Eocene exhumation of the Tuareg Shield (Sahara Desert, Africa)

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ABSTRACT

The arch-and-basin geometry that characterizes North Africa was achieved at the end of Paleozoic times. It has been subsequently reactivated during the Mesozoic-Cenozoic with, in particular, the development of large topographic anomalies. Among these, the Tuareg Shield forms a topographic high in which the Pan-African basement reaches 2400 m above sea level (Hoggar core). While Cretaceous sedimentary remnants suggest a possible stage of subsidence during the Mesozoic, currently the area forms a swell, emphasized by Cenozoic volcanic episodes since 35 Ma. In this context, we present the first apatite (U-Th)/He thermochronological data acquired across this swell, with mean ages ranging from 78 ± 22 Ma to 13 ± 3 Ma. These results demonstrate the existence of a widespread Eocene exhumation of the shield before volcanic activity began, which reflects large-scale vertical processes. In the northeastern part of the swell, Cretaceous continental sedimentary remnants unconformably lying on the basement close to our samples evidence that they were near the surface at that time. This study shows that basement rocks have undergone subsequent heating at ~60–80 °C, suggesting a burial of more than 1 km after the Early Cretaceous. This conclusion can be possibly extended over the whole Tuareg Shield.

INTRODUCTION

Relief evolution of old basements is a key issue to understand intraplate tectonics and geodynamic relationships. Several topographic swells are visible in the northern part of the African continent (Fig. 1). Yielding controversial uplift ages, often associated with volcanic provinces, they suggest the involvement of sublithospheric processes (Sahagian, 1988; Wilson and Guiraud, 1992; Burke, 1996). The Hoggar and Aïr mountains, in the Tuareg Shield of North Africa, form one of these swells (Fig. 1). The age of the basement doming, which reaches 2400 m (mean elevation of ~1200 m), is thought to be related to Late Eocene to Holocene volcanic activity (Liégeois et al., 2005; Azzouni-Sekkal et al., 2007; Beccaluva et al., 2007). Previous apatite fission track data over the Hoggar, giving widespread Mesozoic ages, are too scarce for constraining precisely the age of the last exhumation phase (Carpena et al., 1988). The Mesozoic-Cenozoic evolution of the swell thus remains poorly constrained.

The Tuareg Shield is the result of accretion of Precambrian terranes during the Pan-African orogeny (Black et al., 1994; Liégeois et al., 2005). After the Pan-African orogeny, a mainly clastic sedimentation developed during the Paleozoic, giving birth to the so-called Saharan basins, which surround the shield (Guiraud et al., 2005). At that time, as well as during the Triassic and Jurassic, the vertical motions of the shield remained unconstrained. During Early Cretaceous opening of the South Atlantic Ocean, old structures were reactivated and troughs developed to the southeast (Tenere region, with up to 3-km-thick Cretaceous sediments; Genik, 1993) and to the southwest (Oued Amded region) of the Tuareg Shield (Fig. 1), belonging to a widespread rift system (Guiraud et al., 2005) presently surrounding the West African Craton and the Saharan Metacraton (Abdelsalam et al., 2011; Liégeois et al., 2013). In the Hoggar, rare Cretaceous deposits, resting unconformably directly upon the Precambrian basement, are exposed (Fig. 1): (1) the Serouenout continental sandstones (Bordet, 1953), a continental sediment sequence, which is up to 350 m thick and contains wood remnants of *Metapodocarpoxylon* with a poorly estimated Late Jurassic to Early Cretaceous age (Philippe

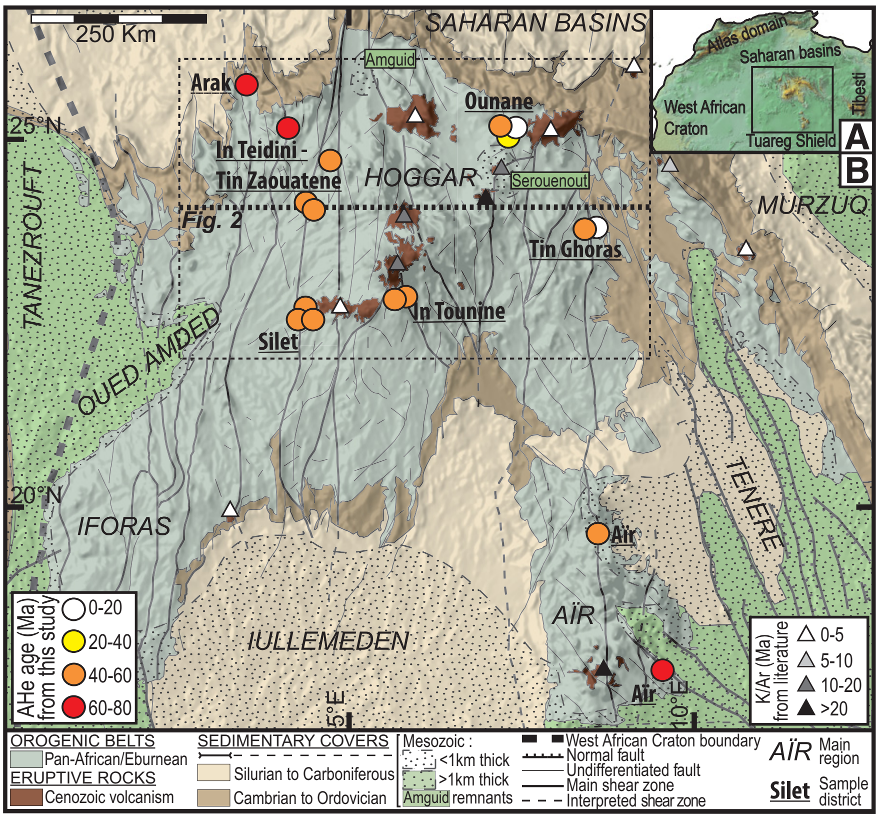

Figure 1. A: Topographic map of North Africa, with main domains and location of study site (B). B: Simplified geological map of the Tuareg Shield area, showing the basement, the sedimentary cover, and the Cenozoic volcanic districts. Sample locations are indicated with circles. The mean apatite (U-Th)/He (AHe) ages are reported using a color code, with 20 Ma increments. They range mostly between 60 and 40 Ma. These results are interpreted as a consequence of widespread exhumation at that time. Cenozoic ages of volcanic onset are taken from the literature, and reported using a color code (see text for references). Dotted lines show the location of the Figure 2 profile (24° ± 2° N).

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et al., 2003), and (2) the Amguid limestones, in which Late Cenomanian–Early Turonian *Calycoceras naviculare* ammonites can be observed (Busson et al., 1999). Volcanic activity started at 35 Ma (end of the Eocene) in the Serouenout district (Fig. 1) (Liégeois et al., 2005). The Lower Cretaceous sandstones are covered by tholeiitic flood basalts, which bury an unflattened paleotopography (Bordet, 1953; Aït Hamou et al., 2000). According to Beccaluva et al. (2007), Eocene–Oligocene igneous provinces have a preponderant lithospheric signature while Miocene to Quaternary alkalic provinces show a mainly asthenospheric signature.

In this paper, we focus on the spatial and temporal extension of the current doming, using apatite (U-Th)/He (AHe) thermochronology, which gives us information about the rock history in the 50–120 °C range (Gautheron et al., 2009; Shuster and Farley, 2009). Seventeen (17) samples were collected in order to cover the wider surface of the Tuareg Shield (Fig. 1). The combination of AHe ages and geological evidence allowed investigating the exhumation history of the Tuareg Shield. Particular attention has been given to (1) the pre-exhumation history, i.e., what the extension of the Lower Cretaceous sedimentary cover on the swell was, (2) the age of sample exhumations, i.e., whether exhumation was exclusively Eocene for all samples, and (3) the origin of this exhumation.

RESULTS

AHe age data present values ranging from 93.5 ± 12.3 to 4.6 ± 0.8 Ma, with scattered ages along replicates for some samples (Fig. 2). An AHe age reflects the He production and its accumulation into the apatite crystal, which is dependent on the diffusion coefficients, crystal size, and thermal history (Reiners and Farley, 2001; Gautheron et al., 2009, 2012). The large amount of AHe age dispersion within replicates implies a long stay in the He partial retention zone (~60–80 °C; detailed results and extended discussion on the significance of the AHe age scatter can be found in the GSA Data Repository[1]). Average ages of the young populations are reported in Figure 1. They present homogeneous values of ca. 40–60 Ma in the central Hoggar, and older values (ca. 60–80 Ma) in the northwestern Hoggar and southern Aïr peripheral areas. In the northeastern Hoggar, we found the youngest ages, down to ca. 5–15 Ma. However, Figure 2 shows that not all samples present the same pattern distribution. Older Arak ages, as well as younger Ounane and Tin Ghoras ages, are supported by a lesser quantity of replicates, because of the low amounts of apatite crystals, whereas an Eocene signal is well represented in most of the samples.

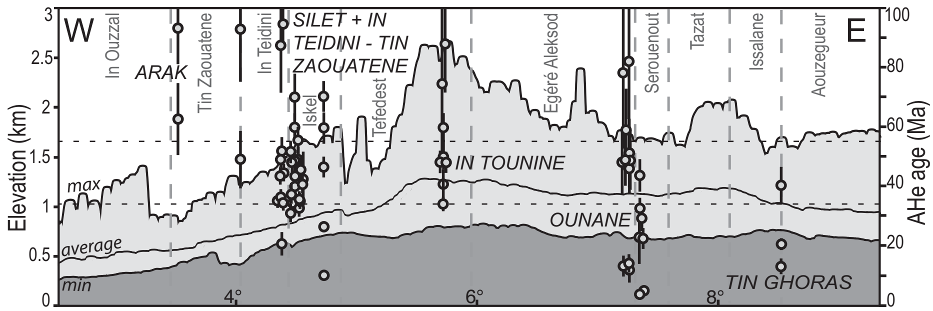

Figure 2. A 700-km-long swath profile (7° × 2° extracted from Shuttle Radar Topography Mission [SRTM] data v. 4, http://srtm.csi.cgiar.org; see Figure 1B for position) across the study area, showing minimum, average, and maximum elevation and projected apatite (U-Th)/He (AHe) replicates, with analytical uncertainty (see the Data Repository [see footnote 1] for details). Vertical dashed gray lines represent major lithospheric-scale shear zones, separating labeled Pan-African terranes (Black et al., 1994); horizontal dashed lines represent the Eocene limits.

The Cenozoic to Quaternary volcanic activity may have influenced the AHe system for the In Tounine, Silet, and Ounane samples, because they could have been in contact with lava flows, although these samples are nowadays at more than 15 km from volcanic fields (Fig. 1). However, AHe measurements present comparable Eocene ages for all sampling sites (except at swell borders), and young ages similar to Ounane samples can be found in the Tin Ghoras volcanic-free area (Fig. 1), demonstrating that the heat brought by volcanism did not imprint a signal onto AHe ages. The possible influence of high surface temperature due to desert conditions on AHe ages has been tested (see the Data Repository): results demonstrate that this effect did not affect significantly the He budget of the grain.

DISCUSSION

Except on the swell borders, AHe ages presented here show a first-order Eocene apatite (U-Th)/He signal over the entire Tuareg Shield. Combining these results with geological constraints and available apatite fission track data allows first-order reconstruction of the Mesozoic-Cenozoic thermal history of the swell. We will now discuss the pre-exhumation history, the age of sample exhumations, and the origin of this exhumation.

Pre-Exhumation History

Sedimentary remnants of Serouenout (Bordet, 1953) and Amguid (Busson et al., 1999), resting unconformably upon the basement (Fig. 1), evidence that the substratum was exposed during the Cretaceous, at least in the northeastern part of the Hoggar, where Tin Ghoras and Ounane samples are located. In the Aïr massif, the occurrence of Cretaceous Tenere deposits, also unconformably overlying the basement and currently outcropping near the studied sample locations (Fig. 1), led to the same conclusion. We thus assume that Ounane, Tin Ghoras, and Aïr samples were near the surface in the Cretaceous. Figure 3A shows the schematic time-temperature path that these samples underwent. As the results show the important replicate dispersion typical of partial opening of the He system, temperature reached by these samples before Cenozoic exhumation can be estimated at 60–80 °C (see the Data Repository). This heating stage can be related only to burial under sedimentary cover on the Cretaceous remnants. Taking into account the uncertainties on topography,

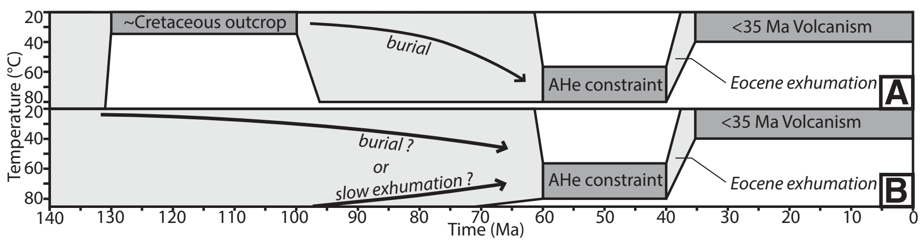

Figure 3. Schematic thermal history deduced from apatite (U-Th)/He (AHe) and geological data. A: Ounane, Tin Ghoras, and Aïr samples (Fig. 1) with the constraint of Cretaceous occurrences. B: Arak, In Teidini–Tin Zaouatene, In Tounine, and Silet samples (Fig. 1) without this constraint. Light gray polygons illustrate possible time-temperature paths between dark gray boxes that constitute major constraints. Temporal and thermal uncertainties are indicated (see text).

[1]GSA Data Repository item 2013168, details of thermochronologic analyses and samples (Tables DR1 and DR2), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

lithosphere, and crustal thickness, and using an upper crustal heat production of 2 μW/m[3], we assume the Eocene thermal gradient to be 22–28 °C/km. Considering a warm Eocene climate (Feakins and DeMenocal, 2010) and a possible water layer over the surface, we assume a surface temperature range of 30 °C to 15 °C. Under these conditions, corresponding burial depths range from 1 to 3 km. Constraining the cause of this subsidence is not easy because contemporaneous sediments have been eroded. Extension of the Tenere rifting process in the Hoggar may be a suitable process to explain this subsidence (Dautria and Lesquer, 1989).

Although the Oued Amded Cretaceous sediments are also lying directly on the basement (Fig. 1), the lack of Mesozoic remnants closer to the core of the Hoggar sheds doubt on the extension of the Cretaceous depositional area. For In Tounine, Silet, In Teidini–Tin Zaouatene, and Arak samples (Fig. 1), there are no strong constraints concerning the Cretaceous history. The AHe signal indicates an Eocene heating; thus it is not possible to investigate the previous thermal history (Fig. 3B). However, the wide dispersion of the replicates implies a long stay in the He partial retention zone and suggests no significant pre-Eocene exhumation. The nature of eroded material during the Eocene, including Mesozoic-Cenozoic sedimentary cover and/or older rocks, remains unconstrained for these samples. To conclude, our results evidence the existence of a Cretaceous to Eocene sedimentary cover over the northeastern Hoggar and the Aïr, but its extension at the scale of the entire Tuareg Shield can be neither confirmed nor excluded.

Mode and Chronology of the Exhumation

Ounane, Tin Ghoras, and Southern Aïr Samples

The Ounane, Tin Ghoras, and southern Aïr samples, located close to the oldest volcanic episodes of the Hoggar and Aïr (respectively 35 and 28 Ma; Liégeois et al., 2005), were necessarily exposed since the Late Eocene to Early Oligocene. This constraint is consistent with AHe results of these samples (Fig. 1), which show Eocene closure of the (U-Th)/He system. Such a scenario implies that these samples underwent rapid cooling, thus a major Eocene erosion. Subsequent erosion must have been weak enough to preserve the samples until today.

However, Ounane and Tin Ghoras samples show additional young AHe signals (Fig. 1), which could be interpreted as evidencing younger exhumation focused on the northeastern part of the shield. The nearby Serouenout 35 Ma volcanism constraint (Fig. 1) supports an Eocene end of exhumation, while younger AHe signals are less printed, due to the small quantity of young replicates compared to the swell-scale Eocene signal (Fig. 2). A late exhumation stage focused on the northeast part of the Hoggar thus remains impossible to prove or refute with available data.

In Tounine, Silet, In Teidini–Tin Zaouatene, Arak, and Northern Aïr Samples

Ca. 20 Ma volcanic rocks close to In Tounine samples (Atakor onset; Liégeois et al., 2005) (Fig. 1) indicate that these samples were at the surface at least at this time. On the other hand, the Silet region does not present any volcanic constraints older than 5 Ma. Thus the end of exhumation cannot be more precisely constrained than between the Eocene and 5 Ma. Concerning the In Teidini–Tin Zaouatene, Arak, and northern Aïr samples, in the absence of any close enough volcanism constraint, it is not possible to infer any end-of-exhumation timing.

AHe ages of these samples are all compatible with an Eocene-only exhumation, as well as with slow exhumation allowing a long stay in the partial retention zone and recent arrival at the surface. In consequence, erosion could have occurred either only during the Eocene (as the Ounane, Tin Ghoras, and southern Aïr samples) or since the Eocene until today.

Toward a Generalized Exhumation of the Tuareg Shield?

Considering initially flat isotherms and a spherical topographic swell, it is theoretically expected that exhumation becomes smaller with increasing distance to the swell core, and thus that the origin of the exposed samples is shallower. In consequence, peripheral samples are expected to come from a more superficial part of the He partial retention zone, and thus to show older AHe ages. As a matter of fact, the northwestern Hoggar and southern Aïr samples present the oldest AHe ages (Fig. 1). This result is therefore consistent with a shield-scale synchronous exhumation.

Based in particular on morphological variations between the terranes, as well as volcanism location, Liégeois et al. (2005) proposed that the Tuareg Shield swell would result from differential vertical motions of the terranes, which acted as independent structural entities, in association with Cenozoic reactivation of the north-south shear zones.

It can be noted that the replicates west of the Egéré Aleksod–Serouenout boundary shear zone (Fig. 2) show older AHe signals than the eastern ones (eastern Ounane and Tin Ghoras). However, there is no significant vertical displacement of the Paleozoic series at the northern tip of the shear zone (Fig. 1). We thus believe that discontinuity in our data could be related to a lower number of replicates in the eastern Ounane and Tin Ghoras samples (Fig. 2).

Concerning the other shear zones, the important dispersion of the AHe measurements, related to a long stay of the samples in the partial retention zone, does not allow us to clearly define some discontinuities in the AHe signal on either side of these structures (Fig. 2). In consequence, Cenozoic structural reactivations could not have exceeded the hectometric scale, and would remain second-order perturbations of a first-order larger-scale process.

Considering the remarkable consistency of the Late Eocene signal over the different samples at swell scale (Fig. 1), the Eocene exhumation for at least Ounane, Tin Ghoras, and southern Aïr samples, the lack of significant discontinuity in the AHe signal on both sides of shear zones, and the older peripheral ages, we propose that exhumation could have been synchronous for the entire swell, and mostly concentrated in the Eocene.

Exhumation Geodynamics

The ultimate process at the origin of the large-scale Eocene Tuareg Shield erosion stage and subsequent igneous activity is still a matter of debate.

During the Middle and Late Eocene, Africa-Eurasia collision in northern Arabia induced significant decrease of African plate velocity, as well as inversion in the northwestern Atlas border (Frizon de Lamotte et al., 2011). Synchronous far-field stress could generate large-scale lithospheric buckling in the Tuareg Shield, but it would generate roughly east-west to northeast-southwest elongated uplifts, and cannot explain the occurrence of magmatism. The mantle plume theory (Aït Hamou et al., 2000) is not favored either, because a shallow upper-mantle upwelling source is suggested by more recent studies (Pik et al., 2006; Beccaluva et al., 2007). Dynamic effects of asthenospheric movements are expected to also have a role; Moucha and Forte (2011) showed that the Hoggar-Aïr area could have undergone up to 300 m of dynamic topography since 30 Ma. Liégeois et al. (2005) proposed that edge-driven convection (King and Anderson, 1998) may have taken place beneath the shield, in association with important lithosphere thickness variations beneath the Sahara (see example of Morocco in Missenard and Cadoux, 2012). The process is unstable, and prone to cancelation if plates are moving (King and Anderson, 1998). Edge-driven convection, possibly combined with far-field lithospheric buckling, both related to Eocene sudden slowdown of Africa coevally with Alpine intraplate deformation in the Eocene, remains the best hypothesis to explain geological features of the Tuareg Shield.

CONCLUSIONS

The first apatite (U-Th)/He datings of the Tuareg Shield lead to further investigations of its thermal history. At swell scale, results show a consistent trend, implying that no significant differential exhumation occurred. We propose that the entire shield underwent synchronous erosion during the Eocene, before <35 Ma igneous episodes.

The outcrops of Cretaceous sedimentary remnants in the northeastern part of the swell are consistent with Upper Cretaceous–Eocene burying under a 1- to 3-km-thick sedimentary cover. Whether this cover was extended to the whole Tuareg Shield is not yet documented. If the depositional area was confined to the Aïr and northeastern Hoggar, Cretaceous Tenere troughs could have crossed the Hoggar on its northeastern part. On the other hand, extension of the cover over the whole shield would evidence that a large intraplate sag basin developed. After near-complete erosion of Cretaceous–Eocene sediments during the Eocene, exhumation decreased significantly.

Eocene sudden slowdown of the African plate would have favored the establishment of sublithospheric convection, inducing exhumation of the Tuareg Shield and subsequent igneous activity. A possible far-field lithospheric buckling effect, related to Eocene Alpine intraplate deformation, should also be considered.

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