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A Late Cenozoic age for long-wavelength surface uplift of the Atlas Mountains of Morocco

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ABSTRACT

The Atlas Mountains have been uplifted by two mechanisms: Cenozoic thickening of the crust and thinning of the mantle lithosphere due to a buoyant thermal anomaly, previously inferred by indirect criteria to have started some 15 Ma. Because crustal shortening-related uplift and mantle-related uplift affect the topography at different spatial scales, we use scattered direct surface evidence to clarify the palaeoelevation dynamics. Uplifted Messinian shallow marine sediments in the southern margin of the Saïss Basin and in the northern Middle Atlas, tilted Pliocene lacustrine deposits in the Saïss Basin and in the piedmont of the southern High Atlas and drainage-network reorganization in the Saïss Basin underscore the long-wavelength rock uplift of the Atlas domain of mantle origin. The low erosion of the aforementioned deposits indicates that such uplift is a true surface uplift that occurred in post-Miocene times at a minimum rate ranging from 0.17 to 0.22 mm yr^{-1}.

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Introduction

The timing of the rise of mountains is important in understanding the relationship between tectonics and erosion. It plays a critical role in determining the degree to which various mechanisms – crustal thickening, thinning of the mantle lithosphere – contribute to the elevation of topography. Uplift of mountains has also profound effects on the moisture distribution at continental scale and consequently, the potential generation of orographically controlled rain shadows and aridification (e.g. Sepulchre *et al*., 2006). One of the main difficulties in establishing uplift histories lies particularly in defining palaeoaltitudes (e.g. Ghosh *et al*., 2006). This is why the occurrence at elevation of marine sediments or of deformed palaeohorizontal markers can provide powerful geological evidence in unravelling the complex uplift history of mountainous regions, such as the Atlas of Morocco, where mountain-building processes have received great attention in recent years.

The High, Middle and Anti-Atlas of Morocco are mountain belts that reach high elevations in the foreland of the Rif-Tell orogen, built at the Iberia-Europe plate boundary in the Western Mediterranean (Fig. 1). The High and Middle Atlas are 100 km wide, intracontinental fold-thrust belts (Mattauer *et al*., 1977) in which mean elevation locally exceeds 2600 and 2000 m respectively (Fig. 1a). Cenozoic inversion of a system of Mesozoic rifts led to crustal thickening that uplifted these mountain belts with respect to the adjoining plains. However, the Atlas mountain belts are surrounded by peripheral plateaux and plains in which the mean elevation is above ~1200 m.

Cenozoic tectonic shortening in the Atlas mountains is small, ranging from 15% to 24% in the central High Atlas (Teixell *et al*., 2003), < 10% in the Middle Atlas (Gomez *et al*., 1998; Arboleya *et al*., 2004), and even less in the Anti-Atlas. Accordingly, crustal thickening is insufficient in accounting for the high topography, and the system is isostatically undercompensated at crustal level (Van Den Bosch, 1971; Makris *et al*., 1985; Ayarza *et al*., 2005). Sub-crustal phenomena, such as a hot, thinned or delaminated lithosphere, have been proposed as an alternative reason for the elevated topography (Seber *et al*., 1996; Ramdani, 1998; Teixell *et al*., 2003). Recent modelling of the lithospheric structure based on potential fields has argued for a thinned lithospheric mantle beneath the Atlas mountains of Morocco (Fig. 1), implying that 1000 m of the topography is supported by mantle processes in the Atlas (Teixell *et al*., 2005; Zeyen *et al*., 2005; Missenard *et al*., 2006; Fullea *et al*., 2007). Based on indirect evidence, such as the age of the alkaline volcanism related to the thinned structure, Teixell *et al*. (2005) and Missenard *et al*. (2006) inferred that the main episode of long-wavelength, mantle-related uplift started some 15 Ma.

In this paper, we present a new model, based on robust geological arguments, for the timing of large-scale topographic doming in the Moroccan Atlas system. We combine new and published scattered observations, such as elevated marine sediments, tilted palaeohorizontal markers and drainage-network reorganization, that taken as a whole indicate a Late Cenozoic (post-Miocene to post-Late Pliocene) surface uplift, more recent than hitherto inferred, and locally exceeding 1000 m.

Geological evidence for Late Cenozoic uplift in Morocco

Uplifted Messinian-age marine deposits on the northern flank of the Middle Atlas

Neogene marine deposits crop out in the northern flank of the folded Middle Atlas, in the Skoura area (Fig. 1b). These correspond to shallow marine sandstone, mudstone and coral reef formations, up to 200 m thick, that accumulated on a gulf south of the

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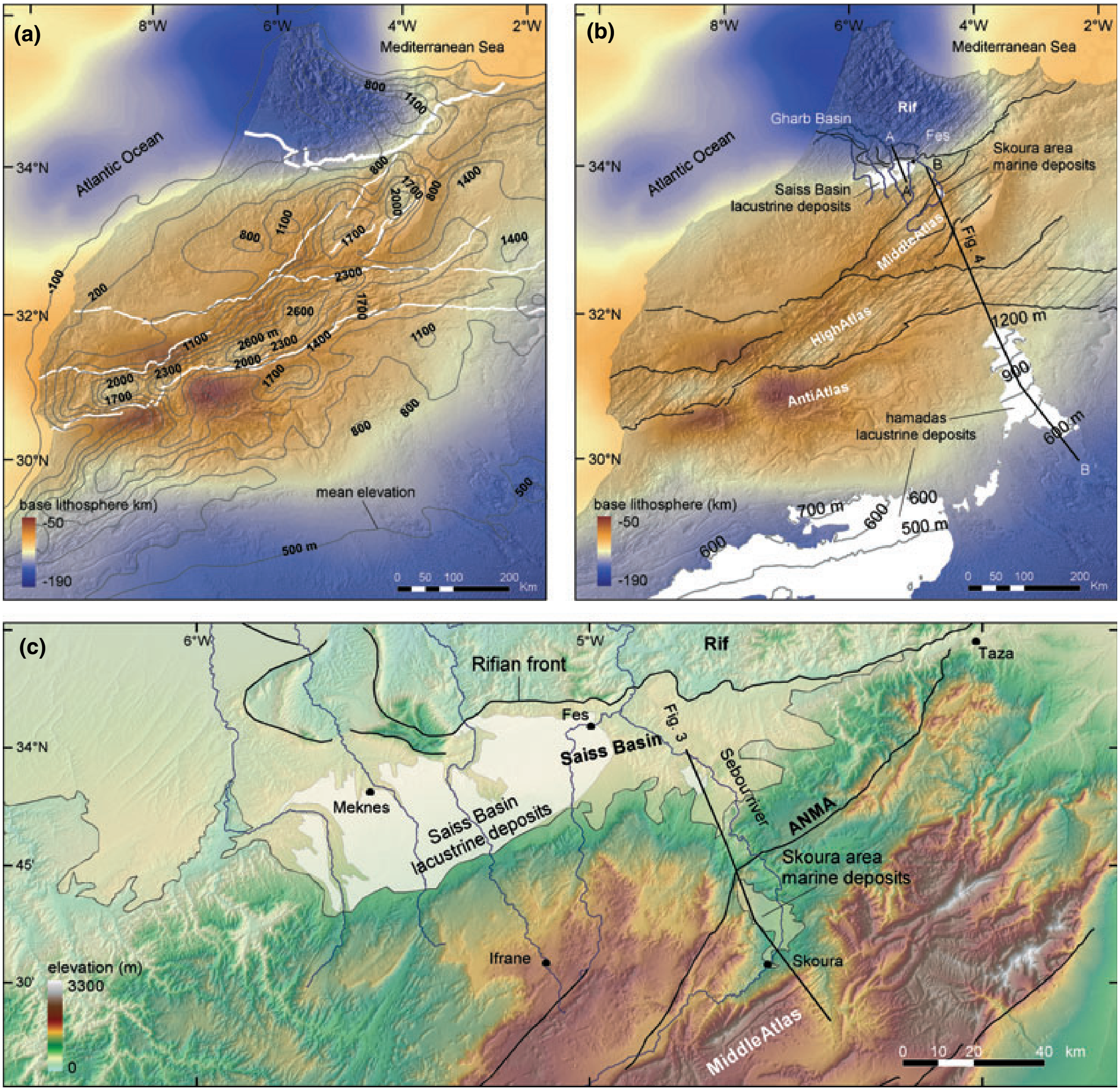

Fig. 1 (a) Map of Morocco indicating: white, the boundaries of the deformed chains and colours, the depth of the base of the lithosphere (after Fullea *et al*., 2007). Contour lines (grey) show the mean elevation calculated by a 30-km diameter moving window. (b) Location of the palaeoelevation criteria. Plotted is the drainage pattern of the northern flank of the Middle Atlas, where rivers cut through the ENE-trending Saïss Basin filled with lacustrine deposits during the Late Pliocene; thick line represents the Sebou River. Contour lines (grey) of the Lower Pliocene lacustrine deposits in the Sahara region show an overall large-scale tilting to the SSE. Black line corresponds to the transect in Fig. 4. (c) Topographic map (SRTM90) showing contours of the Saïss Basin, and of the Late Pliocene lacustrine deposits of the Saïss Basin. The Sebou River and its tributaries (blue lines) that drain the northern flank of the Middle Atlas flow to the north, and incise the Late Pliocene age lacustrine limestone of the Saïss Basin before entering the Rifian thrust front. Such drainage pattern indicates a post-Pliocene tilting of the Saïss Basin to the north.

margin of the Rifian foreland basin (Saïss Basin) during the Tortonian and Messinian (Martin, 1968; Charrière, 1984, 1989; Charrière and Saint-Martin, 1989). Almost undeformed Messinian deposits unconformably overlap folded Mesozoic strata (Figs 2 and 3). In the Skoura area, the Messinian marine deposits reach 1200 m asl, whereas, in the southern margin of the Saïss Basin, they reach an elevation of ~850 m (at 4º42′52″W, 33º48′53″N). This implies a rock uplift of ~850 and ~1200 m respectively. The reverse offset of the base of these deposits on both sides of the deformed zone comprising the Northern Middle Atlas Fault zone (ANMA) and the two thrust faults to the north (Fig. 3) is at most 250 m, which is their actual difference in elevation. This, together with the unconformable nature of the deposits, indicates that they postdate the main

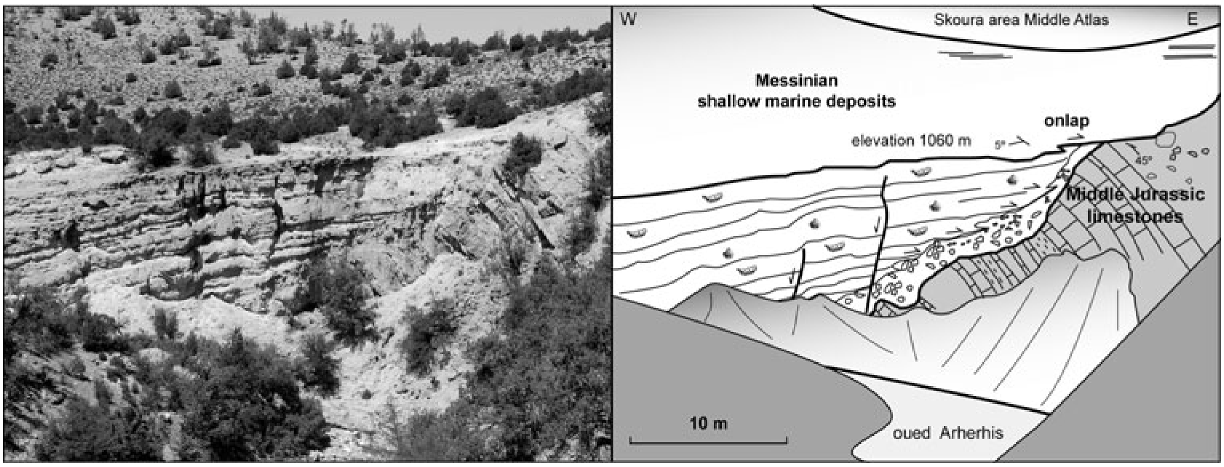

Fig. 2 Photograph of the youngest marine deposits preserved in the Skoura area (Middle Atlas). These shallow marine deposits are Messinian in age and they are almost not affected by contractional deformation. The Messinian marine deposits have been uplifted 1000–1200 m since their deposition between 7.1 and 5.3 Ma.

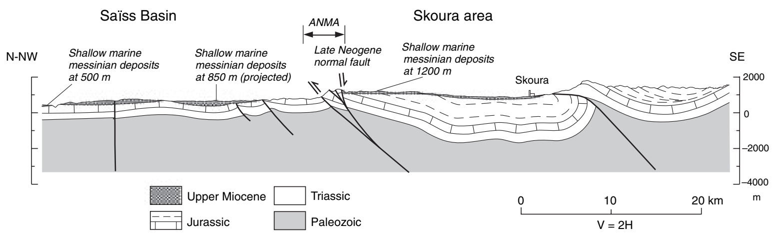

Fig. 3 Cross-section of the northern flank of the Middle Atlas across the Skoura area (location in Fig. 1c). The Miocene sediments lie unconformably upon the Mesozoic-deformed rocks. Messinian marine shallow deposits reach an elevation of 850 and 1200 m in the southern margin of the Saïss Basin and in the Skoura area respectively. ANMA, North Middle Atlas Fault zone.

finite crustal shortening and thickening of the northern sector of the Middle Atlas. Further north (20 km) in the Saïss Basin, the Messinian shallow marine deposits reach 500 m (4º45′W, 33º59′30″N), implying a northward tilt of about ~1º of the northern flank of the Middle Atlas (north of the ANMA, Fig. 3) over 20 km, at the very most since the end of the Miocene (Fig. 3).

Orogen-directed drainage network in the southern Rifian front and tilted Late Pliocene lacustrine deposits in the Saïss Basin

The Saïss Basin constitutes a foreland depression between the Rifian orogenic front and the Middle Atlas. Striking ENE, it projects as a corridor of low lands from the East of the city of Fes to the Atlantic coast, linking with the Gharb coastal basin. The rivers draining from the northern slopes of the Middle Atlas (the Sebou River being the most prominent amongst these) enter the Saïss Basin flowing north to north-westward (Fig. 1b). Once in the basin, the rivers do not deviate to follow the basin axis, as would be usual in foreland basins, but keep their flow direction to cross the Rifian front and enter the Rif orogenic belt. Further north, rivers eventually turn towards the West to reach the Atlantic Ocean (Fig. 1b).

Only a superimposed large-scale northward tilt of the surface, dominating over the topographic building of the Rif wedge, can explain the paradoxal drainage pattern in the Saïss Basin in which rivers flow opposite to the transport direction (Bargach *et al.*, 2004) of the external Rif thrust sheets. Chronological constraints on the development of this anomalous northward flow are provided by (1) up to 20 m thick Late Pliocene age lacustrine limestones in the Saïss Basin (Taltasse, 1953; Martin, 1981; Feinberg, 1986) and (2) by volcanic activity developed in the Middle Atlas during the Quaternary (0.5–1.8 Ma, cf. Harmand and Cantagrel, 1984; El Azzouzi *et al.*, 1999). Cross-sections of the Saïss Basin (Margat and Taltasse, 1953; Martin, 1981) show a tilt of the lacustrine strata to the North (segment A–A′ on Fig. 4). These lacustrine deposits are incised by the northward-flowing tributaries of the Sebou River (Fig. 1c) and are covered by northward flowing Quaternary lavas from the Middle Atlas. The geological record and drainage pattern both indicate a recent tilting of the Saïss Basin to the north that postdated the Late Pliocene and took place prior to 0.5 Ma, which is the age of the youngest dated lavas. Moreover, as discussed above, elevated Messinian shallow marine deposits imply an uplift of ~850 m for the southern margin of the Saïss Basin (Fig. 4).

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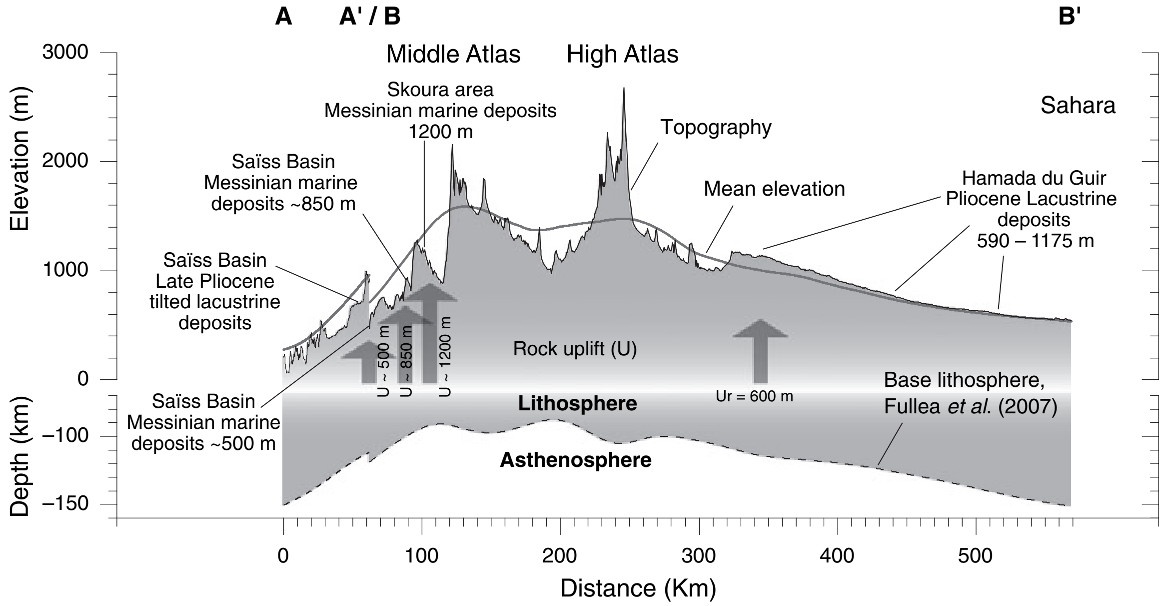

Fig. 4 Topographic transect illustrating the post-Miocene doming of the Atlas Mountains and plateaux of Morocco (location in Fig. 1b). Indicated are the rock uplift criteria used in this work. Mean elevation is calculated by a moving window of 100 km diameter. The position of the lithosphere/astenosphere boundary modelled by Fullea *et al.* (2007) shows a good correlation with the long-wavelength doming.

Tilted Early Pliocene lacustrine deposits south of the High Atlas

South of the Atlas thrust front, in the northern Sahara craton, Neogene terrestrial carbonates form large tablelands (called 'hamadas' in the Sahara region) over hundreds of kilometres. In Morocco, these carbonate deposits are preserved SE of the High Atlas and S of the Anti-Atlas (the Hamadas of Guir and Draa respectively; Fig. 1b), where they were attributed to the end of the Early Pliocene on the basis of gastropod fauna (Lavocat, 1954). The hamada carbonate deposits are several metres thick and lie unconformably on folded Palaeozoic-to-Cretaceous rocks of the Anti-Atlas, being only slightly dissected (≤350 m) by current drainage. They have been interpreted as lacustrine deposits (Lavocat, 1954; Thiry and Ben Brahim, 1997), thus defining a palaeohorizontal surface. However, they are presently tilted towards the SSE with a difference in elevation of more than 600 m over 200 km (Figs 1b and 4), again indicating a Late Cenozoic, broad surface deformation that is unrelated to tectonic shortening and loading in the area, which would have tilted the foreland lacustrine strata northwards.

Discussion and conclusions

When calculated at lithospheric scale, i.e. in a 100-km diameter moving window, mean elevation in the Atlas Mountains and plateaux of Morocco describes a broad topographic swell on which the High and Middle Atlas are superimposed (Fig. 4). Pliocene lacustrine deposits in Morocco have been tilted, and Late Miocene marine deposits have been uplifted, both defining a dome-like shape over 500 km wide that mimics the pattern of the mean elevation (Fig. 4). Such broad-scale surface deformation coincides with the NE-trending imaged thinning of the lithosphere in this region (Figs 1 and 4), the buoyant mantle anomaly giving a simple geodynamic explanation for recent rock uplift.

Although flexural subsidence and isostatic rebound due to erosional unloading could have triggered a similar pattern of deformation, such processes are not realistic explanations, neither in the Sahara region nor in the northern flank of the Middle Atlas. The propagation of the Rif thrust wedge initiated the subsidence and deepening of the Rifian corridor during the Late Miocene (Chalouan *et al.*, 2001). Shallow marine Messinian deposits lie at 850 m in the Saïss Basin and at 1200 m in the Skoura area, indicating that large-scale uplift exceeded the tectonic loading associated to the building of the Rif wedge. At Skoura, the marine deposits lie in a wide palaeodepression surrounded by pre-existing mountains of the Middle Atlas, and the incision of these deposits by the present-day fluvial network is minor (< 200 m). This suggests a small contribution by erosionally driven isostatic rebound to their present high elevation. Moreover, the widespread preservation of Mesozoic series in the High and Middle Atlas and the old ages of apatite-fission tracks recorded (Barbero *et al.*, 2007) imply a low amount of erosion since the onset of mountain building in the Atlas. In the southern part of the hamadas, Quaternary deposits correspond only to a thin veneer; hence, sedimentary loading as a mechanism to tilt the Pliocene lacustrine deposits can be ruled out. The southern piedmont of the High Atlas is incised by rivers, such as the Ziz, between the Hamada du Guir and the Anti Atlas. In the highest section of the Hamada du Guir tableland, the amount of incision is maximum and reaches 350 m. Therefore, a

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part of the whole tilt of the Hamada du Guir is attributed to erosionally driven flexural isostatic uplift. In the Colorado piedmont, at the North Platte-South Platte interfluve, where the same magnitude of erosion between piedmont deposits and current rivers has been reported, estimation of erosionally driven isostatic uplift is about 200 m (Leonard, 2002). Similarly, in the case of the Hamada du Guir a positive feedback between mantle-related uplift and erosionally induced uplift probably did take place, and erosion may also be responsible for some 200 m (1/3) of the total relative rock uplift. Given the low values of erosion in the transect studied (Fig. 4), the described values of rock uplift tend to equate to true values of surface uplift.

A widespread stage of alkaline volcanism in the Atlas domain started in mid-Miocene times. Teixell *et al.* (2005) attributed this to the change in the mantle thermal structure that led to the thinning of the lithosphere. Consequently, the mantle-driven uplift was thought to be contemporaneous (Teixell *et al.*, 2003, 2005; Missenard *et al.*, 2006). The present study argues for an uplift associated to the mantle thermal anomaly that is mostly younger than the Miocene volcanic activity, and probably contemporary with that of the Plio-Quaternary. The amount of this post-Miocene uplift as recorded at Skoura (*ca.* 1000 m), is a large fraction of the total thermal uplift estimated by Missenard *et al.* (2006) for the Atlas domain.

The Guercif Basin lies in the continuation of the Rifian corridor, East of the Saïss Basin. Progressive emergence of deep marine sediments was dated by Krijgsman *et al.* (1999b), who interpreted it mainly as a result of uplift, initiated some 7.1 Ma, attributed to tectonic deformation associated to the Rifian orogen. Missenard *et al.* (2006) hypothesized that this uplift could be related to the mantle thermal anomaly, although a part of it is due to post-Tortonian tectonic shortening as documented by Gomez *et al.* (2000). The Messinian Salinity Crisis resulted from the closure of the Rifian corridor and the Betic Strait that connected the Atlantic to the Mediterranean (Hsü *et al.*, 1973; Krijgsman *et al.*, 1999a). Therefore the large-scale, mantle-driven uplift of the northern Atlas domain we document might have been a process initiated immediately after the Miocene marine sedimentation, not before, and it probably enhanced closure of one of the marine passageways, thus contributing to the Messinian Salinity Crisis.

In summary, we infer that the doming of the Atlas Mountains and plateaux of Morocco, which is mainly a consequence of the mantle thermal anomaly, mostly occurred after the Miocene. Based on new and published scattered surface data, our study gives the first direct evidence for the geophysically inferred ~1000 m of surface uplift generated by the SW-NE lithospheric thinning of north-western Africa, the mean rate of which reaches at least 0.17 to 0.22 mm yr^{-1} (1200 m of uplift since the Messinian, 7.1–5.3 Ma, at the Skoura area, where lithospheric thinning is maximum). It should also be emphasized that the current mean elevation of the Atlas system of mountains and plateaux is young in comparison with the Cenozoic crustal thickening that built the deformed belts of the High and Middle Atlas (mostly Oligocene and Miocene, Görler *et al.*, 1988; Tesón and Teixell, 2006 and references therein). This gives an explanation to the enigmatic Late Cenozoic uplift inferred by de Sitter (1952) to account for renewed erosion and incision of river canyons in the Ziz valley. It remains to be ascertained what the influence of the Late Cenozoic climatic change was, and to what extent this amplified the erosional response (e.g. Molnar and England, 1990) to the new boundary conditions.

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