Fig. 3). Ridges often show sigmoid map patterns, occasionally anastomosing; synclinal basins in the upper Lias-Dogger sediments may have linear or oval planforms in between. Tight to isoclinal anticlines suggest decoupling in the Triassic level (Torres-López et al., 2018). However, the underlying Paleozoic may also be involved in the folding, as observed in the Mougueur basement culmination, 30 km east of the study area (Fig. 2) (El Kochri and Chorowicz, 1996; Teixell et al., 2003).

As the central High Atlas was interpreted to be a former Triassic-Jurassic rift (e.g. Warme, 1988; El Kochri and Chorowicz, 1996; Laville and Piqué, 1992; Beauchamp et al., 1996; Teixell et al., 2003; Torres-López et al., 2018), the main features within the Rich High Atlas were attributed solely to extensional or strike-slip faulting, occasionally with Cenozoic thrust reactivation. Growth strata indicate that folding started in the Jurassic (Laville and Piqué, 1992; Teixell et al., 2017; Torres-López et al., 2018), whereas Triassic shales and basalts observed in ridge cores may be concordant with the overlying Jurassic overburden, or discordant with truncation relationships suggestive of diapiric piercement (Teixell et al., 2017). Therefore, we highlight that salt tectonics of the Triassic source layer was essential in the structural development both during the Mesozoic basin opening and the Cenozoic contractional stages, similarly to what has been proposed in other parts of the High Atlas (Michard et al., 2011; Saura et al., 2014; Martín-Martín et al., 2016; Moragas et al., 2016). Thickness variations in the High Atlas of Rich indicate that halokinesis started locally in the early Lias (Sinemurian-Pliensbachian), consisting mostly of low-amplitude movements contemporaneous with carbonate platform sedimentation. From Toarcian times onward, shale sedimentation prevailed in rapidly subsiding minibasins (up to 3–4 km thick), whereas shallow-water carbonate sedimentation continued in diapiric highs or in episodes of subdued minibasin bathymetric relief. An episode of maximum subsidence by salt withdrawal was recorded in the Azag minibasin (Figs. 2 and 3) in Bajocian-Bathonian (?) times (Teixell et al., 2017). Jurassic salt-flow related folding probably proceeded during late Dogger and Malm times, as deduced to the west in the Imilchil area (Michard et al., 2011; Saura et al., 2014), although there is no preserved record in the High Atlas of Rich. Total tectonic shortening in a traverse of the High Atlas near Rich during the Cenozoic orogeny was estimated to be about 24% (Teixell et al., 2003). Inferred preexisting salt walls were often squeezed and welded.

4. Datasets and methods

The field area in the Central High Atlas was investigated by structural analysis and mapping, based on field observations and on Google Earth satellite imagery. Geological cross-sections were constructed directly from field data using the *Move* platform. Near-surface stratigraphic thicknesses were derived from sedimentological field observations and dip data. Well or seismic information is not available for the interior of the High Atlas. Basin-scale thickness variations in the deep subsurface were therefore not observed, and thickening or thinning trends were extrapolated conservatively from observations at the surface, although uncertainties persist. Specific structures were kinematically restored in cross-section prior to the Atlas shortening using the built-in *line-length unfolding* and *flexural-slip unfolding* algorithms in the *Move* software. Although these methods may provide valid restoration of inter-diapir minibasins, the original widths of the diapirs remains conjectural.

5. Salt walls of the study area

The Agounou-Sidi Hamsa study area of the Rich High Atlas is characterized by an array of E-W to NE-SW ridges and intervening synclinal basins with a relatively simple linear form in planview (Fig. 6), although there are complex lateral variations in detail within individual ridges and basins, or between adjacent ridges. Linear ridges are continuous along strike for several kilometers but show lateral terminations of diverse nature, as described below. As mentioned above, thickness variations and growth strata in the Jurassic sediments, along with truncations by Triassic rocks at ridge cores cannot be simply explained by Cenozoic compressional folding and Mesozoic rift faulting, and similarly to what we proposed for the Azag basin ~8 km to the SE of this study (Teixell et al., 2017) (Fig. 3), we interpret that much of the ridge-and-basin structure of the Agounou-Sidi Hamsa area is linked with salt tectonics. The ridges can be classified as salt anticlines (e.g. Jebel Maoutfoud), thrust faults or thrust welds (Jebel Afaday, Fig. 7a), or salt walls with diapiric cores with different degrees of aperture (Jebel Aouja-Zerkoun, Jebel Aari Mdourt) (Figs. 6 and 7b). Isolated salt stocks were not observed, nor were salt ridge intersections enclosing polygonal minibasins like the Azag basin. Likewise, shortcut thrusts or connecting fault splays between major ridges were not observed.

The salt walls of the study area can be symmetric, that is, with steep panels of Lower Lias carbonates on both sides or can have the upturned limestones on only one side (usually the south side) (Fig. 6). Accordingly, synclinal basins between salt walls can be upright (e.g. at Sidi Hamsa or Tissidelt, Fig. 6), with rather symmetric limbs, or can be asymmetric, appearing tilted (Taoudrart, Tifikra). While the central part of the salt ridges exhibits a relatively simple structure, with varying degrees of diapiric aperture or welding, the lateral terminations may be buried by sedimentary wedges exhibiting complex structural relationships. We used salt tectonics concepts in the interpretation of two comprehensive cross-sections that help to illustrate the general structure of the study area (Fig. 8). The individual structures are described in the following sections, with special emphasis on the Agounou-Mdourt ridge and minibasin ensemble.

5.1. Afaday and Aouja-Zerkoun ridges

The Jebel Aouja segment is rather symmetric along much of its length, with a central weld or narrow core of Triassic basalt and steep Idikel-Foum Zidet and Ouchbis layers on both sides (two-sided megaflaps; Figs. 6 and 8). These Lias carbonates appear concordant or pierced by the diapiric core, but the most proximal relationships have been eroded along much of the ridge, so it cannot be discarded that segments of it were originally salt anticlines.

In the SW part of the Aouja-Zerkoun structure the salt wall is open, up to 1.2 km wide (Zerkoun diapir in Fig. 7b and 8a), cored by Triassic basalt and gabbro plutons with only small Keuper remains. The plutons are restricted to the diapir interior, as it happens elsewhere in the High Atlas. It is worth noting that when gabbro is at the diapir boundary in direct contact with Jurassic sediments there is no contact metamorphic aureole, which suggests the past existence of an intervening Keuper body (most probably salt-rich) that has been squeezed out during shortening. Similarly, the gabbro-basalt contacts often preserve a Keuper seam in between (Fig. 9a). These seams, composed of shale and

Fig. 7. (a) Panoramic view of the Jebel Afaday thrust over the southern limb of the Sidi Hamsa synformal basin. Keuper slivers along the contact suggest that it can be classified as a thrust weld (see text for discussion). (b) View looking east of the eastern margin of the Zerkoun diapir, flanked by steep Lower Jurassic beds. The Ouchbis formation locally onlaps carbonate mounds of the Idikel formation. Black circles in dip symbols indicate overturned bedding. See Fig. 6 for picture location.

cargneule, are highly sheared and discolored, and can be from 50 cm to a few meters thick. They attest that the plutons probably intruded into larger Keuper bodies that were later evacuated.

In contrast to the Aouja segment, the flanks of the Zerkoun diapiric segment are asymmetric, as in the case of the Mdourt salt wall described below. A Lias upturned megaflap is observed only on the SE side, whereas in the NW there is the Taoudrart syncline in the upper Lias-Dogger sediments (Fig. 8a). The southern limb of the Taoudrart syncline is short and concordant over the diapir (a diapir shoulder) and contains growth strata, whereas the northern limb forms a thick, steeply dipping panel of upper Lias-Dogger strata inclined towards the diapir and in stratigraphic continuity with the Liassic carbonates of the Jebel Afaday (Fig. 8a).

Although there is a bed angularity in the uppermost part (Fig. 8a), near the syncline core, much of the steep Afaday-Taoudrart Jurassic succession is almost homoclinal and isopachous without indications of growth folding. This succession concordantly overlies Keuper occasionally slivers and overthrusts the Sidi Hamsa basin (Fig. 7a). The Afaday steep structure resembles a megaflap, but with differences with respect to the original definition by Rowan et al. (2016) that are discussed below.

5.2. Mdourt salt wall and Agounou syncline

The Mdourt structure and the Agounou syncline provide clear example of the along-strike variations occurring in natural salt wall-minibasin systems, as illustrated by the satellite image and geological map (Figs. 5 and 6) and the serial detailed profiles of Fig. 11. In the central and eastern parts, the Mdourt salt wall shows a simple structure (Fig. 8b), which is asymmetric and continuous for over 12 km featuring a one-sided lower Jurassic megaflap in the southern flank (Figs. 6 and 8b). The salt wall appears welded in its easternmost part, but it shows an open diapir in the central part where there are large bodies of Triassic basalt (here called Mdourt diapir; Figs. 8b and 10). The basalt shows layering related to original lava flows presently in a subvertical position, suggesting that it was steeply upturned during diapir rise and/or diapir shortening. The NW corner of the open diapir shows an overhang (Fig. 9b) that is welded at its tip and passes laterally to an anticline-syncline fold pair (Fig. 6).

The southern megaflap is defined by steep to overturned Idikel and Ouchbis carbonates that form the prominent relief of the Jebel Aari Mdourt. Much of the contact between the Ouchbis and overlying upper Lias-Dogger shales and turbidites is poorly exposed, but a discontinuity can locally be observed, where overturned Ouchbis strata are onlapped by upper Lias-Dogger shales, exhibiting a fan of growth strata (Fig. 9c). Gentle stratal wedging is observed already in the Ouchbis formation, and a small Keuper sheet interleaved between the Idikel and Ouchbis formations near the pass of Tizi n'Ourhioul, in the central part of the structure (Figs. 6 and 8b), indicates localized salt extrusion in the early Lias.

On the northern flank, the Mdourt salt wall is in contact with the upper Lias-Dogger sequence, which forms an asymmetric syncline adjacent to the salt wall (Tifikra basin, Fig. 8b). Its northern limb is a large panel of tilted layers in continuity with the lower Lias carbonates of the Aouja-Zerkoun salt ridge, whereas the southern limb in the eastern and central part is a short succession of vertical to overturned layers defining a perched flap (with early Bajocian level A approximately at its base) (Fig. 8b). Laterally, this flap is truncated under the northwestern overhang of the Mdourt diapir. The perched flap of unit A on the northern side of the Mdourt salt wall attests to an older diapir roof, upturned by continued diapiric rise. This roof may have covered all or part of the diapir.

The salt wall structure changes markedly towards its western end, as illustrated by the detailed cross-sections in Fig. 10. The exposure of the Mdourt diapir disappears, covered by the mid-late Bajocian marker level C, which also lies over its NW overhang (Figs. 6 and 10a). To the south,

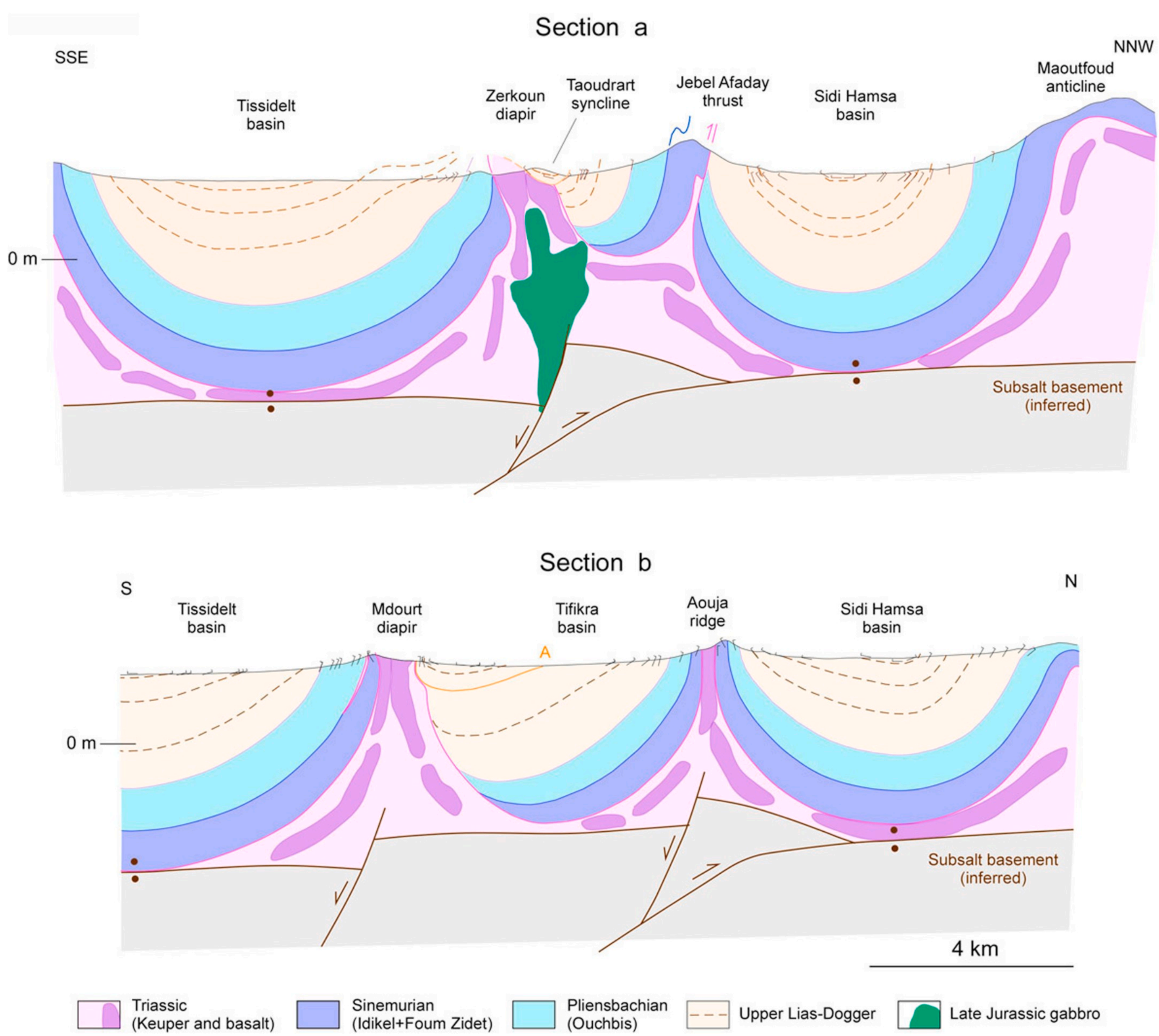

Fig. 8. Interpretative general cross-sections across the salt structures of the Agounou-Sidi Hamsa area, from the Maoutfoud salt anticline to the Tissidelt minibasin (no vertical exaggeration, location in Fig. 6). In the absence of seismic data and the likely decoupling at the Keuper unit, there is no control on the deep structure of the minibasins and of the subsalt basement, so the geometry proposed is speculative. Similarly, the position of the basalt and gabbro inclusions in the deep subsurface is conjectural. Primary welds formed during the Jurassic sedimentary loading are likely to underlie the thicker minibasins, and normal faults are assumed to be associated with the origin of the longest salt walls. The Atlas compressional structure in the basement is represented by low-angle, shortcut thrusting, in analogy with the physical models of inverted extensional salt-related systems by Dooley and Hudec (2020) and Ferrer et al. (2023) and with field observations in the High Atlas of Marrakech by Domènech et al. (2015).

level C is welded against the Mdourt megaflap, attesting to the closure of a narrower inboard diapir in between. Thus, bed C lies over a diapir shoulder (Fig. 1). The entire burial sequence is folded into a km-scale syncline (the Agounou syncline; Figs. 5, 6 and 10).

An obliquely trending weld truncates the surface exposure of the Mdourt Liassic megaflap and connects with a Keuper sheet in the southern limb of the Agounou syncline (Figs. 6 and 9d,e). We interpret that the megaflap continues in the subsurface, but with a reduced height (Fig. 10d). The Keuper sheet which extends westwards for 2.5 km (Figs. 5 and 6), is composed of red shale and siltstone, and includes basalt and sediment inclusions near its western end. We propose that the Keuper sheet, which is covered by the Bajocian bed A, formed as salt extruded from the Mdourt diapir during a sedimentary interruption in late Aalenian-earliest Bajocian times, as indicated by the ammonite fauna above and below (see the stratigraphy section). The oblique weld, which is steep in its eastern part, becomes more gently N-dipping westward, featuring Keuper rocks and overlying strongly overturned beds of Ouchbis fm. and upper Lias halokinetic growth strata (Fig. 9c and d). The geometry conforms to a diapir overhang or flare, attesting to rapid salt flux in the southern margin of the Mdourt diapir since the late Pliensbachian times. This overhang eventually passes to the aforementioned bedding-parallel Keuper sheet further west (Fig. 9e), providing a rare field example of the transition from a flaring diapir to a salt sheet, comparable to those reported in the Flinders Ranges of Australia by Hearon IV et al. (2015).

The structural position of the terminal Agounou syncline is

Fig. 9. Field photographs of salt structures (see location in Figs. 5 and 6). Black circles in dip symbols indicate overturned bedding. (a) Contact between Triassic basalt and Jurassic gabbro in the Zerkoun diapir. An unmetamorphosed Keuper sliver in between suggests that the gabbro intruded into a salt body, which was later largely expelled; (b) View looking west of the edge of the Mdourt diapir showing the northern overhang and flare. In the foreground is a perched flap with approximately level A at the base (overturned). In the background, level C forms the sole of a sedimentary succession over a shoulder atop of the diapir. A weld is exposed to the left of the image (see section 10a); (c) View looking west to the south of the Agounou syncline showing the tip of the Ouchbis megaflap under the Mdourt weld and flare, and a fan of onlapping growth strata of the overlying upper Lias shale and carbonate unit (including megabreccia layers); (d) View of the Mdourt oblique weld in the southern part of the Agounou syncline (see text for explanation). To the right is a Keuper flare that passes laterally to the weld. The Ouchbis fm. of the SE side of the weld is overturned, forming a megaflap that includes the Idikel fm. visible in the background; (e) The salt sheet at the southern limb of the Agounou syncline, looking north.

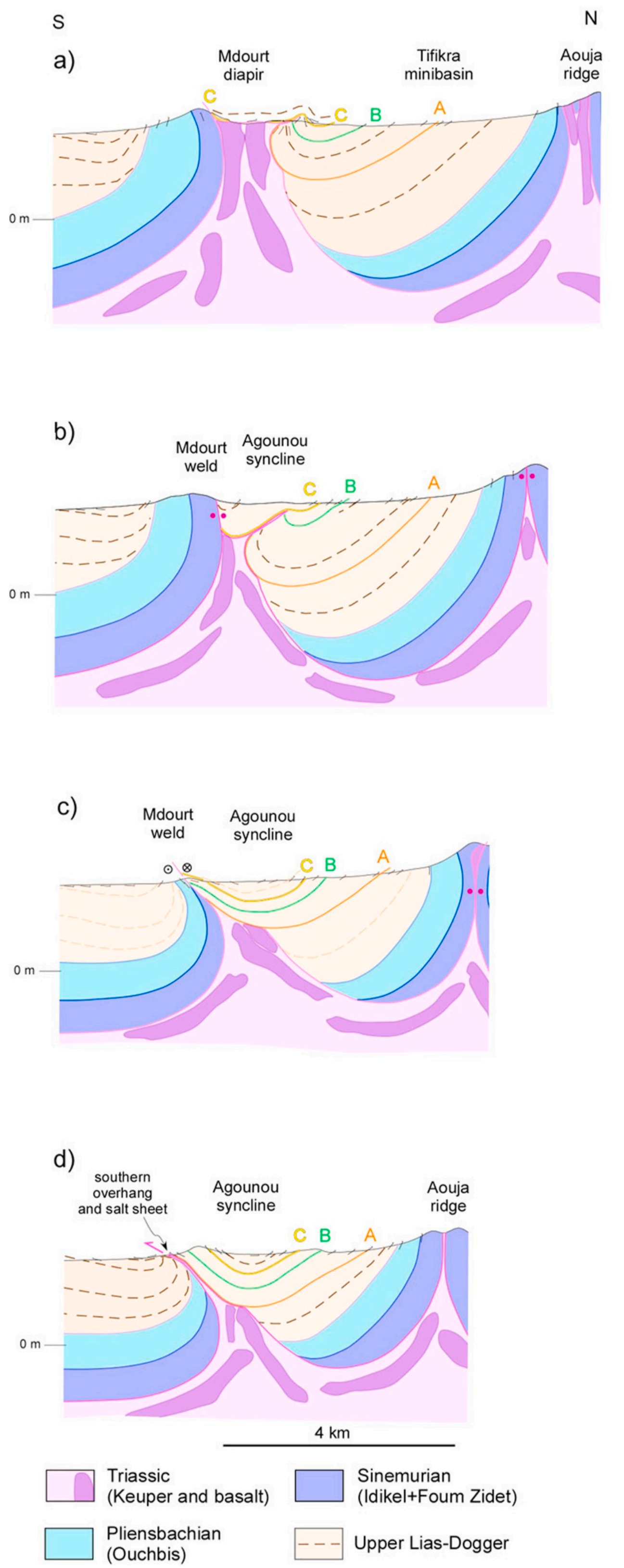

Fig. 10. Serial interpretative detailed cross-sections of the Mdourt-Agounou structures showing the lateral variation from diapir to weld to salt sheet (location in Fig. 6). Section (b) crosses the oblique transfer fault-weld structure. The southern salt sheet in (d) is thought to have reactivated as a thrust with further extrusion to account for the shortening accommodated by welding in (a) and (b) (see text and Fig. 14 for explanation).

comparable to that of the Taoudrart syncline reported above for the Aouja-Zerkoun salt wall end: the northern limb lies above a larger, flanking minibasin succession, while the southern limb lies over a diapir/salt sheet or an equivalent weld (Fig. 8a and 10).

6. Restored models for the halokinetic Agounou-Mdourt structure prior to shortening

Fig. 11 shows the retrodeformation of two profiles across Agounou-Mdourt to illustrate our interpretation of the pre-shortening configuration of the salt wall-basin ensemble. As in the Afaday-Taoudrart case, where the homoclinal layer dips in most of the succession indicate a considerable amount of post-depositional tilting during shortening, we favor the same process for the Tifikra tilted minibasin. Gentle growth folding during the depositional phase is suggested by decreasing dips in the upper Lias-Dogger succession, and hence we suggest that the Tifikra basin during the Jurassic had only a gentle wedge geometry (sensu Rowan and Weimer, 1998) and that much of the basin inclination was acquired during the Atlas shortening (compare Figs. 10 and 11).

Major extensional faults or rollovers were not recognized in the study area (or in other parts of the High Atlas of Rich), suggesting diffuse extensional strains during the rifting phase, largely acquired by diapir opening and/or stretching. It is likely that the linear salt walls of the Central High Atlas originated in association with basement normal faults, like the Triassic and Jurassic faults of the same orientation visible in the exposed subsalt at the Marrakech High Atlas (Qarbous et al., 2003; Domènech et al., 2015; Perez et al., 2019). How these behaved in compression under thick salt is unknown, but there must have been some shortening accommodated in the basement and Lower Triassic despite being usually ignored. Analog references from physical models were provided by Dooley and Hudec (2020) and Ferrer et al. (2023), where inverted or preserved extensional faults and shortcut thrusts form a basement system roofed by salt or primary salt welds, entirely decoupled from the diapir and minibasin system above. A similar configuration may exist under the study area, as tentatively represented in the general sections of Fig. 8. Decoupling between different levels of diapiric systems and the basement was also reported in the natural case of the Sivas thrust belt by Legeay et al. (2020).

A comparison of the restored sections of the Mdourt diapir shows that while the diapir shoulder is covered by suprasalt bed C in the eastern part, the diapir roof and salt sheet in the west are covered by bed A, defining the complex structure of the buried diapir top under the Agounou syncline (Fig. 12).

7. Discussion

The structure of the Agounou-Sidi Hamsa area of the High Atlas appears at a first approximation as a relatively simple salt wall system initiated during rifting and later orthogonally shortened. Nevertheless, it shows interesting complexities and uncertainties that merit discussion and illustrates general issues common in the shortening of salt walls.

For most of the structures of the study area, growth strata and thickness variations provide a pre-contractional record of halokinesis that spans for 70 my during the early and mid Jurassic. However, sedimentary layers flanking or burying the diapirs often appear steeply dipping or folded in forms that cannot be solely achieved by halokinesis, as discussed below. The shortening during the Cenozoic Atlas orogeny has no syntectonic sedimentary record in the study area or in the vicinity.

7.1. How do megaflaps form?

In inverted salt basins, minibasins may tilt during halokinesis and asymmetric subsidence or during subsequent shortening. In the Afaday case (Fig. 8a), the steep homoclinal bedding dips described suggest layer upturning largely post-dating subsidence that we attribute to the Atlas

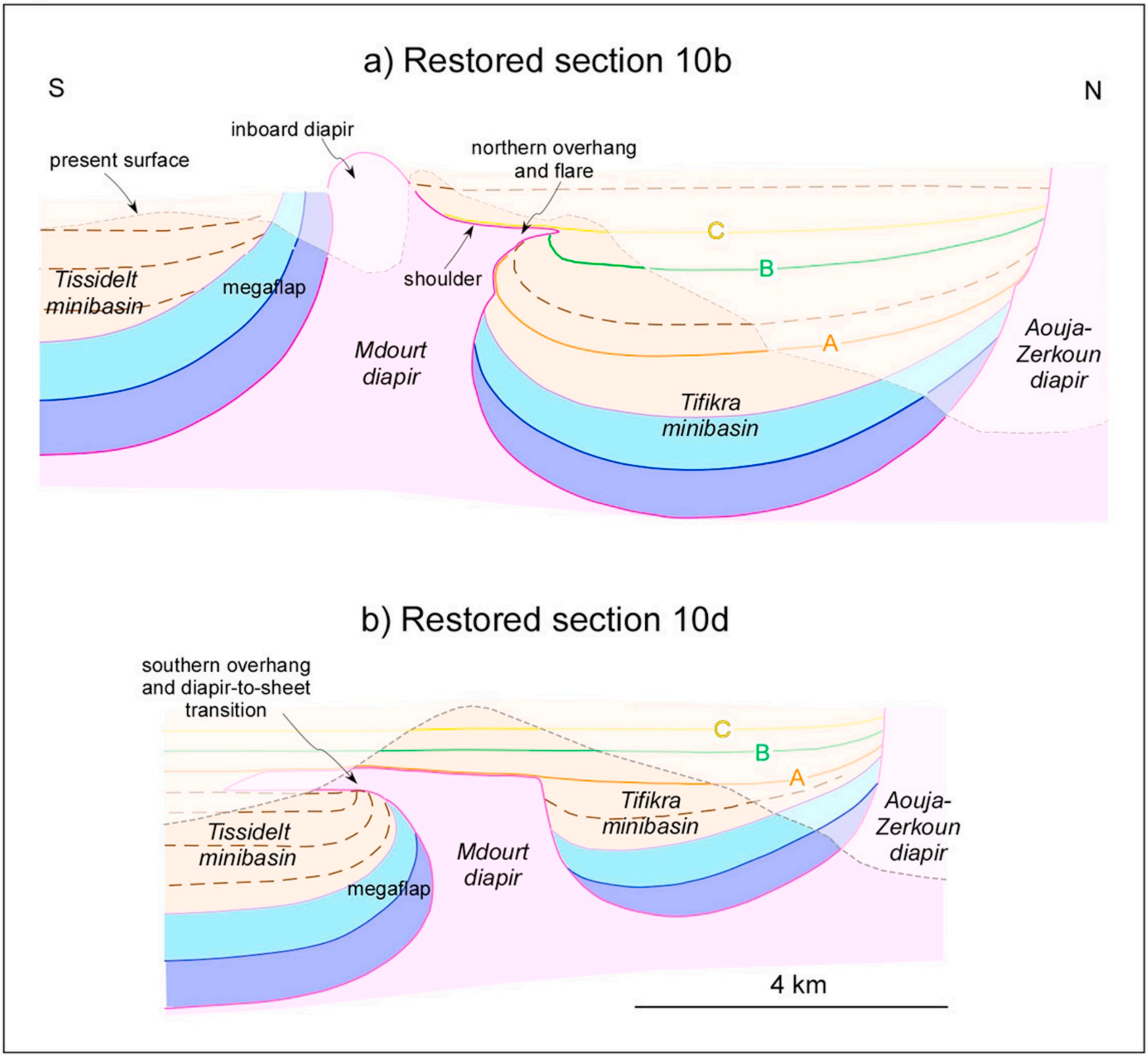

Fig. 11. Restored sections of the Mdourt and Agounou structures and flanking minibasins before the Atlas shortening showing the northern and southern diapir overhangs, and the suprasalt sedimentary units of different age covering shoulders and roofs. Figure (a) coincides with the present-day section of Fig. 10b–and (b) with 10d. Note that the Mdourt salt wall is covered by different stratigraphic levels (A to C) along strike.

compression, and we proposed that much of the tilting of the Tifikra basin can also interpreted in this way (section 6). Bulk minibasin tilting during shortening has been proposed for other natural salt-bearing contractional belts such as the Turkish Sivas basin or the Austrian Alps (Kergaravat et al., 2017; Granado et al., 2019; Legeay et al., 2020), and in physical models of shortened salt walls with little or no syncontractional sedimentation (Dooley and Hudec, 2020; Santolaria et al., 2021).

The lower strata infilling minibasins, if forming upright panels concordant with steep salt bodies are often called megaflaps; a definition by Rowan et al. (2016) limited the use of the term to steep stratal panels that extend far up the sides of diapirs or their equivalent welds (but not in salt anticlines or pillows). These authors differentiated halokinetic megaflaps, formed by differential salt loading in the adjacent minibasins without compression, from those assisted by syndepositional shortening, in all examples showing growth strata sequences near the diapirs. We note that a distinction is needed for those steep panels followed by post-flap sequences that do not show salt-related growth strata, even if they belong to a minibasin originally adjacent to a salt diapir. This is the case of the Afaday limestone ridge, which, rather than being a halokinetic megaflap originally adjacent to the rising diapir, is interpreted as a strongly upthrust portion of the minibasin floor. In this interpretation, the near-diapir margin, which could have contained a halokinetic megaflap, has been eroded. We call such structures upthrust megaflaps, in contrast to those formed by load-induced salt migration, be the later assisted by compressional buckling or not (Fig. 13). Thin Keuper remains along the Afaday basal contact, truncating the middle Jurassic marls of the Sidi Hamsa basin, allow us to identify it as a thrust weld derived from a diapir. In contrast, the Mdourt megaflap, where the overturned lower Lias carbonates are onlapped by upper Lias-Dogger growth strata

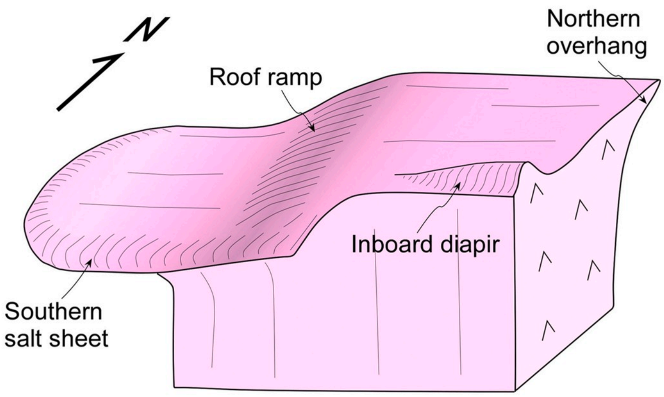

Fig. 12. Reconstruction of the shape of the Mdourt diapir buried under the Agounou syncline, featuring overhangs, salt sheets, and a ramp roof by which the diapir top is covered by level A in the west and level C in the east.

qualifies as a halokinetic megaflap (Fig. 9c and 10), even if it was slightly oversteepened during shortening.

7.2. What controls the localization of secondary welds?

The flanks of the salt walls of the Agounou-Sid Hamsa area often appear welded, which we attribute to the Atlas shortening. Some of the salt ridges show a sinuous map pattern, but there is no regionally consistent pattern of diapir width or welding in relation to the orientation or position within the salt wall (i.e. at salt wall ends or waists). The Zerkoun and Mdourt open segments trend distinctly (NE-SW and E-W, respectively, Fig. 6); on the other hand, they are both characterized by large bodies of basalt or gabbro.

While the non-welded segments (i.e. where both diapir flanks have not been brought in contact, although some salt must have been expelled) contain a large proportion of basalt and gabbro bodies, we may speculate that welded segments lacked them. Alternatively, the inclusions could have been expelled upwards above the present erosion level prior to welding or could have remained in the diapir pedestals without being mobilized upwards. Even if the late Jurassic gabbro intrusions were always emplaced within salt structures, we expect an inhomogeneous distribution, as by nature, they are localized phenomena. The late Triassic basalt may have been a more continuous feature overlying the Keuper salt in the High Atlas basin, but several local factors may have prevented their incorporation into diapirs, like absence of basalts due to pre-Jurassic erosion or stretching and dismembering of the basalts before salt-driven uplift.

On the other hand, Q-tip open diapirs (Fig. 1) were not systematically observed at the study salt wall terminations. This could be due to further squeezing during continued salt wall shortening or to burial by the suprasalt sedimentary wedges at Agounou and Taoudrart. Adjacent salt walls may also have interacted during the Atlas shortening. It is worth noting that the Afaday upthrust ridge plunges out just where the Zerkoun diapir becomes welded (Fig. 6). This relationship is probably not a coincidence and illustrates a case of shortening relay between salt walls.

7.3. What is the significance of the western end of the Mdourt salt wall?

The concordant roof/shoulder over the western map termination of the Mdourt open diapir where the diapir is widest suggests that it continues under the Agounou syncline, and as such has been represented in the cross-sections of Fig. 10. However, the subsurface Mdourt diapir must eventually terminate westward because it does not link with the Zerkoun salt wall, which trends at an almost right angle. The precise location and nature of the diapir termination are unknown, probably near the western periclinal end of the Agounou syncline, although a clear surface expression (e.g. a dip inflection) could not be observed, by which we can deduce that the termination was gradual, probably caused

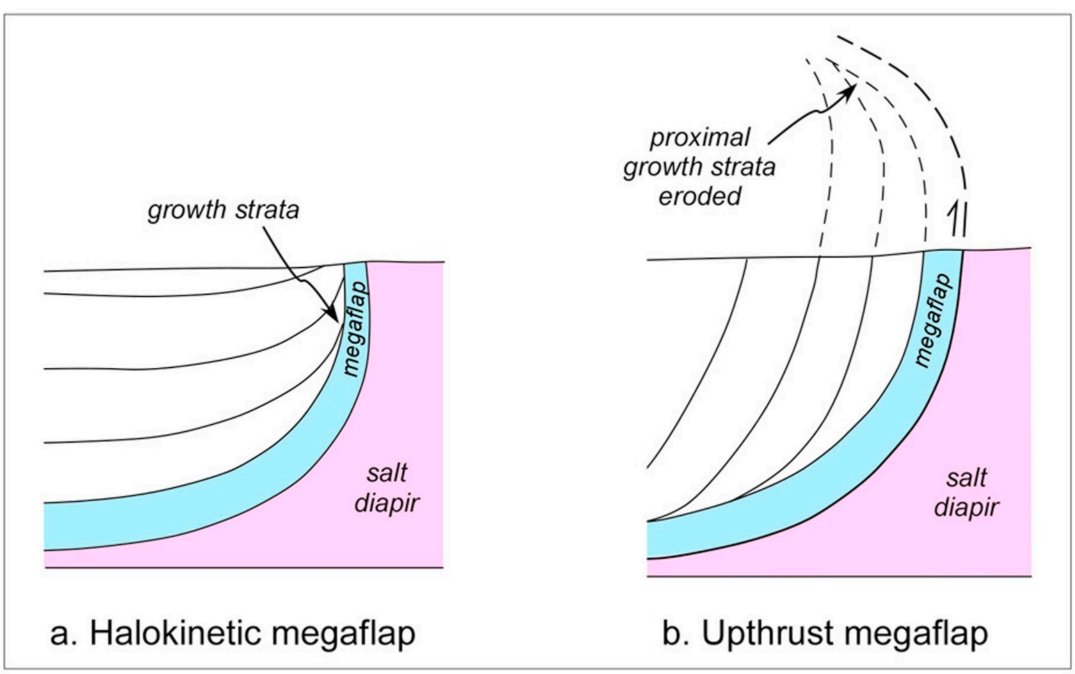

Fig. 13. Types of megaflaps that can be distinguished in Moroccan salt walls. a) Classic halokinetic flap formed by drape folding above rising salt during minibasin sedimentation, after Rowan et al. (2016). The Mdourt megaflap qualifies as this type. Onlaps and growth strata in the post-flap succession are found adjacent to the megaflap. Note that a process of layer upturning caused by shortening with contemporaneous minibasin deposition could produce a similar result. b) Upthrust megaflap produced by minibasin upthrusting and rotation during shortening; note the absence of adjacent growth strata in outcrop. These probably existed (i.e. the minibasin could have had a halokinetic megaflap adjacent to the diapir), but have been eroded during basin-margin rotation and uplift. The Afaday megaflap conforms to this case.

by a decrease in salt availability due to the competition for salt with the adjacent Aouja-Zerkoun salt wall. In fact, beds of the western pericline of the Agounou syncline over the presumed end of the Mdourt diapir do not dip away from the diapir as in other described cases of salt wall terminations (for example, Escosa et al., 2019), but towards the east because of larger-scale upturning adjacent to the Aouja-Zerkoun salt wall (Fig. 6).

The distribution of the marker beds indicates that the central part of the Mdourt diapir was still exposed at the surface between marker-bed A-C time, while the western end was buried at Agounou (Figs. 10–12). The northwestern overhang of the Mdourt open diapir attests to a period of rapid salt flux compared with the sedimentation rate between layers A and C; the latter eventually buried the resulting salt horn. Incidentally, the overhang tip that passes into a tight anticline-syncline fold pair suggests further inflation once the edge was buried/pinned, possibly during the syndepositional halokinetic phase, although the folds may have been tightened during the later compression.

Whereas marker-bed A that forms the roof of the diapir in the westernmost part of Agounou also overlaps the salt sheet observable in the southern limb of the syncline, the Mdourt and oblique Agounou welds eventually truncate levels B and C, reinforcing that diapiric rise and piercement continued in the east after the extrusion of the salt sheet. This late Aalenian-early Bajocian extrusion is contemporaneous with sedimentary interruptions and hardgrounds reported at Azag and Jebel Aberdouz (the latter over a salt sheet too) (Teixell et al., 2017; Carrión et al., 2023), indicating that salt extrusion and subsequent diapir burial at Agounou can be correlated to a regional event in the Central High Atlas basin.

Why should the western end of the Mdourt structure be buried first while the central part was still inflating? We do not have a clear answer for this; it could be due to the specific arrangement of the intrasalt inclusions blocking salt flow at the western end or to the competition for salt with the Aouja-Zerkoun salt wall.

7.4. *How did the roof on the western end of the diapir influence the shortening accommodation?*

We have seen that the eastern and central parts of the Aouja-Zerkoun and Mdourt salt walls responded to the Atlas shortening by pure diapir squeezing and welding. The relatively simple Mdourt weld formed in this way. However, we infer that the oblique weld that marked the diapir-to-salt sheet transition at Agounou played a special role during the Atlas compression, accommodating differential shortening mechanisms along strike. During the shortening of the Agounou syncline, salt evacuation from under the syncline could only be accommodated via the southern salt sheet once the sheet was eroded and exposed at the surface (or via an upper diapir segment outboard). Hence, we propose that the Agounou oblique weld behaved as a tear fault transferring the shortening observed in the Mdourt weld to thrust shear and/or further extrusion along the southern salt sheet at Agounou (Fig. 14). Brecciation

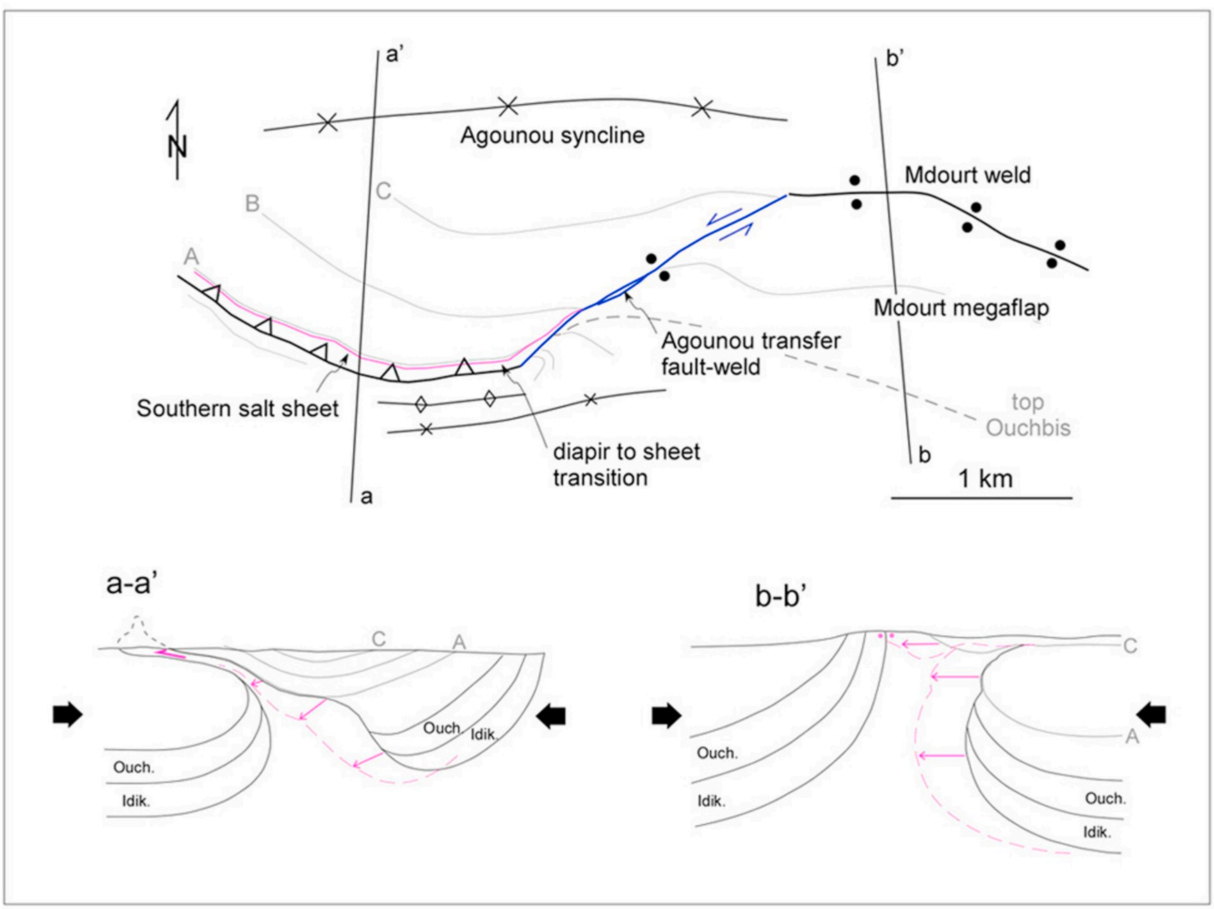

Fig. 14. Cartoon illustrating the transition between the welded Mdourt diapir and the salt sheet at the southern limb of the Agounou syncline illustrating their inferred behavior during the Atlas shortening. While in the east the shortening was accommodated by diapir squeezing and welding, in the west it is inferred to have been accommodated by salt expulsion and/or thrusting via the salt sheet (see text for further explanation). It is difficult to ascertain whether an upper diapir segment, now eroded, pierced layers A to C of the southern limb of the Agounou syncline outboard of the exposed sheet, with a composite geometry comparable to those previously observed by Hearon IV et al. (2015), or whether those layers once buried completely the salt structure. An upper diapiric horn is tentatively represented in Fig. a–a'.

of carbonate wall rocks and highly sheared Keuper slivers in the weld are compatible with a fault-weld nature, although kinematic indicators could not be found.

7.5. Shoulder synclines: a combination of halokinesis and shortening

The Agounou and Taoudrart synclines (Fig. 6) are suprasalt structures containing the upper part of the upper Lias-Dogger succession that once buried, partially or completely, the western ends of the Mdourt and Aouja-Zerkoun diapirs. As a first approximation we could interpret that the synformal shape and the existence of the southern salt sheet at Agounou are indicative of secondary minibasins subsiding into diapir stems (i.e. Fig. 15a). However, the lack of an equivalent northern salt sheet or weld and of dip inflections marking the buried diapir margin in the north does not favor such a simple interpretation. In fact, at both Agounou and Taoudrart, the northern limb of the synclines is in continuity with the larger basins flanking the diapirs, while the southern limbs overlie the diapir or the related salt sheet. Thus, we propose that the Agounou and Taoudrart suprasalt sedimentary wedges lay on diapir shoulders or roofs and were later refolded, most likely during the shortening (Fig. 15d). At Taoudrart the synclinal hinge is seen to coincide with the northern diapir edge. Salt shoulders may form during deposition of a burial wedge flanked by an inboard diapir neck (Giles et al., 2018; Langford et al., 2022), or after continuous diapir roofs that are later pierced by a narrower upper diapir. Both may produce the same result as for the salt structure, being distinguishable by the geometrical features of the sedimentary wedge. Why should they fold into synclines during shortening?

Several types of suprasalt folding on top of diapir stems or shoulders have been identified (Fig. 15). In diapir shortening, diapir roofs are typically arched upward by shortening-driven salt rise (Fig. 15b). This is not the case at Agounou and Taoudrart, by which we deduce that there has been little bulk diapir rise in these specific structures during shortening. This may be explained by several factors: i) the thick burial succession (min. 830 m preserved at Agounou), ii) the occurrence of basalt and gabbro inclusions, iii) the past existence of open diapir necks or overhangs focusing salt evacuation, and iv) the original syndepositional tilt of the burial succession: a gentle growth fan is visible in the core of the Taoudrart syncline, suggesting that the synformal shapes could be partly inherited from the syndepositional stage, inhibiting antiformal arching during subsequent shortening. Halokinetic sequences were not identified in Agounou, possibly due to erosion, although Bajocian layers are tabular and pierced at high angles (a T-shaped contact in the terminology of Ribes et al., 2015) at the Agounou weld, (Fig. 9d), indicating that salt rise rates were balanced with sedimentation rates in that area.

Cross-sections of Fig. 8a and 10c,d illustrate that the southern limbs of the Agounou and Taoudrart synclines lie above diapir overhangs, while the northern limbs dip concordantly with the flanking minibasins. We thus propose a hybrid fold mechanism in which the southern limbs were uplifted above the N-dipping overhanging diapir margin, and the northern limbs were formed by continued rotation of the larger, flanking minibasin (probably associated with rise of the Aouja and Afaday ridges) (Fig. 15d). We envision that these processes occurred principally during the Atlas shortening, although it is likely that the gentle growth folding during the Jurassic sedimentation conditioned the subsequent tightening. During shortening, salt in the contracting diapirs must have been (a) laterally evacuated via the Agounou salt sheet or the southern edge

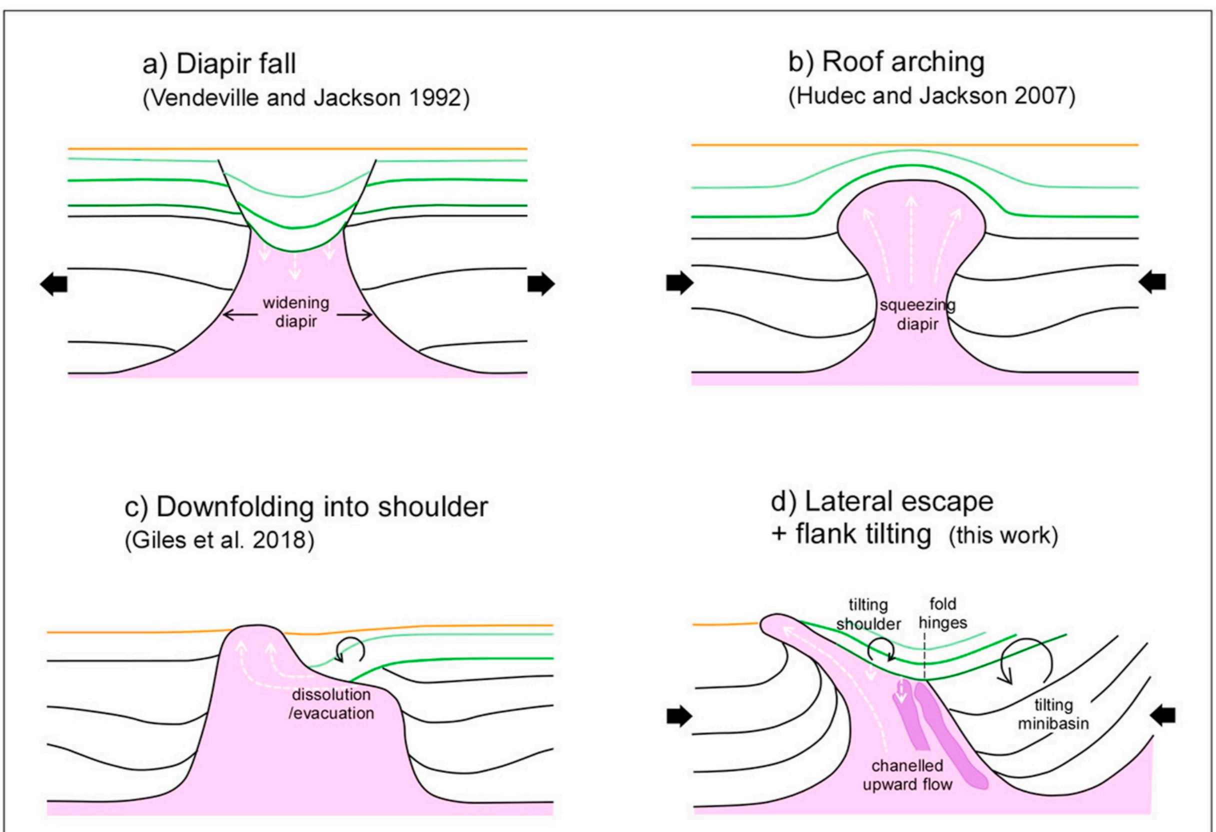

Fig. 15. Mechanisms of suprasalt folding of suprasalt strata (green) over roofs or shoulders. White arrows indicate the salt flow. Figure (d) is guided by the Agounou and Taoudrart examples; the suprasalt half syncline is downfolded partly by buckling and by inhomogeneous salt rise during shortening, possibly channelized by the existence of rigid inclusions in the diapir core (Hudec and Jackson, 2007; Vendeville and Jackson, 1992). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of the Zerkoun diapir, and/or (b) moved along the axis of the diapir towards the still-exposed central parts of the structure.

It must be noted that both the Agounou and Taoudrart cases involve large inclusions that inhibited complete diapir shortening and arching, but a large amount of salt must have certainly existed at some time of the history to account for diapir rise, having been evacuated during the shortening through the inboard diapir necks or overhanging horns. In fact, the diapir inclusions are likely to have induced very heterogeneous salt flow during the diapir rise, favoring local, channeled salt rise towards salt necks rather than producing continuous upward arching. It turns evident that the role of inclusions in inhomogeneous internal diapir flow needs to be further explored by systematic field observations and modelling.

We are not aware of analogs for the geometry of shoulder folding that we observe here. The folding of sedimentary wedges on salt shoulders has been little explored so far, and two mechanisms have been proposed: i) rollover tilting towards the inboard diapiric neck by salt expulsion or dissolution collapse in the shoulder (Giles et al., 2018; Pichel and Jackson, 2020, Langford et al., 2022) (Fig. 15c), and ii) outboard-directed tilting in small, transient shoulders associated with tapered halokinetic sequences that extend inboard over the diapir within a composite system (Pichel and Jackson, 2020). We report a new fold type associated with lateral escape within the diapir governed by overhangs and/or inclusions, combined with the tilting of the flanking basin (Fig. 15d).

In addition to compressional push during shortening, Hudec et al. (2009), Jackson et al. (2019) and Fernandez et al. (2020) argued that minibasins could tilt by asymmetric diapir rise on their margins. We underline that in the Tifikra and Afaday-Taoudrart cases, minibasin tilting is away from the welded salt wall in the northern margin (which have megaflaps or upturned flanking strata) and towards the open salt wall with inclusions. We propose that the now welded salt wall segments, which originally had a higher proportion of salt, experienced more vigorous uplift during shortening than those with large inclusions. This could provide an explanation for minibasins tilting away from inclusion-free segments, which may apply equally to halokinetic and compressional phases of diapir rise.

8. Conclusions

The Agounou-Sidi Hamsa area of the Central High Atlas near Rich provides a case for the shortening of precursor salt structures in salt wall provinces, where the first extension direction and the subsequent compression direction were close in orientation. Along- and across-strike structural variations in the salt wall and minibasin system appear controlled by the inclusions within diapirs, by the existence of overhanging segments, and by the geometry of roofs and perched shoulders. The range of structures produced in the study case is synthesized in Fig. 16. The shortening of the salt walls in the area is accommodated primarily by diapir squeezing and welding, upturning/thrusting of flank strata, and minibasin bulk rotation (tilting), processes that dominate along much of the length of the walls. However, the existence of suprasalt sedimentary wedges near the salt wall ends caused the accommodation of shortening in more complex ways, including folding and thrust detachment, with the lateral variation locally enabled by transfer fault-welds within individual salt walls.

We interpret that large intrasalt inclusions of igneous rocks previous to or postdating rift-related halokinesis played a major role during subsequent orogenic shortening by 1) preventing complete welding of the diapir flanks, 2) inhibiting bulk diapir pop-up during shortening and arching of diapir roofs, and, consequently, 3) inhibiting minibasin tilting away from inclusion-rich diapirs because of less shortening-driven uplift compared to adjacent salt walls devoid of inclusions.

Sedimentary wedges on diapir roofs or shoulders can fold into synclines during shortening, controlled by heterogeneous diapir reactivation and flanking minibasin rotation, illustrating a new mechanism

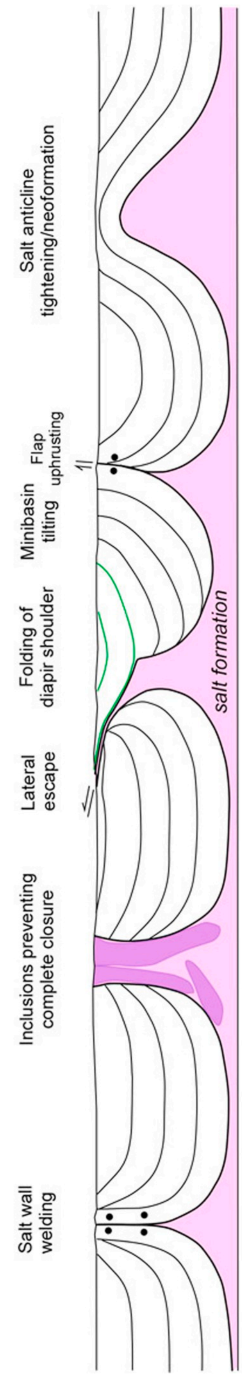

Fig. 16. Summary diagram showing the types of processes proposed for the shortening of the salt walls in the study field cases.

for suprasalt folding. These suprasalt folds are hinged over outboard diapir margins, and were also conditioned by the position of diapir overhangs.

CRediT authorship contribution statement

Antonio Teixell: Writing – original draft, Visualization, Investigation, Funding acquisition, Conceptualization. **Michael R. Hudec:** Writing – review & editing, Investigation, Conceptualization. **María-Luisa Arboleya:** Writing – review & editing, Investigation. **Naiara Fernandez:** Writing – review & editing, Investigation.

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.

Data availability

Data will be made available on request.

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