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Successful combination of electron spin resonance, luminescence and palaeomagnetic dating methods allows reconstruction of the Pleistocene evolution of the lower Moulouya river (NE Morocco)

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A B S T R A C T

Based on a combination of Electron Spin Resonance (ESR) dating of quartz, luminescence dating of K-feldspar and palaeomagnetism, this study presents the first chronostratigraphic framework for the Pleistocene fluvial deposits of the lower Moulouya river in the Triffa basin (NE Morocco). K-feldspar $pIRIR_{225}$ and $pIRIR_{290}$ signals of all samples are saturated, suggesting fluvial deposition at least as early as the Middle Pleistocene (~0.39–0.80 Ma). Consequently, further chronological information was obtained with ESR dating of quartz grains from the ancient Pleistocene fluvial deposits. As for ESR, the multiple centres approach provides equivalent dose values derived from the Al and Ti centres that mostly agree within 1σ-error, suggesting complete signal resetting from the former during fluvial transport. ESR dating results yield Calabrian deposition ages for all river profiles from ~1.1 to ~1.5 Ma. These ages are remarkably consistent with the palaeomagnetic results: the occurrence of mostly reversed polarity in the deposits indicates a Matuyama age (>0.78 Ma). While low incision rates in the Triffa basin (0.025 ± 0.003 mm/a) related to thrusting activity during the Calabrian could be inferred, the fluvial record points to an acyclic and discontinuous sedimentation pattern over the last ~1.3 Ma. It thereby probably rules out climate as the main driver for fluvial aggradation in the lowermost sedimentary basin. At a regional scale, several indicators point to transient fluvial response resulting from major Quaternary tectonic activity along the Beni Snassen gorge, located directly upstream of the investigated basin. We suggest that a capture event at the margin of the uplifting Beni Snassen massif occurred between 1.04 and 1.36 Ma at the latest and subsequently led to the creation of the gorge.

1. Introduction

The investigation of fluvial archives is of significant interest for unravelling palaeoenvironmental changes linked to Quaternary climatic fluctuations (e.g., Macklin et al., 2002; Bridgland and Westaway, 2008) and/or long-term tectonic activity (e.g., Demir et al., 2012; Demoulin et al., 2017). In the western Mediterranean, a sharp contrast exists between the well-studied fluvial systems draining the Iberian Peninsula (e.g., Macklin et al., 2002; Santisteban and Schulte, 2007; Wolf et al., 2014; Benito et al., 2015), also on longer timescales (Schulte et al., 2008; Martins et al., 2010; Soria-Jáuregui et al., 2016; Cunha et al., 2017), and those draining the north-western part of Africa, which remain poorly investigated to date. This is especially true for the Quaternary fluvial landscape evolution resulting from interplays between tectonic and climatic drivers. With the exception of studies dealing with the reconstruction of palaeoenvironmental changes together with human-environment interactions on a few local river reaches

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in North Africa over the last ~30 ka (e.g., Barathon et al., 2000; El Amrani et al., 2008; Zielhofer et al., 2008, 2010), chronological data for river archives predating MIS 2 are almost absent in this region.

Consequently, the Pleistocene palaeoenvironment of North Morocco is as yet poorly investigated. Drained by the Moulouya river, one of the largest river systems in North Africa, the north-eastern part of Morocco is characterised by complex geodynamics due to its location within the convergent zone between the African and Eurasian plates (e.g., Meghraoui et al., 1996). Crustal deformation related to the main W-E striking deformational front between the Rif belt and the Atlas mountains affected the lowermost ~65 km-long reach of the Moulouya during the Pliocene and Quaternary (Barcos et al., 2014; Rixhon et al., 2017a). This resulted in contrasting fluvial environments on each side of a W-E striking thrust zone in this area: thick, stacked terraces in the footwall reach and a terrace staircase in the hanging-wall reach (Rixhon et al., 2017a). Nevertheless, the timing of fluvial aggradation and terrace formation over the Pleistocene remains very poorly known in the Moulouya valley and, overall, in all river systems draining this convergent zone in NE Morocco.

Establishing chronologies for river terrace sequences remains challenging, but represents a key task for understanding fluvial landscape development (Rixhon et al., 2017b). In the northern catchment of the lower Moulouya it has been shown that optically stimulated luminescence (OSL) of quartz reaches saturation at ~70 ka (Bartz et al., 2015). Alternatively, feldspar infrared stimulated luminescence (IRSL) dating may serve as a valuable tool for dating old Pleistocene deposits (Buylaert et al., 2012), as demonstrated by the studies of Cunha et al. (2008) and Martins et al. (2010) in the fluvial context. While IRSL ages may suffer from anomalous fading, leading to a loss of signal over time (e.g., Wintle, 1973; Huntley and Lamothe, 2001), elevated temperature post-infrared infrared (pIRIR) stimulated luminescence offers feldspar signals which are less or unaffected by anomalous fading (Thomsen et al., 2008; Thiel et al., 2011a). However, even for pIRIR signals, anomalous fading can result in luminescence signals which appear finite, but may reflect an equilibrium level between electron trapping and detrapping *via* anomalous fading. An athermal detrapping model (cf., Huntley, 2006; Kars et al., 2008) can be used to screen samples for this effect, and the reliability of this model has been tested in a range of studies (e.g., Li and Li, 2008; Kars and Wallinga, 2009; Guralnik et al., 2015). In contrast to luminescence methods, electron spin resonance (ESR) dating of optically bleached quartz grains potentially covers the whole Quaternary (e.g., Voinchet et al., 2010; Duval et al., 2017). In particular, the reliability of the method has been recently improved by the development of the multiple centres (MC) approach (Toyoda et al., 2000): the systematic measurement of both the Al and the Ti centres in quartz offers the possibility to produce more robust ages (Duval et al., 2017). In addition to the use of luminescence and ESR dating techniques, palaeomagnetic analyses have been applied to the same Moulouya deposits in order to independently check our newly established chronological framework based on numerical age estimates. Palaeomagnetism has long proven its usefulness to provide additional chronological constraints to river terrace deposits (e.g., Jacobson et al., 1988; Li et al., 1997; Sancho et al., 2016).

In summary, our study aims to (i) present the first geochronological framework for fluvial deposition in the lower Moulouya valley, based on a combination of ESR dating of quartz using the MC approach, luminescence dating and palaeomagnetic analysis applied on four different sections along the Moulouya river; (ii) compare the merits of each dating method; (iii) use luminescence dating techniques to study IRSL signals and field saturation, and (iv) provide new insights into the long-term geomorphological evolution of this region of Morocco.

2. Study area

2.1. Geodynamic background

The NW-SE convergence between Africa and Iberia from the Miocene to the Quaternary has strongly affected the northern part of Morocco. Crustal deformation in the Western Mediterranean most likely results from the shortening of the Betic-Rif mountain ranges and extension of the Alborán Sea (e.g., Fadil et al., 2006). Indicated by kinematic analyses of fault populations in the Rif and Tell Atlas, shortening directions and rates are characterised by an anti-clockwise block rotation of 15–25° (from NNE to NNW) and by movements of 1–2.3 mm/a, respectively (Meghraoui et al., 1996; Meghraoui and Pondrelli, 2012). The Rif mountain range showed NE-SW folding during the Quaternary characterised by left-lateral, strike-slip faults and associated overthrust structures (Meghraoui and Pondrelli, 2012). For instance, horizontal and vertical slip rates of ~0.9 and ~0.5 mm/a, respectively, have been determined for the Trougout fault in the northeastern Rif region (Poujol et al., 2014). Trend-topography surface analyses highlighted an E-W trending lithospheric dome in the eastern Rif and in the Beni Snassen massif (Barcos et al., 2014). The latter is affected by N-S shortening resulting in active deformations at its northern margin according to morphometric indicators (Barcos et al., 2014). A disequilibrium state of the Moulouya catchment is reflected by anomalies in its drainage network and the presence of large knickpoints (Barcos et al., 2014; Pastor et al., 2015; Rixhon et al., 2017a). Finally, deformation affecting Middle Pleistocene terraces in areas westward (Oued Kert) and eastward (Oujda region) of the Moulouya river was also reported (Ait Brahim et al., 2002).

2.2. The Moulouya catchment

2.2.1. Geological and geomorphological settings

The Moulouya, with a drainage area of ~74.000 km^2 (Fig. 1), represents the largest fluvial system in NE Morocco (Pastor et al., 2015). From its headwaters at the junction of the High and Middle Atlas to the outlet into the Mediterranean Sea, the ~600 km-long, SW-NE oriented main trunk flows across four successive basins filled by Neogene and Quaternary sediments: Arhbalou, Ksabi-Missour, Guercif and Triffa (Fig. 1; Pastor et al., 2015; Rixhon et al., 2017a). The upper reaches (Arhbalou basin), encompassing the southern to south-eastern foot slopes of the Middle Atlas and the northernmost flanks of the High Atlas, composed of Palaeozoic rocks deformed by the Hercynian orogeny. In the middle reaches (Ksabi-Missour and Guercif basins), the Moulouya drains the western flanks of the Moroccan High Plateaus. The Triffa basin, which forms the lowermost reach, is bordered by the Beni Snassen mountains to the south and the Kebdana mountains to the north (Fig. 2a; Ruellan, 1971; Boughriba et al., 2006). Both mainly consist of Mesozoic carbonate rocks, sandstone and slate formations (Ruellan, 1971; Khattach et al., 2004).

2.2.2. Fluvial archives in the lowermost Moulouya reach

Within the Triffa basin, our study area encompasses the ~20 km-long river reach draining the northwestern rim of the so-called Triffa plain and the Ouled Mansour plateau (Fig. 2b). Recently, Rixhon et al. (2017a) have highlighted contrasting fluvial environments on both sides of a W-E trending thrust zone. In the northern hanging wall (i.e., Ouled Mansour plateau), a terrace staircase encompasses three Pleistocene terrace levels, i.e., T1, T2 and T3 (Fig. 2b and c), whose bases lie at relative elevations of ~68, ~36 and ~26 m above the modern stream bed, respectively. The contact with