When did the Moroccan High Atlas Mountains get high? Constraints on neo- and active tectonics from fluvial geomorphology and palaeoaltimetry

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Abstract: The surface uplift of mountain belts can have profound effects on precipitation patterns and moisture distribution, potentially resulting in the development of orographic rain shadows and aridification. Within Africa, the Moroccan High Atlas Mountains are the highest (2-4km elevation) topographic relief formed by Alpine tectonics. However, the uplift history of the Moroccan High Atlas has been a matter of debate for many years. New palaeoaltimetry data from Late Miocene lacustrine limestones that suggest that the High Atlas had a mean altitude of 1200 ± 500 m through the Middle/Late Miocene. While geomorphic data (river long profiles and river terrace data) support models that propose ~1000 m of elevation have been gained during the Plio-Quaternary. These new data provide independent constraints on the timing and magnitude of orogenic development in the High Atlas driven by mantle upwelling and fault reactivation.

Key words: Morocco, Neotectonics, Palaeoelevation, Fluvial Geomorphology, Uplift

Introduction

The High Atlas Mountains are a Cenozoic mountain belt trending ENE-WSW for over 2000 km from Morocco in the west to Tunisia in the east, and have the most significant relief in North Africa rising to over 4000 m in elevation. Alpine shortening resulted in the inversion and uplift of Mesozoic rift basins sometime between the Late Eocene and Quaternary (e.g., Frizon de Lamotte et al., 2000; Balestrieri et al., 2009), developing a bivergent mountain chain.

However, the timing of topographic growth of the High Atlas Mountains of Morocco has proved to be a contentious topic. Several lines of evidence point to two phases of surface uplift. Deposition of two distinct conglomeratic units within the Ouarzazate foreland basin (Fig. 1) have been related to phases of active uplift triggering enhanced erosion in the hinterland (e.g., El Harfi et al., 2001) with intervening lacustrine facies being interpreted by El Harfi et al. (2001) as evidence for a period of tectonic quiescence during the Middle Miocene. Similarly, the regional unconformities of the late Eocene/Oligocene (~ 35 – 25 Ma) and early Pliocene (~ 5 – 1 Ma) have been attributed to pulses of deformation separated by tectonic quiescence (Fraissinet et al., 1988). In contrast, apatite fission-track analyses (Missenard et al., 2006; Barbero et al., 2007; Balestrieri et al., 2009) have constrained the onset of exhumation to the late Oligocene (~27 Ma). While continuous tectonic activity and structural shortening throughout the Oligocene to Pliocene has been deduced by Teson and Teixell (2008) using syn-sedimentary relationships in the fold and thrust belt, all suggesting a single continuous deformation event.

Here we investigate the palaeoelevation of the High Atlas from the Middle/Late Miocene to the present using dual stable isotope ratios (Horton and Oze, 2012) from lacustrine carbonates deposited in the Ouarzazate Basin to investigate when topography was generated in the High Atlas Mountains prior to the Plio-Quaternary. We then address the magnitude and rate of Plio-Quaternary uplift using fluvial geomorphology of rivers flowing southwards into the Ouarzazate Basin.

Ouarzazate Basin

The Ouarzazate Basin (Fig. 1) developed as the southern foreland basin to the High Atlas Mountains in the Cenozoic and contains a comprehensive record of sedimentation from that time (Teson et al., 2010). From 20 Ma to ~ 0.5 Ma, the basin was characterized by endorheic drainage and continental sedimentation in alluvial fan and palustrine environments (El Harfi et al., 2001). The ~ 1000 m sedimentary fill of the basin is tripartite, with Middle Miocene conglomerates (Ait Ouglit Fm.), Middle-Late Miocene lacustrine limestones, marls and gypsum layers, and Plio-Quaternary conglomerates (Ait Ibrinn and Ait Seddrat members of the Ait Kandoula Fm., respectively (El Harfi et al., 2001).

Magnetotratigraphic evidence of the succession (Benammi et al., 1996; Teson et al., 2010) demonstrates that the deposition of lacustrine facies of the Ait Ibrinn Mb. took place from ~13.5 – 5 Ma. Therefore, the carbon and oxygen isoerte composition of these sediments can provide a record of the mean catchment elevation for Ouarzazate Basin lakes in the Middle-Late Miocene. At ~0.5 Ma the headward erosion of the Draa River captured the drainage of the Ouarzazate Basin resulting in incision of the earlier deposits. The present day drainage pattern is dominated by the Dades-Draa River system and associated tributaries that drain southwards across the Southern Atlas Thrust front, exiting the basin south of the town of Ouarzazate (Fig. 1).

Miocene Palaeoelevation
Lake sediments can serve as powerful archives of palaeoclimatic and palaeoenvironmental information, including palaeotopography (Talbot, 1990). Carbonate sediments precipitated in lakes typically form in chemical equilibrium with lake water, reflecting the input of surface precipitation from the surrounding catchment, because the oxygen isotopic composition of modern precipitation exhibits a well-documented relationship with surface elevation (Bowen and Wilkinson, 2002). However, this original isotopic composition can be subsequently modified by evaporation, masking the original elevation signal. Comparisons of lake carbonate δ¹⁸O with the composition of lake inflow show that a strong covariance exists between the two isotopic ratios (Horton and Oze, 2012). This covariant relationship has a consistent slope (Horton et al., 2015) allowing combined δ¹⁸O and δ¹³C measurements to be used to correct for evaporative enrichment. The resulting parameter, referred to as ¹³C-excess, is strongly correlated to lake catchment elevation (Horton and Oze, 2012).

We sampled lacustrine carbonates from five sections of the Alt Ibrim Mb. in the Ouarzazate Basin, spanning 7.5 Myrs for palaeoelevation estimates. Two sections exhibit relatively constant isotope ratios, with no stratigraphically coherent shifts in either δ¹³C or δ¹⁸O. By contrast, the other three sections exhibit a ∼3‰ negative shift in both δ¹³C and δ¹⁸O (Fig. 2). Determining catchment elevation from ¹³C-excess first requires accounting for the impacts of other factors known to influence δ¹⁸O: latitude, continentality and temperature of carbonate precipitation. We apply normalizations of 2.9 ‰ and 0.6 ‰ to δ¹⁸O for the modern latitude of 31°N and coastal distance of 300 km, respectively. Accounting for lake temperature is more difficult, due to the absence of independent regional temperature estimates; we therefore apply a range of possible lake

![Fig. 1 Simplified geological map of the Ouarzazate region showing the main geological units present, key locations, trunk rivers and (where present) knickpoints (black circles). Rivers 7, 10 and 13 shown in Fig. 2 are also indicated. Light grey squares indicate locations sampled for isotope analysis (modified from Boulton et al., 2014).](image-url)
water temperatures of 20-35°C, resulting in normalizations of -1.0 to 1.9 % for $\delta^{18}O$ and 0.7 to 1.3 % for $\delta^{13}C$. As temperature is a second-order effect on lacustrine carbonate $\delta^{18}O$, this imposes an additional uncertainty to the elevation estimates of only $\sim$150 m. After correcting for these effects on our data, these sections produce catchment elevation estimates of 1.2 ± 0.5 km for the Middle-Late Miocene, suggesting that surface elevation was relatively stable for the $\sim$ 7.5 Myr that these data span.

![Fig. 2. Cross-plot showing $\delta^{18}O$ versus $\delta^{13}C$ measurements from lacustrine carbonates in the Ouarzazate Basin.](image)

**Plio-Quaternary Uplift**

Modern mean elevation of the High Atlas Mountains north of the sampled locations is $\sim$ 2300m and ranges from 1800 – 2600 m, further suggesting that $\sim$ 1000 m of surface uplift has occurred in the post-Miocene period. Similar magnitudes of surface uplift have also been proposed for Middle Atlas Mountains by Babault et al., (2008) who recognised Messinian marine deposits at 1200 m elevation and Pastor et al., (2015) using reconstructed river profiles indicating up to 1000 m of rock uplift.

![River profiles](image)

We quantitatively analysed the long profiles of 32 rivers that drain southwards across the Southern Atlas Fault (SAF) into the Ouarzazate Basin (Boulton et al., 2014). The majority of the rivers exhibit at least one knickpoint upstream of the thrust front (Fig. 3). The height of the knickpoints varies from 100 – 1300 m, with calculated incision at the range bounding fault ranging from 80-1040 m (Fig. 3). In map view, knickpoint locations generally plot along sub-parallel lines and there are no obvious relationships with lithological units for knickpoints exhibiting slope-break morphology. Channel reaches below slope-break knickpoints have higher mean concavities (0.76) than above the knickpoint. This observation combined with a lithological or river-capture origin for the knickpoints having been ruled out indicates that an increase in uplift rate along a planar fault zone during the Plio-Quaternary caused the initiation of the transient response (i.e., knickpoint formation) to a change in base-level observed in the river profiles.

The knickpoint elevation and magnitude of incision indicated by the river profile analysis indicates $\sim$ 1000 m of surface uplift has taken place in the Plio-Quaternary, supporting previous estimates and in accordance with Pre-Pliocene estimates of palaeoelevation.
Discussion and Conclusions

We show that the mean elevation of the catchments feeding the Tortonian Ouarzazate Basin lake system was ~1000 m lower than the present day mean elevation of the same region, consistent with estimates of rock uplift determined from river profile analysis of rivers flowing across the Southern Atlas Fault system (Boulton et al., 2014) and previous estimates for the magnitude of Quaternary surface uplift in the Middle Atlas (Babault et al., 2008). This result supports models for a two-phase development for the topography of the High Atlas. The sections measured span > 8 Myr during the Late Miocene, yet the derived paleoelevations are similar for each section, suggesting either that any uplift during this time period was balanced by denudation, or it was a period of tectonic quiescence. Both interpretations imply that tectonic deformation was not significantly changing the mean elevation of the mountain range; during the Late Miocene period and thus supporting increased rates of uplift during the Quaternary. This pulse of uplift is recorded in the fluvial systems through knickpoint generation and landscape rejuvenation as a response to reactivation of crustal-scale reverse faults. Offset Quaternary terraces in the Ouarzazate basin also suggest that active thrusting is occurring at the thrust front and may have stepped forward into the foreland basin (i.e., Arboleya et al., 2008; Pastor et al., 2012a).

Therefore, although current levels of seismicity along the SAF are low, the evidence of Quaternary active faulting combined with historical events (i.e., the 1960 Agadir earthquake) that are generally < 70 km in depth (Medina and Cherkaoui, 1991) suggests that the seismic hazard along the SAF may be higher than previously recognised.

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