Syn- to post-rift diapirism and minibasins of the Central High Atlas (Morocco): the changing face of a mountain belt

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Abstract: The Atlas Mountains are classically regarded as a failed Mesozoic rift arm subject to Alpine inversion, folding and thrusting. Here, we present new integrated structural and sedimentological studies that have revealed numerous Early–Middle Jurassic diapiric ridges and minibasins, characterized by distinctive halokinetic structures. Diachronocity in halokinesis is observed across the Central High Atlas, waning first in the SW during the Early–Middle Jurassic (Jbel Azourki and Tazoutl ridges) and continuing to the late Middle Jurassic towards the NE (Imilchil region). The halokinetic structures are readily differentiated from the effects of later Alpine deformation, allowing a new picture of the Central High Atlas to emerge. The most pervasive deformation in the Central High Atlas is associated with Early–Middle Jurassic diapirism, whereas the impact of Alpine inversion is mostly focused at the basin margins. This new understanding helps explain previously problematic aspects of the Atlas Mountains, which we now recognize as an exceptionally well exposed natural laboratory for understanding the interactions between halokinesis, tectonics and sedimentation.

The Central High Atlas Jurassic diapiric province

Geological setting and regional stratigraphy

The ENE–WSW-trending, 2000 km long Atlas basin extending from Morocco to Tunisia formed coevally with Late Permian–Early Triassic Central Atlantic opening within a large-scale left-lateral transtensive rift system (Fig. 2; Piqué et al. 2000). In this scenario, Triassic sediments were unconformably deposited on top of the folded Hercynian basement in half-graben basins bounded by ENE–WSW faults (Piqué et al. 2000; Frizon de Lamotte et al. 2008). These basins were filled by more than 1 km of reddish siltstones and evaporite-bearing shales including irregularly distributed halite and gypsum during the Late Triassic as proved by seismic lines and borehole data (Benaouiss et al. 1996; Courel...
These deposits were unconformably overlain by Upper Triassic to lowermost Jurassic tholeiitic basalts of the Central Atlantic Magmatic Province (Fig. 2; Marzoli et al. 2004). 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). These evaporite-bearing shales and associated evaporites became the main source layer for the diapirc structures of the Central High Atlas described here but also in the Sahara Atlas (Vially et al. 1994; Frizon de Lamotte et al. 2000; Bracene et al. 2003) and Tunisian Atlas (Hlaiem 1999; Zouaghi et al. 2005; Zouaghi et al. 2013). The scarcity of evaporites along some of the studied ridges as well as the frequent diapir inclusions reveals a complex diapiric evolution as discussed below.

The Jurassic succession is composed of Hettangian–Pliensbachian platform carbonates that are developed across the Central High Atlas, interfingering with basin deposits characterized by hemipelagic and slope sedimentation, and covered by a Pliensbachian–Aalenian eastward prograding, mixed clastic–carbonate platform with source areas around the western closure of the Tethys realm (Fig. 1; Souhel et al. 2000). These sediments are overlain by a shallowing upwards succession, from oolitic limestones and corals to continental red beds, deposited across the Atlas basin from Aalenian to Callovian times (Fig. 1; Bouchouata et al. 1995; Fadile 2003).

The Central High Atlas is characterized by alkaline transitional gabbroic magmatism during the Late Dogger and Malm (Fig. 2), which resulted in multiple intrusive, subvolcanic and volcanic rocks across the area (Hailwood & 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. 2; Lhachmi et al. 2001; Haddoumi et al. 2010).

Halokinetic structures of the Central High Atlas

The Central High Atlas is formed by 15–80 km long ENE–WSW-trending ridges, slightly oblique to the main tectonic boundaries (Fig. 1b). Intersecting these ridges is a subsidiary NW–SE ridge set, separating elliptical to subcircular basins <30 km wide. These ridges expose Upper Triassic shales, evaporites and basalts, with metre- to hectometre-scale slivers of Hettangian carbonates and Middle Jurassic gabbro. Lower to Middle Jurassic deposits filling these basins have typical thicknesses of 3–4 km, and comprise halokinetic sequences sensu Giles & Lawton (2002) (Fig. 2) that are diachronous from one basin to the next. This well-exposed polygonal array of interrelated ridges and basins forms an intricate system similar to that described in other salt basins (Mart & Ross 1987; Rowan & Vendeville 2006). Here we describe structures from the Central High Atlas in the context of a platform–basin transition.

In the SW of the study area the Jbel Azourki ridge (Fig. 1) is a key structure separating Early Jurassic shallow platform environments to the south from basinal environments to the north. This c. 80 km long ENE–WSW-trending highly segmented structure contains numerous elongate Triassic outliers, interpreted as diapir pedestals localized along an inferred basement normal fault system at depth. The diapiric structures are complex, with both erosional features and narrow minibasins subparallel to the fault system at depth.
along the eastern part of the Jbel Azourki ridge. However, diapirism overlap the ridge, recording Middle Aalenian waning of diapirism Aalenian–Early Bajocian platform carbonates onlap and finally the flanks of the diapiric ridge. In contrast, the overlying Late Jurassic succession onlaps the diapir at a very low angle and defines halokinetic hooks on a scale of hundreds of metres, with observed thicknesses of 900 m on both flanks of the ridge. The overlying Toarcian–Aalenian mixed platform succession also onlaps the diapir, defining stacked halokinetic sequences with thicknesses of tens of metres reaching up to c. 730 m and c. 2500 m in thickness on the northern and southern flanks, respectively (Fig. 5b). The southern succession with subvertical to overturned attitude is located below the salt canopy and represents an exceptional field example of such features, which are rarely described in the literature (Davison et al. 1996; Ringenbach et al. 2013). The Tazoult ridge plunges both to the NE and SW at its terminations. A diapiric weld forms the NE termination of the ridge, which is overstepped by Late Aalenian–Early Bajocian platform carbonates. These carbonates, however, fossilize the entire Tazoult ridge, as also observed along the cross-section in Figure 5b and in its SW termination. The proposed basement normal fault at depth is inferred by the variations in thickness of the lower Pliensbachian–Early Aalenian depositional units in both flanks of the Tazoult ridge in agreement with the regional rift setting (Fig. 2; Frizon de Lamotte et al. 2008).

Further to the basin centre is the Imilchil diapiric system. It consists of interrelated diapir walls and elongated minibasins mildly deformed during Cenozoic shortening, from which the Tassent and Ikkou ridges and adjacent minibasins are shown here (Fig. 6a). The cores of the ridges in this area contain a significant component of Middle Jurassic gabbro (Michard et al. 2011) and scattered slivers of Hettangian limestones. The Middle Jurassic gabbro often forms more than 50% of the exposed lithologies and in some ridges it may constitute the whole diapiric core. However, these rocks are always younger than the enclosing materials as indicated by the radiometric ages of the intruded bodies as well as the cross-cutting relationships of the associated subvolcanic and volcanic bodies with the Jurassic succession (Hailwood & Mitchell, 1971; Fadile 2003). Thick Pliensbachian–Bajocian mixed carbonate–siliciclastic strata comprise unambiguous halokinetic sequences with diagnostic structural and stratal relationships along the northern limb of the Tassent ridge (Fig. 6b). Middle Jurassic strata (Bathonian and Callovian in age) seal the Ikkou ridge and thus record the end of its diapiric activity (Fig. 5c). The most outstanding characteristic of the Imilchil diapiric region is the diachronity in the subsidence of the minibasins. Up to 2.5 km thick Toarcian–Lower Bajocian strata comprise the main fill of the Ikassene basin, <1.9 km of Upper Bajocian–Bathonian strata dominate the Lake Plateau minibasin fill, and c. 2 km of Bathonian–Lower Callovian sediments are the main Ikkou basin fill (Fig. 6). SE of the Amagmag Ridge, the Almghou minibasin (Fig. 1b) contains a Toarcian–Lower Bajocian halokinetic succession >1 km thicker than the time-equivalent fill of the Lake Plateau and Ikkou minibasins. Thickness variations within minibasins record shifts of the basin depocentres and lateral

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**Fig. 2.** Synthetic chart showing the timing of most important geodynamic processes in the Central High Atlas. Data according to (1) Marzoli et al. (2011), (2) Frizon de Lamotte et al. (2008), (3) Haddoumi et al. (2010), (4) Michard et al. (2011) and (5) Charrière et al. (2009).
Fig. 3. (a) Halokinetic hooks on the southern limb of the Moussa diapir. HS, halokinetic sequence. (b) Field view of the eastern termination of the Moussa diapir. On the northern flank, Dogger beds lay unconformable on top of Hettangian layers. (c) Field view of the Toumliline diapir, exposing Triassic salts. (See Fig. 1 for location.)

Fig. 4. View of the Taghia diapiric pedestal, in the central part of the Jbel Azourki ridge. Halokinetic strata can be seen on the western flank of this structure. In its central part, remnants of the collapsed diapir roof are also found. (See Fig. 1 for location.)
Fig. 5. (a) Geological map of the Tazoult area. (See Fig. 1 for location.) (b) Cross-section across the Tazoult salt wall. The uppermost post-diapiric Dogger units allow restoration and differentiation of diapiric and Alpine deformation (here c. 10% shortening). (c) Halokinetic hooks and wedges on the northern limb of the Tazoult ridge. (d) Map view of the halokinetic sequences on the SW termination of the Tazoult ridge. (e) Steep halokinetic hooks below the Tazoult canopy. (f) Panoramic view of the Lias to Dogger sedimentary succession on the southern flank of the Tazoult ridge, showing a fanning attitude from overturned to gently dipping beds away from the ridge.
Fig. 6. (a) Geological map of the Imilchil area. (See Fig. 1 for location.) (b) ‘Le Vélodrome’: halokinetic wedges on the northern flank of the Tassent ridge in the Imilchil area. (c) Halokinetic strata on the flank of the Ikkou ridge. (d) Panoramic view of the Lake Plateau minibasin. (e) Composite cross-section across the Imilchil minibasin system.
moves of their substrate. Maximum subsidence becomes younger from NW to SE through the Ikassene, Lake Plateau and Ikkou minibasins (Fig. 6d). Sedimentation rates of about 2 km Ma⁻¹ occurred during periods of maximum minbasin subsidence.

Discussion: evolution of the Central High Atlas diapiric basin

Previously, Jurassic ridges in the Central High Atlas have been related to transpressional tectonics and Middle Jurassic plutonism (Gonzague Dubar 1938; Laville & Harmand 1982), preceded by Early Jurassic diapirism (Bouchouata et al. 1995; Michard et al. 2011). Evaporites are, however, observed in only a few ridges (e.g. Ikerzi and Toumliline), around the southwestern closure of the Central High Atlas Jurassic basin and in scarce relics within the remaining ridges and diapirs. In addition, large salt pedestals are inferred from gravity modelling below the Toumliline ridge and beneath the Tassent ridge (Ayarza et al. 2005). Scarcity of Triassic evaporites at outcrop could result from the original configuration of the Late Triassic basin associated with a variable distribution of evaporites or/and from post-Triassic processes that could result from a combination of the following factors: (1) extrusion to the sea floor and seawater dissolution during passive diapir growth; (2) extrusion and hydrothermal evaporite dissolutionfavoured by Middle Jurassic plutonism; (3) potential extrusion during Cenozoic diapir rejuvenation; (4) surficial dissolution during Tertiary uplift and exhumation of the Central High Atlas. In this sense, it is interesting to highlight that c. 61% of the Tassent ridge outcropping core is formed by subvolcanic bodies with emplacement ages >10 myr younger than the enclosing strata (Hailwood & Mitchell 1971; Armando 1999; Bensalah et al. 2013). This entails a large amount of replaced material, which in our opinion could correspond to the missing evaporite rocks. Nevertheless, overpressured shale could also have played a significant role in the diapiric evolution of the Central High Atlas.

The angular relationship between halokinetic strata and diapiric ridge walls in the Jbel Azourki and Tazoutl area shifts from subparallel to high angle at the top of the Hettangian–Pliensbachian strata (Fig. 7). Syndepositional faulting and hooks on a scale of hundreds of metres associated with the Lower Jurassic beds are interpreted here as the result of initial pillow growth followed by reactive and active diapirism over 18 myr during the Hettangian–Pliensbachian. After this period, thick Toarcian–Aalenian mixed carbonate–siliciclastic eastward prograding platforms stacked in halokinetic sequences against the wall of the growing diapirs. These tens of metres thick sequences might record the passage to passive diapirism, which lasted over 12 myr ending in the Late Aalenian in the Jbel Azourki–Tazoutl area. We interpret this shift to passive and more extrusive diapir evolution as triggered by sediment loading as described in other similar scenarios (Demercian et al. 1993; Diegel 1995). Additionally, the changing nature of the stratigraphic succession may also control the variation of the cut-off angle on the diapir flank (Alsop et al. 2000). The diapir activity shift towards the Imililch area is indicated by the age of the minibasins, with observed halokinetic strata of Pliensbachian to Callovian age (Fadile 2003). Based on stratal patterns and available biostratigraphic data (Fadile 2003) minibasin subsidence occurred over 13.7 myr for the Ikassene minibasin and 3 myr for the Lake Plateau and Ikkou minibasins (Figs 6 and 7).

Conclusions

Field and remote sensing mapping and structural analysis of the study area in the Central High Atlas Jurassic System have been used to identify ten diapiric ridges and eight minibasins. Detailed study of the Jbel Azourki, Tazoutl, Tassent and Ikkou ridges and associated minibasins provide multiple examples of halokinetic strata. This analysis showed that diapiric activity migrated from the margin to the centre of the basin and from the west to the east from Lias to Dogger times.

This new work revolulonizes understanding of the Central High Atlas, the structure of which is best interpreted as a diapiric basin, characterized by intense syn- and post-rift diapirism and minibasin formation. The Jurassic Central High Atlas basin shares many features with other basin-fills deposited on a mobile substrate (Cobbold & Szatmari, 1991; Vially et al. 1994; Rowan & Vendeville, 2006; Callot et al. 2012; Davison et al. 2012).

Probably the strongest analogy is, however, to the Moroccan passive margin (Tari et al. 2003; Hafid et al. 2006) and Tertiary diapirism of the Red Sea (Mart & Ross 1987; Davison et al. 1996; Bosworth et al. 2005). Alpine inversion of the Central High Atlas is here interpreted as overprinting the well-recognized Jurassic diapiric basin and mostly focused at the basin margins.

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References

Alsop, G.L., Brown, J.P., Davison, I. & Gibling, M.R. 2000. The geometry of drag zones adjacent to salt diapirs. Journal of the Geological Society, London, 157, 1019–1029.
Souhel, A., Canérot, J., Elbehari, F., Chafki, D., Ghribi, A., El Harbi, K. & Bouchouата, A. 2000. The Liassic carbonate platform on the western part of the central High Atlas (Morocco): Stratigraphic and paleogeographic patterns. Mémoires du Muséum National d’Histoire Naturelle, 182, 39–56.

Tari, G., Molnár, J. & Ashton, P. 2003. Examples of salt tectonics from West Africa: A comparative approach. In: Arthur, T., MacGregor, D.S. & Cameron, N.R. (eds) Petroleum Geology of Africa: New Themes and Developing Technologies. Geological Society, London, Special Publications, 207, 85–104.

Teixell, A., Arboleya, M.-L. & Julivert, M. 2003. Tectonic shortening and topography in the central High Atlas (Morocco). Tectonics, 22, doi:10.1029/2002TC001460, 002003.

Téxon, E. & Teixell, A. 2008. Sequence of thrusting and syntectonic sedimentation in the eastern Sub-Atlas thrust belt (Dades and Mgoun valleys, Morocco). International Journal of Earth Sciences, 97, 103–113.

Trusheim, F. 1960. Mechanisms of salt migration in northern Germany. AAPG Bulletin, 9, 1519–1540.

Vially, R., Letouzey, J., Benard, F., Haddadi, N., Deforges, G., Askré, H. & Boudiema, A. 1994. Basin inversion along the North African Margin, the Sahara Atlas (Algeria). In: Roure, F. (ed.) Peri-Tethyan Platforms. Technip, Paris, 79–118.

Zayane, R., Essaïfi, A., Maury, R.C., Pié, A., Laville, E. & Bouabdel, M. 2002. Cristallisation fractionnée et contamination crustale dans la série magmatique jurassique transitionnelle du Haut Atlas central (Maroc). Comptes Rendus, Géoscience, 334, 97–104.

Ziegler, P.A., Cloetingh, S. & Vanwees, J.-D. 1995. Dynamics of intra-plate compressional deformation: The Alpine foreland and other examples. Tectonophysics, 252, 7–59.

Zouaghi, T., Bedir, M. & Inoubli, M.H. 2005. 2D seismic interpretation of strike-slip faulting, salt tectonics, and Cretaceous unconformities, Atlas Mountains, central Tunisia. Journal of African Earth Sciences, 43, 464–486.

Zouaghi, T., Bedir, M., Ayed-Khaled, A., Lazzez, M., Soua, M., Amri, A. & Inoubli, M.H. 2013. Autochthonous versus allochthonous Upper Triassic evaporites in the Sbiba graben, central Tunisia. Journal of Structural Geology, 52, 163–168.

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