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DR YVES MISSENARD (Orcid ID : 0000-0001-7484-7544)

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A Tortonian onset for the Algerian margin inversion: evidence from low temperature thermochronology

Authors

Alice Recanati¹, Yves Missenard^{1*}, Rémi Leprêtre², Cécile Gautheron¹, Jocelyn Barbarand¹,
Fatiha Abbassene³, Nachida Abdallah³, Aziouz Ouabadi³, Mohamed El Messaoud Derder⁴,
Claire Boukari¹, Rosella Pinna-Jamme¹, Frédéric Haurine¹

* corresponding author: yves.missenard@u-psud.fr – phone 0033169154864

Affiliations

⁽¹⁾ GEOPS, Univ Paris Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 504,
Orsay, F-91405, France

⁽²⁾ GEC, Université Cergy Pontoise, Département Géosciences et Environnement, Maison
Internationale de la Recherche, 1 rue Descartes, 95000 Neuville-sur-Oise, France

⁽³⁾ LGGIP/FSTGAT, Univ. des Sciences et de la Technologie Houari Boumediene, BP 32, El
Alia Bab Ezzouar, Algiers, Algeria.

⁽⁴⁾ CRAAG, BP 63, Bouzaréah, 16340, Algiers, Algeria.

Running Head

Tortonian inversion of the Algerian margin

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Keywords

Algerian margin, apatite, thermochronology (U-Th-Sm)/He, young passive margin inversion, Tortonian

Abstract:

In North Africa, the Algerian margin is made of basement blocks that drifted away from the European margin, namely the Kabylia, and docked to the African continental crust in the Early Miocene. This young margin is now inverted, as dated Miocene (17 Ma) granites outcrop alongshore, evidencing kilometre-scale exhumation since their emplacement. Age of inversion is actually unknown, although Pliocene is often considered in the offshore domain. To decipher the exhumation history of the margin between 17 and 5 Ma, we performed a coupled apatite fission track (AFT) and (U-Th-Sm)/He (AHe) study in the Cap Bougaroun Miocene granite. AFT dates range between 7 ± 1 and 10 ± 1 Ma, mean AHe dates between 8 ± 2 Ma and 10 ± 1 Ma. These data evidence rapid and multi-kilometre exhumation during Tortonian times. This event cannot be related to slab breakoff but instead to the onset of margin inversion that has since developed as an in-sequence north-verging deforming prism.

Introduction

Western Mediterranean geodynamics has been extensively studied for more than 20 years and is now relatively well constrained (Gueguen *et al.*, 1998, Carminati *et al.*, 1998, 2012; Spakman *et al.*, 2004; Jolivet *et al.*, 2008; Van Hinsbergen *et al.*, 2014). The N-S convergence between Africa and Eurasia began in the Late Cretaceous (Rosenbaum *et al.*, 2002). It ended with a major collisional event in the middle-late Eocene that preceded the opening of the Oligo-Miocene back-arc basins (e.g. Alboran, Algerian, Provençal and Ligurian basins,

Fig. 1A; Réhault *et al.*, 1984; Gueguen *et al.*, 1998). This opening allowed the replacement of the Ligurian and “Maghrebian” Tethys branches by the West Mediterranean oceanic basins through a globally southward roll-back motion (Van Hinsbergen *et al.*, 2014). The final shaping involved a large-scale slab tearing that permitted eastward and westward lateral escapes of the slab at the origins of the Calabrian and Alboran orogenic arcs, respectively.

The breaking of the slab enabled the asthenosphere to rise and heat/melt the overriding lithosphere, as inferred by Davies and von Blanckenburg (1995). As a matter of fact, a more than 1000 km-long succession of magmatic rocks lies in Northern Maghreb, the geochemistry and petrology of which are related to the slab breakoff (Maury *et al.*, 2000; Coulon *et al.*, 2002; Chazot *et al.*, 2017). In Northern Algeria (Fig. 1B), more especially in the Lesser Kabylia, Beni Touffout and Bougaroun, Miocene granitoids were emplaced during the slab breakoff, which occurred ~17 Ma ago (Ouabadi, 1994; Fourcade *et al.*, 2001; Abbassene *et al.*, 2016).

Lesser Kabylia, belonging to the internal domain of the Tell-Rif orogen (Wildi, 1983), was docked to the South Tethys margin during the Early Miocene (among others Bouillin, 1977; Courme-Rault, 1985). Its northern boundary represents the passive margin of the Algerian Basin since at least the latest Oligocene-Aquitainian. Interestingly, the passive margin is already a compressional domain, at least since the beginning of the Pliocene for the offshore domain (Leprêtre *et al.*, 2013; Arab *et al.*, 2016). However, whereas the origin and evolution of the Algerian margin is one of the pending questions in Western Mediterranean geodynamics (Leprêtre *et al.*, 2013), very few studies exist about the uplift and denudation history of this part of North Africa. The presence of lower Miocene granites already outcropping raises questions about the evolution of the relief and its timing. Nowadays, vertical movements along the Algerian margin are poorly constrained.

In the present work, we investigate the chronology of exhumation in the Bougaroun massif (Lesser Kabylia, Fig. 1B), using apatite fission-track (AFT) and (U–Th–Sm)/He (AHe) thermochronology and associated thermal modelling by the computer code QTQt (Gallagher, 2012). Those methods allow us to determine the thermal history of rocks, and to quantify rock exhumation in the 40–120°C range (Gallagher *et al.*, 1998; Gautheron *et al.*, 2009; Djimbi *et al.*, 2015). No such combination of AHe and AFT datasets has ever been acquired on the Algerian margin. Our new dataset represents a first attempt to decipher the post-collisional evolution of the Kabylia basement. It allows us to discuss the respective influence of the slab-break-off versus inversion processes in the relief evolution of a young passive margin.

Geological setting

1. Tell-Rif system: general organization & timing of deformation

The western Mediterranean domain is surrounded by mountain ranges built during the Alpine orogeny from the Palaeogene until today. Among them, the Maghrebide belt extends over >2000 km between the Gibraltar Arc and Sicily (Durand-Delga and Fontboté, 1980). It includes the Betics-Rif cordillera (Crespo-Blanc and Frizon de Lamotte, 2006), the Algerian-Tunisian Tell (Wildi, 1983) and the Calabro-Sicilian arc (Fig. 1A). The Tell-Rif system is composed of three major units from north to south: (1) the internal Kabylia domain, constituted of basement blocks originating from the dismantling of the AlKaPeCa domain (for Alboran-Kabylia-Peloritani-Calabria; Bouillin, 1986); these elements come from the North Tethys margin that drifted away during the Cenozoic before the Miocene docking; they sandwich the “Dorsale Calcaire” unit, which is the former passive margin of AlKaPeCa, against the Flysch domain; (2) the Flysch domain, formerly covering the “Maghrebian” Te-

thys (Fig. 1B); (3) the external domain, which is the more-or-less inverted former South Tethys margin (Wildi, 1983; Fig. 1). The belt is at first-order organized as a south-verging stack of these three domains, although important along-strike variations exist (Leprêtre *et al.*, in press).

The deformation chronology for the Tell-Rif system is well-described (e.g. Wildi, 1983; Benaouali-Mebarek *et al.*, 2006; Abbassène *et al.*, 2016; Leprêtre *et al.*, in press). The docking of the Kabylia occurred in the late Burdigalian-Langhian along the margin after a complex extensional evolution of the basement during the Oligo-Miocene (Aïté and Gélard, 1997). Previous study of preserved sediments on the Kabylia basement did not allow a clear examination of the successive deformation steps after the docking stage (Bouillin, 1977; Géry *et al.*, 1981; Arab *et al.*, 2016). Nevertheless, since the 2000s, numerous offshore studies have helped understanding and dating the more recent deformation stages (Deverchère *et al.*, 2005; Domzig *et al.*, 2006; Strzeczynski *et al.*, 2010; Leprêtre *et al.*, 2013; Arab *et al.*, 2016). Arab *et al.* (2016) give evidence that after the Late Burdigalian-Langhian docking, compression has resumed at least from the Messinian. However, note that no well calibration exists in the Algerian Basin and that dating is still debatable.

2. Lesser Kabylia geology and magmatism

Lesser Kabylia mainly consists of a magmatic and metamorphic basement along with Palaeozoic metasediments (Bouillin, 1977). Scarce Mesozoic sediments are found on top of the basement, and only along the southeastern boundary of the basement (SSE of Skikda, Fig. 1B), in the “Dorsale Calcaire”. The basement is unconformably overlain by the detrital “Oligo-Miocene Kabyle” (Fig. 1B), which is Late Oligocene to Burdigalian (Géry *et al.*, 1981). These are syn-rift deposits related to back-arc basins formation (Aïté and Gélard,

1997; Géry et al., 1981). In the Kabylia, post-docking sediments are scarce and even absent after the Langhian in Lesser Kabylia, whereas Langhian to Tortonian formations rest on top of the “Oligo-Miocene Kabyle” offshore (Arab *et al.*, 2016).

Other Miocene rocks crop out in Lesser Kabylia. Indeed, the two largest magmatic outcrops of Algeria occupy the northernmost part of the Lesser Kabylia: Kabylia de Collo and Chetaïbi-Cap de Fer (Fig. 1B). The Cap Bougaroun massif is located in the Kabylia de Collo region (Bouillin, 1977). Following Ouabadi *et al.* (1992; 1994), the Bougaroun pluton is composed of granodiorites and monzogranites, related to continental collision processes. U–Pb and K–Ar dating (whole rock and separated minerals) suggest an emplacement age of 17 ± 0.5 Ma (Abbassene *et al.*, 2016), close to the age of the neighbouring El Milia microgranite (16.5 ± 0.8 Ma, Bellon, 1976, Bellon *et al.*, 1977). The Bougaroun pluton now crops out between 0 and 800 m above sea level.

Methodology and results

Four samples (CB53, 27, 32 and 49; Table S1) were collected and analysed (analytical details in supplementary data). ICP-AES data of the four granitoids have been published in Abbassene et al. (2016). AFT results are presented in Table 1 and figure S2. Central AFT ages range from 7 ± 1 Ma to 10 ± 1 Ma, and mean Dpar is 1.2 ± 0.1 to 1.6 ± 0.2 μm . AHe data are presented in Table 2. Single-grain AHe dates vary between 5 ± 0 Ma and 12 ± 1 Ma and mean AHe dates range from 8 ± 1 Ma (CB53) to 10 ± 1 Ma (CB49). eU ranges between 2 and 200 ppm (table 2). AFT and AHe ages are younger than the rock emplacement age of 17 Ma (Abbassene *et al.*, 2016).

We ran numerical simulations using the QTQt software (Gallagher, 2012) to extract thermal histories in order to deduce the timing and the rate of the post-17 Ma exhumation. QTQt enables us to inverse the dataset, defining a suite of thermal histories that reproduce the thermochronometric dates. The AHe and AFT datasets were inverted for each sample, using the annealing model of Kecham *et al.* (2007) and the Gautheron *et al.* (2009) radiation damage model. The modelled thermal path for CB53 is provided in figure 2 (Fig. S3 for the three other samples). Three constraints on the temperature/time history were used: (i) the pluton is at present at a surface temperature of $20\pm 10^{\circ}\text{C}$, and (ii) the pluton formed at a temperature $> 700^{\circ}\text{C}$ around 17 Ma ago (Abbassene *et al.*, 2016) and (iii) whole rock K–Ar ages indicate that the pluton had cooled to $400\text{--}200^{\circ}\text{C}$ by 15 Ma (Abbassene *et al.*, 2016). Further information about the modelling procedure can be found in the Supp. Info. (Text S2).

The modelled thermal histories predict a rapid cooling episode between 9 Ma and 8 Ma (Fig. 2) for all samples. The Bougaroun pluton thus underwent rapid cooling in *ca.* 2 Ma, during Tortonian times. We interpret this cooling episode as the consequence of a major exhumation event at that time.

Discussion

Our thermal models evidence two cooling episodes of the Kabylia basement (Fig. 2). The first cooling episode occurred very quickly between 17 and 15 Ma from $>700^{\circ}\text{C}$ to $400\text{--}200^{\circ}\text{C}$. We interpret this event as an initial heat loss concentrated within a narrow time interval. Nevertheless, the petrological constraints on the early evolution of the Cap Bougaroun granite are relatively scarce, and the thermal path related to this early cooling event is only indicative.

After this initial cooling stage, the granite remained at temperatures around 200°C to 300°C, which roughly corresponds to a depth of 6.6 to 10 km considering a palaeogeotherm of 30°C/Km. The second cooling episode took place in a very short time between 9 and 7 Ma, that is during Tortonian time. The quickness of cooling evidenced by modelling agrees with the absence of correlations between AHe dates and eU, Rs and altitude (Fig. S1), which testifies to a short stay in the helium partial retention zone. The cooling rate cannot be precisely quantified as (1) there is no correlation between sample altitudes and AHe ages and (2) AFT ages are similar to AHe ages. Following Ouabadi *et al.* (1992), this pluton was emplaced at shallow crustal levels (thermobarometric analyses of the Beni Touffout massif envision maximum pressures of 3 kbar, yielding depths less than 10 km) and now crops out at the surface. We thus interpret this second cooling episode as a major exhumation event during Tortonian times in a very short time, less than 2 Myr as testified by QtQt models (Fig. 2). The pluton then stayed near the sub-surface since the Pliocene (Fig. 2). This Tortonian event is clearly distinct from the initial heat loss and therefore must be interpreted differently.

We propose that this cooling is induced by the decrease of cover thickness by erosion. We thus deal with an erosional hypothesis, suggesting that, even if the palaeogeotherm was rather high (>30°C/km) after 15 Ma, most of the cooling is related to exhumation. In the light of this hypothesis, two scenarios can explain our results: (i) the slab break-off triggered massive isostatic rebound or (ii) this late erosion phase is related to crustal shortening induced by the inversion of the margin.

1. Origin of the Tortonian exhumation phase: a consequence of slab breakoff?

Davies and von Blanckenburg (1995) proposed that slab breakoff could explain surface uplift and exhumation phases in orogens. Different authors have modelled the duration

and the displacement amplitude related to a putative isostatic surface uplift related to slab breakoff, by analogue or numerical simulations. Chatelain *et al.* (1992) and Buitter *et al.* (2002) suggested that surface uplift would be extremely large (maximum 2–6 km) and would occur very quickly (<100,000 years) after slab detachment. Duretz *et al.* (2012) proposed a general surface uplift in a maximum timespan of ~5 Ma.

Given these works and the fact that slab breakoff occurred in Lesser Kabylia ~17 Ma ago (Abbassene *et al.*, 2016), we may expect rapid cooling and erosion very quickly after it. Nonetheless, our data do not constrain the pre-Tortonian thermal history. According to the most optimistic lifespan of the isostatic uplift, we thus do not expect the Tortonian cooling to be related to the slab breakoff and must consider another scenario. Yet, let us add that the 17–15 Ma cooling could be regarded as a composite cooling signal mixing crystallization heat loss together with exhumation due to slab breakoff. However, the fact that the Langhian deposits show a clear transgressive marine trend (from 16 to 14 Ma; Arab *et al.*, 2016) does not support the mixed hypothesis, and the initial 17–15 Ma cooling is best interpreted as heat loss of the cooling pluton.

2. *A Tortonian onset of inversion?*

The timing of the late Cenozoic inversion in the onshore section of the Tell-Rif belt has been extensively studied (among others Meghraoui *et al.*, 1986; Deverchère *et al.*, 2005; Mauffret, 2007; Strzeczynski *et al.*, 2010; Arab *et al.* 2016). Strzeczynski *et al.* (2010) recalled that onshore outcrops evidenced compression since the Late Miocene (post-11 Ma/Tortonian), as also proposed by Perrodon (1957) and Thomas (1985) in the Cheliff area, by Aïte and Gélard (1997) in Greater Kabylia, and in the Tunisian Tell by Rouvier (1977)

(Fig. 1A). Carbonnel and Courme-Rault (1997) also pointed to a particular event at this time, studying the sedimentary record there, as Arab *et al.* (2016) did by showing the regressive character of the Tortonian sedimentation.

On the contrary, the offshore studies up to now do not propose such an early compressional phase, and most authors agree that compression resumed in the Pliocene in the deep basin (among others Déverchère *et al.*, 2005; Strzeczynski *et al.*, 2010; Arab *et al.*, 2016) even though it could have locally started in the Late Miocene (Mauffret, 2007). These late Cenozoic deformations sign the inversion of the margin since the structures are not yet south-verging but globally north-verging, with the development of underthrusting of the Algerian Basin.

Our results thus bring the first evidence for the onset of this north-verging inversion within the onshore Kabylia domain after the initial previous compressional docking event in the Late Burdigalian-Langhian (Roure *et al.*, 2012). The poor evidence for a Tortonian inversion in the offshore domain could be understood as an in-sequence development of an orogenic prism, represented by the whole inverted Algerian margin and the Kabylia basement, the Tell foreland representing the rear of the system. As such, the expression of the deformation offshore became more significant by the Pliocene, as shown by the migration of deformation outward of the system, relocalized at the foot of the margin. These inverted structures would branch on Kabylia basement neofaults, as north-dipping normal faults inherited from the Oligo-Miocene extension are unlikely to be reactivated (Fig. 3). Such a scenario of an initial imbrication mechanism in the upper margin during the Tortonian followed by the development of in-sequence thrusts in the outer wedge during the Plio-Quaternary is in line with classical evolution of the frontal part of accretionary prisms (e.g. Moore *et al.*, 2007; Yamada *et al.*, 2014).

Finally, this Tortonian event fits well in the West Mediterranean geodynamics. Indeed, this period shows strong mechanical coupling between Africa and Europe, with widespread development of compressional structures. This is for instance particularly well-evidenced in the Betics belt (Braga *et al.*, 2003; Augier *et al.*, 2005; Do Couto *et al.*, 2014; Janowski *et al.*, 2017) and in the Alboran basin (Do Couto *et al.*, 2016).

Conclusion

Our study delivers the first combined AFT and AHe study on the Lesser Kabylia domain in Algeria. Through thermal modelling, we demonstrate that major exhumation of the Algerian margin occurred in the Tortonian. This event cannot be regarded as a consequence of the slab breakoff because it occurred too late. Instead, we propose that it dates the onset of inversion of the internal part of the Tell. Interestingly, this new onshore data confirms the Late Miocene resumption of compression along the Tell belt, whereas the offshore domain seems to have remained exempt of compression before the Pliocene. We thus propose that the compression began onshore in the Kabylia, and progressively migrated to the north until it was clearly expressed offshore during the Plio-Quaternary (Fig. 3). Our results shed light on the compression “jump” from the former south-verging Tell front, situated southward of the Tell nappes, toward a north-verging Kabylia front that developed in-sequence deformation leading to the strong inversion of the Algerian margin since then. It would now be interesting (1) to investigate whether this scenario established for the Lesser Kabylia is also valid westward, or if the Tethyan slab-tear propagation did influence the tectonic agenda and (2) to date in Lesser Kabylia with hotter thermochronometers to decipher the older history of the basement.

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References

- Abbassene, F., Chazot, G., Bellon, H., Bruguier, O., Ouabadi, A., Maury, R., Déverchère, J., Bosch, D., Monié, P., 2016. A 17 Ma onset for the post-collisional K-rich calc-alkaline magmatism in the Maghrebides: evidence from Bougaroun (Northeastern Algeria) and geodynamic implications. *Tectonophysics*, **674**, 114-134.
- Aïté Mohamed, O., Gélard, J.P., 1997. Distension néogène post-collisionnelle sur le transect de Grande Kabylie (Algérie). *Bulletin de la Société Géologique de France*, **168** (4), 423-436.
- Arab, M., Rabineau, M., Deverchère, J., Bracène, R., Belhai, D., Roure, F., Marok, A., Bouyahiaoui, B., Grangeon, D., Andriessen, P., Sage, F., 2016. Tectonostratigraphic evolution of the eastern Algerian margin and basin from seismic data and onshore-offshore correlation. *Marine and Petroleum Geology*, **77**, 1355-1375.
- Augier, R., Agard, P., Monié, P., Jolivet, L., Robin, C. and Booth-Réa, G. (2005), Exhumation, doming and slab retreat in the Betic Cordillera (SE Spain): in situ $^{40}\text{Ar}/^{39}\text{Ar}$ ages and P–T–d–t paths for the Nevado-Filabride complex. *Journal of Metamorphic Geology*, **23**, 357-381. doi:10.1111/j.1525-1314.2005.00581.x
- Bellon, H., 1976. Séries magmatiques néogènes et quaternaires du pourtour de la Méditerranée occidentale, comparées dans leur cadre géochronométrique: implications géodynamiques. PhD, Université Paris-Sud.
- Bellon, H., Letouzey, J., 1977. Volcanism related to plate tectonics in the Western and Eastern Mediterranean. International Symposium on the Structural History of the Mediterranean Basins.
- Benaouali-Mebarek, N., Frizon de Lamotte, D., Roca, E., Bracène, R., Faure, J.L., Sassi, W., Roure, F., 2006. Post-Cretaceous kinematics of the Atlas and Tell systems in central Algeria: Early foreland folding and subduction-related deformation. *C.R. Geoscience*, **338**, 115-125.
- Buiter, S.J.H., Govers, R., Wortel, M.J.R., 2002. Two-dimensional simulations of surface deformation caused by slab detachment. *Tectonophysics*, **354**, 195-210.
- Bouillin, J.P., 1977. Géologie alpine de la petite Kabylie dans les régions de Collo et d'El Milia (Algérie). Phd, Paris.
- Bouillin, J.P., 1986. Le « bassin maghrébin » ; une ancienne limite entre l'Europe et l'Afrique à l'Ouest des Alpes. *Bulletin de la Société Géologique de France* II, **4**.
- Braga, J.C., Martin, J.M., Quesada, C., 2003. Patterns and average rates of late-Neogene recent uplift in the Betic Cordillera, SE Spain. *Geomorphology*, **50** (1-3), 3-26.
- Carbonnel, G., Courme-Rault, M.D., 1997. Ostracodes miocènes d'Algérie : Revue : systématique, biostratigraphie, distribution palinspatique. Muséum de Lyon.
- Carminati, E., Wortel, M.J.R., Spakman, W., Sabadini, R., 1998. The role of slab detachment processes in the opening of the western-central Mediterranean basins: some geological and geophysical evidence. *Earth and Planetary Science Letters*, **160**, 651-665.

- Carminati, E., Lustrino, M., Doglioni, C., 2012. Geodynamic evolution of the central and western Mediterranean: Tectonic vs. igneous petrology constraints. *Tectonophysics*, **579**, 173-192.
- Chatelain, J.L., Molnar, P., Prévot, R., 1992. Detachment of part of the downgoing slab and uplift of the New Hebrides (Vanuatu) islands. *Geophysical Research Letters*, **19** (14), 1507-1510.
- Chazot, G., Abbassene, F., Maury, R.C., Deverchère, J., Bellon, H., Ouabadi, A., Bosch, D., 2017. An overview on the origin of post-collisional Miocene magmatism in the Kabylies (Northern Algeria): evidence for crustal stacking, delamination and slab detachment. *Journal of African Earth Sciences*, **125**, 27-41.
- Coulon, C., Megartsi, M., Fourcade, S., Maury, R.C., Bellon, H., Louni-Hacini, A., Cotten, J., Coutelle A., Hermitte, D., 2002. Post-collisional transition from calc-alkaline to alkaline volcanism during the Neogene in Oranie (Algeria): magmatic expression of a slab breakoff. *Lithos*, **62**, 87-110.
- Courme-Rault, M.-D., 1985. Stratigraphie du miocène et chronologie comparée des déformations suivant deux transversales des atlasides orientales (Algérie, Sicile). PhD thesis, Orléans University.
- Crespo-Blanc, A., Frizon de Lamotte, D., 2006. Structural evolution of the external zones derived from the Flysch Through and the South Iberian and Maghrebian paleomargins around the Gibraltar Arc: A comparative study. *Bulletin de la Société Géologique de France*, **177** (5), 267-282.
- Davies, J.H., von Blanckenburg, F., 1995. Slab breakoff: a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth and Planetary Science Letters*, **129**, 85-102.
- Deverchère, J., Yelles, K., Domzig, A., Mercier de Lépinay, B., Bouillin, J.P., Gaullier, V., Bracène, R., Calais, E., Savoye, B., Kherroubi, A., Le Roy, P., Pauc, H., Dan, G., 2005. Active thrust faulting offshore Boumerdès, Algeria, and its relation to the 2003 Mw 6.9 earthquake. *Geophysical Research Letters*, **32** (4).
- Djimbi, D.M., Gautheron, C., Roques, J., Tassan-Got, L., Gerin, C., Simoni, E., 2015. Impact of apatite chemical composition on (U-Th)/He thermochronometry: an atomistic point of view. *Geochimica et Cosmochimica Acta*, **167**, 162-176.
- Do Couto, D., Popescu, S.M., Suc, J.P., Melinte Dobrinescu, C., Barhoun, N., Gorini, C., Jolivet, L., Poort, J., Jouannic, G., Auxietre, J.L., 2014. Lago Mare and the Messinian salinity crisis: evidence from the Alboran sea (S. Spain). *Marine and Petroleum Geology*, **52**, 57-76.
- Do Couto, D., Gorini, C., Jolivet, L., Lebret, N., Augier, R., Gumiaux, C., d'Acremont, E., Ammar, A., Jabour, H., Auxietre, J.-L., 2016. Tectonic and stratigraphic evolution of the Western Alboran Sea Basin in the last 25Myrs. *Tectonophysics*, **677-678**, 280-311.
- Domzig, A., Yelles, K., Le Roy, C., Deverchère, J., Bouillin, J.-P., Bracène, R., Mercier de Lépinay, B., Le Roy, P., Calais, E., Kherroubi, A., Gaullier, V., Savoye, B., Pauc, H., 2006. Searching for the Africa-Eurasia Miocene boundary offshore western Algeria (MARADJA'03 cruise). *Comptes Rendus Geosciences*, **338**(1-2), 80-91.
- Durand-Delga, M., Fontboté, J.M., 1980. Le cadre structural de la Méditerranée Occidentale, 26è Cong. Géol. Int., Colloque C5, Paris, *Mém. BRGM*, **115**, 67-85.
- Duretz, T., Schmalholz, S.M., Gerya, T.V., 2012. Dynamics of slab detachment. *Geochemistry, Geophysics, Geosystems*, **13**(3).
- Ethève, N., Frizon de Lamotte, D., Mohn, G., Martos, R., Roca, E., Blanpied, C., 2016. Extensional vs. Contractual Cenozoic deformation in Ibiza (Balearic Promontory, Spain): Integration in the West Mediterranean back-arc setting. *Tectonophysics*, **682**, 35-55.
- Fourcade, S., Capdevila, R., Ouabadi, A., Martineau, F., 2001. The origin and geodynamic significance of the Alpine cordierite-bearing granitoids of northern Algeria. A combined petrological, mineralogical, geochemical and isotopic (O, H, Sr, Nd) study. *Lithos*, **57**, 187-216.
- Gautheron, C., Tassan-Got, L., Barbarand, J., Pagel, M., 2009. Effect of alpha-damage annealing on apatite (U-Th)/He thermochronology. *Chemical Geology*, **266**, 166-279.
- Gautheron, C., Tassan-Got, L., 2010. A Monte Carlo approach to diffusion applied to noble gas/helium thermochronology. *Chemical Geology*, **273**, 212-224.

- Gallagher, K., Brown, R., Johnson, C., 1998. Fission-track analysis and its application to geological problems. *Annual Review of Earth and Planetary Sciences*, **26**, 519-572.
- Gallagher, K., 2012. Transdimensional inverse thermal history modeling for quantitative thermochronology. *Journal of Geophysical Research*, **117**.
- Géry, B., Feinberg, H., Lorentz, C., Magné, J., 1981. Définition d'une série type de l'Oligo-Miocène kabyle anté-nappes dans le Djebel Aïssa-Mimoun (Grande Kabylie, Algérie), *C. R. Acad. Sci. Paris*, **292**, 1529-1532.
- Gueguen, E., Doglioni C., Fernandez M., 1998. On the post-25 Ma geodynamic evolution of the western Mediterranean. *Tectonophysics*, **298**, 259-269.
- Janowski, M., Loget, N., Gautheron, C., Barbarand, J., Bellahsen, N., Van den Driessche, J., Babault, J., Meyer, B., 2017. Neogene exhumation and relief evolution in the Eastern Betics (SE Spain): insights from the Sierra de Gador. *Terra Nova*, **29** (2), 91-97.
- Jolivet, L., Brun, J.P., Meyer, B., Prouteau, G., 2008. *Géodynamique Méditerranéenne*. Vuibert Eds.
- Ketcham, R.A., Gautheron, C., Tassan-Got, L., 2011. Accounting for long alpha-particle stopping distances in (U–Th–Sm)/He geochronology: Refinement of the baseline case. *Geochimica et Cosmochimica Acta*, **75** (24), 7779-7791.
- Leprêtre, A., Klingelhoefer, F., Graindorge, D., Schnurle, P., Beslier, M.O., Yelles, K., Deverchère, J., Bracène, R., 2013. Multiphased tectonic evolution of the Central Algerian margin from combined wide-angle and reflection seismic data off Tipaza, Algeria. *Journal of Geophysical Research*, **118** (8), 3899-3916.
- Leprêtre, R., Frizon de Lamotte, D., Combier, V., Gimeno, O., Mohn, G., Eschard, R., 2018. The Tell-Rif orogenic system (Morocco, Algeria, Tunisia) and the complex heritage of the southern Tethys margin. *Bull. Soc. Geol. Fr.*, **189** (10).
- Mauffret, A., 2007. The northwestern (Maghreb) boundary of the Nubia (Africa) plate. *Tectonophysics*, **429** (1-2), 21-44.
- Maury, R.C., Fourcade, S., Coulon, C., El Azzouzi, M., Bellon, H., Coutelle, A., Ouabadi, A., Semroud, B., Megartsi, M., Cotton, J., Belanteur, O., Louni-Hacini, A., Piqué, A., Capdevilla, R., Hernandez, J., Réhault, J.P., 2000. Post-collisional neogene magmatism of the Mediterranean Maghreb margin: a consequence of slab breakoff. *C.R. Academie des Sciences de Paris*, **331**, 159-173.
- Meghraoui, M., Cisternas, A., Philip, H., 1986. Seismotectonics of the lower Cheliff basin: structural background of the El Asnam (Algeria) earthquake. *Tectonics*, **5** (6), 809-836.
- Moore, G.F., Bangs, N.L., Taira, A., Kuramoto, S., Pangborn, E., Tobin, H.J., 2007. Three-Dimensional Splay Fault Geometry and Implications for Tsunami Generation. *Science*, **318**, DOI: 10.1126/science.1147195
- Ouabadi, A., Capdevila, R., Fourcade, S., Semroud, B., 1992. Le granite à biotite et cordiérite du Cap Bougaroun (Algérie), un analogue alpin des granites de type « S » de la ceinture de Lachlan (Australie). *C.R. Acad. Sci. Paris*, **314**, 1187-1194.
- Ouabadi, A., 1994. Pétrologie, Géochimie, origine des granitoïdes péralumineux à cordierite (Cap Bougaroun, Beni Touffout, et Filfila), Algérie Nord Orientale. PhD. Université de Rennes 1.
- Réhault, J. P., Boillot, G., Mauffret, A., 1984. The western Mediterranean basin geological evolution. *Marine Geology*, **5**, 447-477.
- Rouvier, H., 1977. Géologie de l'extrême nord tunisien : tectoniques et paléogéographies superposées à l'extrémité orientale de la chaîne nord-maghrébine. Thèse doctorat en sciences, Univ. Pierre et Marie Curie.
- Rosenbaum, G., Lister, G.S., Duboz, C., 2002. Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene. In: Rosenbaum G. and Lister, G.S., 2002. Reconstruction of the evolution of the Alpine-Himalayan orogen. *Journal of the Virtual Explorer*, **8**, 107-130.
- Roure, F., Casero, P., Addoum, B., 2012. Alpine inversion of the North African margin and delamination of its continental lithosphere. *Tectonics*, **31**, <http://dx.doi.org/10.1029/2011TC002989>.
- Spakman, W., Wortel, M.J.R., 2004. A tomographic view on the Western Mediterranean Geodynam-

ics. In The TRANSMED Atlas, The Mediterranean region from crust to mantle. Eds: Cavazza W., Roure F., Spakman W., Stampfli G.M., Ziegler P. p: 31-52.

Strzeczynski, P., Deverchère, J., Cattaneo, A., Domzig, A., Yelles, K., Mercier de Lépinay, B., Babonneau, N., Boudiaf, A., 2010. Tectonic inheritance and Pliocene-Pleistocene inversion of the Algerian margin around Algiers: insights from multibeam and seismic reflection data. *Tectonics*, **29** (2).

Van Hinsbergen, D. J. J., Vissers, R. L. M., Spakman, W., 2014. Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation. *Tectonics*, **33**, doi: 10.1002/tect.20125.

Wildi, W., 1983. La chaîne tello-Rifaine (Algérie, Maroc, Tunisie): structure, stratigraphie, et évolution du Trias au Miocène. *Rev. Géol. Dynam. Géog. Phys. Paris*, **24**, 201-297.

Yamada, Y., Bab, K., Miyakawa, A., Matsuoka, T., 2014. Granular experiments of thrust wedges: Insights relevant to methane hydrate exploration at the Nankai accretionary prism. *Marine and Petroleum Geology*, **51**, 34-48.

Figure captions

Figure 1: (A) Structural map of the West Mediterranean domain (modified after Ethève *et al.*, 2016). The different Alpine ranges are indicated with emphasis on the AlKaPeCa-related belts: the Betics, the Tell-Rif, the Apennines and the Calabria-Sicily arc (CSA). The red frame indicates the location of Lesser Kabylia, a geological map of which is shown in (B), with the location of the Bougaroun pluton (adapted from Abbassene *et al.*, 2016). Blue dots: samples analysed in this study.

Figure 2: (A) Age/elevation results for all samples. U–Pb and whole rock K–Ar dates are from Abbassene *et al.* (2016). AHe and AFT date: this study. (B) Thermal history of CB53 issued from inverse modelling. (C) Predicted ages against observations for all samples. Blue: AFT. Red: AHe.

Figure 3: General evolution of the Algerian margin since the Early Miocene. OMK: “Oligo-Miocene Kabyle”; DC: “Dorsale Calcaire”. See text for discussion.

Tables

Table 1: AFT results*

Sample	Rock-type	Location	Elevation (m)	$\rho_s (10^5 \cdot \text{cm}^{-2}) / N_s$	$\frac{\rho_i (10^5 \cdot \text{cm}^{-2})}{Ni}$	$\rho_d (10^5 \cdot \text{cm}^{-2}) / Nd$	P (χ^2) (%)	Central age (Ma) $\pm 1\sigma$	U (ppm)	Dpar (μm)
CB53	granite	6°21'57"E	10	0.073	1.167	6.490	76	7 \pm 1	22	1.6 \pm 0.2
		37°04'36"N		<i>89</i>	<i>1429</i>	<i>5479</i>		27		
CB49	granite	6°20'13"E	360	0.159	1.844	6.483	40	10 \pm 1	35	1.5 \pm 0.2
		37°01'20"N		<i>182</i>	<i>2110</i>	<i>6710</i>		30		
CB32	granodr.	6°23'30"E	790	0.066	1.212	6.534	34	6 \pm 2	23	1.2 \pm 0.1
		37°01'41"N		<i>61</i>	<i>1115</i>	<i>6710</i>		26		
CB27	granite	6°23'24"E	520	0.056	0.861	6.584	36	8 \pm 1	16	1.2 \pm 0.1
		37°03'34"N		<i>84</i>	<i>1285</i>	<i>6710</i>		30		

* ρ , density of tracks (*s* and *i* indicate spontaneous and induced densities respectively in apatite crystals and the mica detector, and *d* indicates the track density of the neutron glass monitor (CN5)); densities are expressed in 10^5 t.cm^{-2} . *N_s*, *N_i* and *N_d* are the number of counted tracks for ρ_s , ρ_i and ρ_d respectively, given in italics. MTL, mean track length. Values in parentheses for the central age are the number of single-grain ages. 1σ is the standard deviation. Dpar corresponds to a kinetic factor determined for each sample (Barbarand *et al.* 2003).

Granodr. : granodiorite.

Table 2: AHe results*

	Name	Prism Termination	L (μm)	W (μm)	T (μm)	Rs (μm)	Weight (μg)	FT	⁴ He (ncc/g)	U (ppm)	Th (ppm)	Sm (ppm)	eU (ppm)	Th/U	Age (Ma)	Age c. (Ma)*
<i>CB53</i>	CB53Q	1 bf	125	113	100	51	3.0	0.78	9907	9	19	123	14	2.1	5	7.0 ± 0.6
	CB53R	No pyr	100	88	88	42	1.7	0.69	14814	14	26	181	20	1.9	6	8.2 ± 0.7
	CB53V	No pyr	138	125	88	47	2.8	0.75	21745	21	14	153	25	0.7	7	9.3 ± 0.8
	CB53W	No pyr	112,5	88	88	44	2.0	0.71	18686	24	13	164	27	0.5	5	7.6 ± 0.6
	CB53F	No pyr	188	100	100	55	4.2	0.77	13905	18	23	119	24	1.3	5	6.0 ± 0.5
	CB53G	No pyr	125	113	100	51	3.0	0.75	14863	16	11	131	19	0.7	6	8.4 ± 0.7
	CB53H	1 pyr, 1 bf	125	125	100	48	2.3	0.77	18191	17	22	161	22	1.3	6	8.3 ± 0.7
	CB53J	No pyr	137,5	113	100	52	3.3	0.75	15517	18	21	141	23	1.2	5	7.1 ± 0.6
	CB53M	2 bf	187,5	125	100	56	4.8	0.87	15884	14	22	114	20	1.6	6	7.4 ± 0.6
	CB53P	No pyr	175	125	125	64	6.2	0.79	2986	2	7	85	4	3.5	5	6.7 ± 0.5
	CB53N	2 pyr	200	100	88	50	2.7	0.58	24867	29	35	218	37	1.2	5	9.1 ± 0.6
	CB53X	1 pyr	100	88	88	40	1.3	0.66	21759	26	33	245	34	1.3	5	7.6 ± 0.6
	CB53B	1 bf	163	113	88	49	3.2	0.80	23840	26	36	179	35	1.4	5	6.8 ± 0.6
	CB53C	2 bf	225	113	75	45	3.4	0.87	8427	5	13	197	9	2.6	7	8.5 ± 0.8
	CB53D	2 bf	100	88	75	39	1.4	0.78	48933	44	33	260	52	0.8	8	8.6 ± 0.8
	CB53S	No pyr	150	88	63	36	1.6	0.70	51159	78	25	225	84	0.3	5	6.3 ± 0.6
	CB53T	1 bf	138	63	50	30	0.9	0.70	29970	37	30	315	44	0.8	5	7.6 ± 0.7
	CB53Y	No pyr	88	75	75	37	1.1	0.65	19456	26	39	280	35	1.5	4	6.2 ± 0.5
	<i>CB53Z*</i>	1 bf	138	100	69	39	1.8	0.77	15414	11	12	126	14	1.1	9	13.2 ± 1
	CB53AA	1 bf	150	100	100	52	3.4	0.79	8089	9	15	95	13	1.7	5	6.3 ± 0.5
CB53DD	1 bf	88	88	75	37	1.2	0.72	22117	28	6	109	30	0.2	6	8.3 ± 0.7	
<i>CB49</i>	<i>CB49AA*</i>	No pyr	250	250	163	85	18.1	0.86	50646	32	10	50	35	0.3	12	13.9 ± 1.1

	CB49CC	No pyr	200	100	88	50	3.8	0.77	197772	197	10	160	200	0.1	8	11.3 ± 0.9
	CB49DD	No pyr	150	63	63	36	1.3	0.67	58550	62	12	229	65	0.2	7	10.8 ± 0.9
	<i>CB49GG*</i>	No pyr	188	75	63	38	1.8	0.70	131094	111	27	281	118	0.2	9	12.9 ± 1.1
	CB49II	No pyr	125	100	113	51	3.0	0.75	81225	77	7	85	79	0.1	8	11.2 ± 0.9
	CB49JJ	No pyr	125	113	113	54	3.6	0.76	27185	28	5	140	29	0.2	8	9.9 ± 0.8
	CB49LL	No pyr	113	113	100	49	2.7	0.74	43740	52	16	172	56	0.3	6	8.5 ± 0.7
<i>CB32</i>	CB32A	No pyr	138	88	75	103	25.2	0.71	1712	2	1	13	2	0.5	7	10.0 ± 0.8
	<i>CB32D*</i>	1 bf	113	100	88	45	2.1	0.76	54243	33	14	200	36	0.4	12	15.7 ± 1.4
	CB32F	1 pyr, 1 bf	138	100	113	50	2.6	0.79	27373	31	15	181	35	0.5	6	7.9 ± 0.7
	CB32I	1 pyr	138	88	75	41	1.6	0.63	24449	32	19	216	37	0.6	5	8.4 ± 0.6
	CB32Q	1 pyr	125	100	88	44	1.8	0.68	30585	32	13	223	35	0.4	7	10.0 ± 0.8
	CB32V	1 bf	144	125	113	57	4.4	0.81	15952	18	9	105	20	0.5	6	7.8 ± 0.6
	CB32M	1 pyr, 1 bf	181	163	125	64	5.6	0.83	30284	32	20	121	36	0.6	7	8.1 ± 0.7
	CB32U	No pyr	125	113	100	51	3.0	0.74	13328	23	22	140	28	1	4	5.1 ± 0.4
	<i>CB32W*</i>	No pyr	138	113	94	50	3.0	0.75	26772	21	13	143	24	0.6	9	11.7 ± 1
	CB32Z	No pyr	150	100	100	52	3.4	0.76	15082	17	9	112	19	0.5	6	8.1 ± 0.7
	CB32AA	No pyr	150	113	94	51	3.3	0.76	16355	21	10	127	23	0.5	6	7.4 ± 0.6
	CB32G	No pyr	125	75	75	40	1.6	0.69	17306	18	16	179	22	0.9	6	8.8 ± 0.7
	CB32O	No pyr	138	75	93	36	1.4	0.72	35761	35	20	218	40	0.6	7	9.8 ± 0.9
	CB32H-	2 bf	125	100	75	41	1.8	0.82	21688	23	14	194	26	0.6	7	8.0 ± 0.7
	CB32T	No pyr	138	100	75	42	2.0	0.72	17746	18	14	148	22	0.8	6	8.8 ± 0.8
	CB32Y	No pyr	113	75	63	35	1.1	0.66	22304	27	14	191	31	0.5	6	8.6 ± 0.7
<i>CB27</i>	CB27A	No pyr	238	88	75	45	3.3	0.73	25592	19	61	185	33	3.2	6	8.4 ± 0.1
	CB27B	No pyr	175	113	113	59	5.0	0.77	7462	6	17	103	10	2.8	6	7.3 ± 0.1
	CB27D	1 bf	113	88	75	40	1.6	0.73	38839	27	95	358	50	3.5	6	8.4 ± 0.1
	CB27F	No pyr	188	113	100	56	4.6	0.77	14994	10	34	148	19	3.4	6	8.2 ± 0.1
	CB27E	No pyr	125	100	100	50	2.9	0.73	15228	10	36	162	19	3.6	6	8.7 ± 0.1
	CB27H	No pyr	163	100	88	49	3.0	0.74	24120	17	61	199	32	3.6	6	8.2 ± 0.1

* R_s (sphere equivalent radius) and F_T (ejection factor) have been calculated using the procedure developed by Gautheron and Tassan-Got (2010) and Ketcham *et al.* (2011). eU (effective uranium) has been calculated with the formula $[eU] = [U] + 0.24 \times [Th] + 0.008 \times [Sm]$. 'Age c.' means (U–Th–Sm)/He age corrected for alpha ejection with the F_T . The error is estimated to be a maximum of 8%. ncc, nano cubic centimer. L, W, T give the measurements of the individual crystals for length, width and thickness, respectively. In the Prism Termination column: bf : broken face; no pyr: no pyramid, meaning no bf and quite rounded grain; 1pyr, 1bf: 1 pyramid and 1 broken face (see Brown *et al.*, 2013).



