13

Intégration des minéralisations des Beni Bou Ifrour : du Rif oriental à la Méditerranée occidentale

Cet ultime chapitre est consacré à l'intégration du massif des Beni Bou Ifrour et de ses minéralisations à l'échelle régionale. Le modèle d'évolution tectono-sédimentaire et magmatique proposé dans le Chapitre 12 y est ainsi confronté à la géologie régionale, plus particulièrement au sein du Rif oriental.

Par ailleurs, les minéralisations néogènes sont nombreuses en Méditerranée occidentale, principalement associées à un magmatisme qui se met en place dans un contexte géodynamique contrôlé par le retrait de panneaux plongeants. La deuxième partie de ce chapitre sera consacrée à l'apport du magmatisme et des minéralisations associées dans la caractérisation d'un évènement de déchirure du panneau plongeant.

13.1 Intégration régionale du massif des Beni Bou Ifrour

Nous avons réalisé une coupe à l'échelle de la péninsule de Melilla-Nador, afin de discuter l'intégration régionale du massif des Beni Bou Ifrour (Figure 13.1). Cette coupe a été construite à partir d'informations recueillies dans la littérature : (1) pour l'anticlinal de Tarjat, NEGRO (2005) et MICHARD *et al.* (2008), (2) pour la plateforme carbonatée, les différents travaux de CORNEE *et al.*, (2002, 2006). Le style tectonique est inspiré des travaux de CRESPO-BLANC & FRIZON DE LAMOTTE (2006), du profil Transmed I (FRIZON DE LAMOTTE *et al.*, 2004), de MICHARD *et al.*, 2008…

Cette coupe interprétative montre que le modèle de type pli sur chevauchement d'avant-pays que nous proposons pour le massif des Beni Bou Ifrour s'intègre particulièrement bien dans l'histoire régionale du Rif oriental. Il montre qu'à l'échelle régionale, la compression est le processus majeur en œuvre à partir de 8 Ma, malgré les modèles régionaux qui font intervenir des phases individualisées d'extension après la mise en place des nappes rifaines (GUILLEMIN & HOUZAY, 1982 ; MOREL, 1989). FRIZON DE LAMOTTE (1982) estimait déjà que la subsidence des bassins post-nappes n'est pas liée à des phases extensives mais plutôt la conséquence de mouvements verticaux amorcés par la réactivation des accidents qui bordent les bassins lors de phases compressives. Nous sommes en accord avec cela, et proposons donc que les failles normales identifiées dans notre étude au sein du

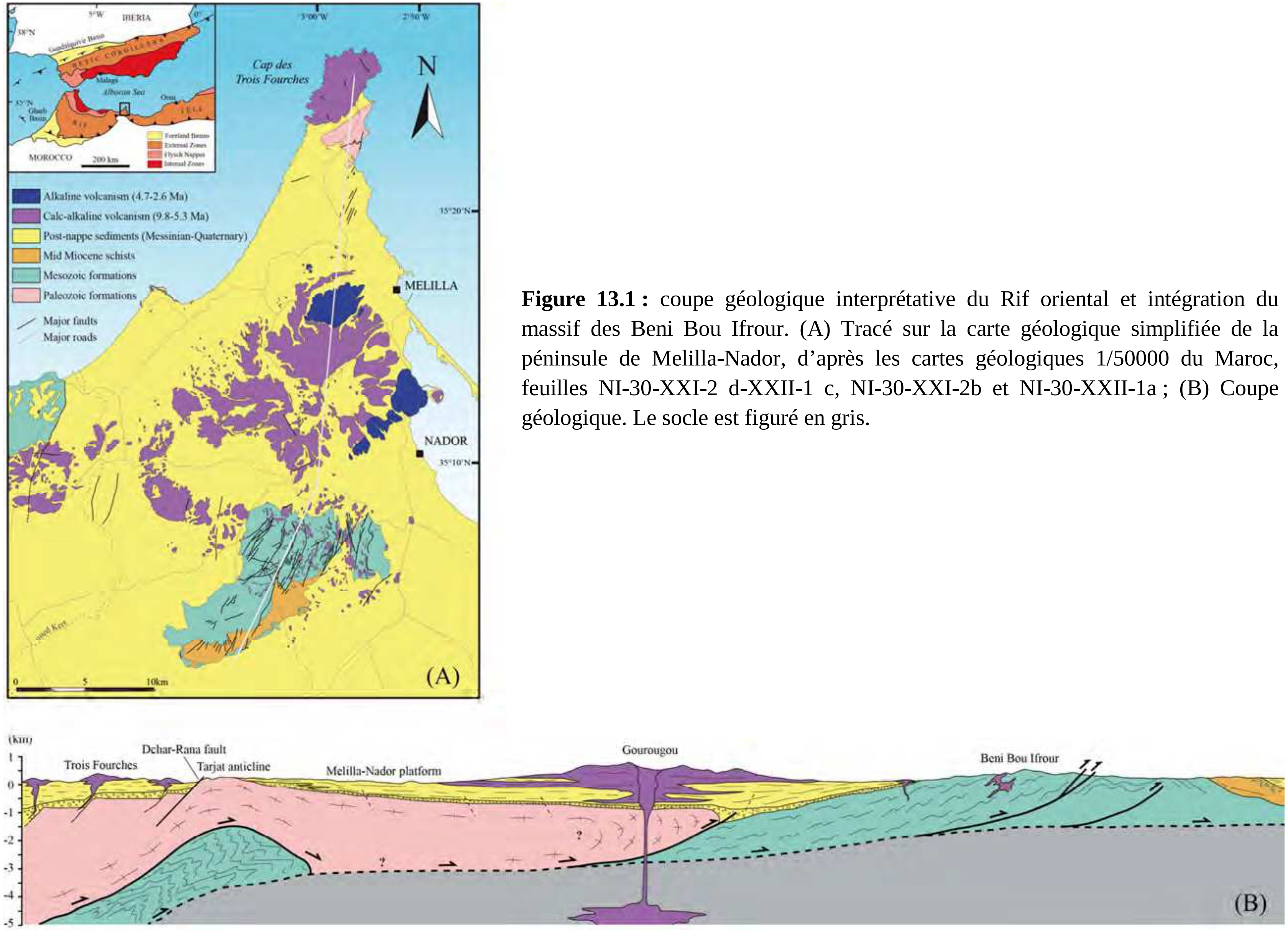

Figure 13.1 : coupe géologique interprétative du Rif oriental et intégration du massif des Beni Bou Ifrour. (A) Tracé sur la carte géologique simplifiée de la péninsule de Melilla-Nador, d'après les cartes géologiques 1/50000 du Maroc, feuilles NI-30-XXI-2 d-XXII-1 c, NI-30-XXI-2b et NI-30-XXII-1a ; (B) Coupe géologique. Le socle est figuré en gris.

massif des Beni Bou Ifrour accommodent en fait la compression et le soulèvement généralisé du massif.

Par ailleurs, le mode d'exhumation du massif mésozoïque des Beni Bou Ifrour semble fondamentalement différent de celui du massif paléozoïque des Trois Fourches, qui est *a priori* accommodé par le jeu de la faille normale de Dchar-Rana dont le jeu premier est tortonien.

Concernant l'intégration du massif des Beni Bou Ifrour dans l'ensemble géologique du Rif oriental, quelques points mériteraient davantage de réflexion :

(1) Notre modèle étant restreint dans le temps (entre 8 et 6 Ma environ), il serait intéressant de savoir ce qu'il se produit en amont à l'échelle régionale. Plus spécifiquement, la réalité des mouvements vers l'Est que nous n'avons pas retrouvé au sein du massif : si la limite entre le Domaine Nord et le Domaine Sud était le vestige d'une limite latérale (et non frontale) d'un système de chevauchement initié plus tôt au Miocène, voire à l'Oligocène, cela s'accorderait avec les stades ultimes du scénario de NEGRO (2005) et NEGRO *et al.* (2007) en ce qui concerne l'exhumation des Temsamane. La réponse pourrait résider au NE du massif, au niveau de Afra.

(2) Le poids de l'édifice volcanique du Gourougou a-t-il une incidence sur la sédimentation et la localisation des accidents tectoniques ? EL BAKKALI *et al.* (2001) identifie la dépression d'Oumassine, située entre le stratovolcan et le massif des Beni Bou Ifrour, à une cuvette qui serait symptomatique d'une caldeira (§ 3.1.4.c). Les coupes de MOREL (1985, 1987 ; Figure 13.2) ne montrent cependant pas d'aspect incurvé des dépôts volcano-sédimentaires, mais plutôt un infléchissement vers le Gourougou. Par ailleurs, les failles normales méridiennes sont particulièrement concentrées dans le massif des Beni Bou Ifrour, immédiatement au Sud de l'édifice, tandis qu'elles sont peu cartographiées ailleurs. Or, il est démontré que la charge des édifices volcaniques à un effet sur la propagation des structures régionales lorsqu'elles sont compressives (BRANQUET & VAN WYK DE VRIES, 2001).

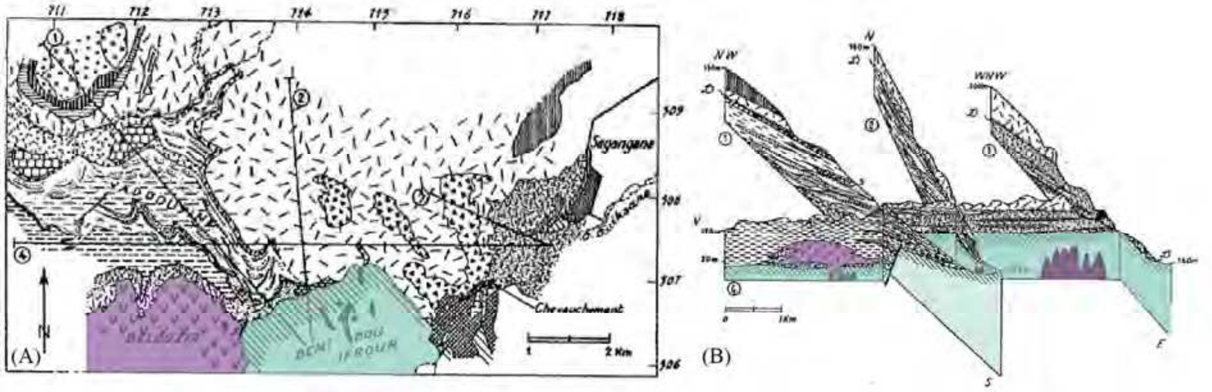

Figure 13.2 : coupes géologiques de la cuvette d'Oumassine (MOREL, 1985, 1987). (A) Carte géologique ; (B) Coupes géologiques en perspective.

12.2 Projet d'article : Migration of Neogene magmatism and associated mineralizations, reflecting slab tearing in the western Mediterranean

Cet article en cours de rédaction représente le stade final de ce travail de thèse. En effet, son objectif est de retracer les processus géodynamiques de la Méditerranée occidentale au travers du magmatisme et des minéralisations qui y sont associées. En particulier ici, les âges du magmatisme de la mer d'Alboran et de la Marge Maghrébine – près de 450 datations compilées en une base de données (Annexe VIII) et géolocalisées sous SIG – sont replacés dans de nouvelles reconstitutions paléogéographiques (en collaboration avec la thèse de Damien Do Couto, 2014).

Reporter ces datations le long de deux transects Ages *vs* Distance, l'un parallèle au couloir trans-Alboran (NE-SW) et l'autre parallèle à la Marge Maghrébine (WE), nous a permis d'identifier la migration du magmatisme et de la caractériser plus finement. Notamment, l'évolution le long du transect NE-SW est bien compatible avec celle proposée par DUGGEN *et al.* (2004), qui la relie à la subduction d'une lithosphère océanique téthysienne sous la mer d'Alboran. L'évolution le long du transect WE, en revanche, reflète un évènement de rupture de panneau plongeant en Méditerranée occidentale tel que proposé par CARMINATI *et al.* (1998), et confirmé par les expérimentations pétrologiques de MAURY *et al.* (2000) et de COULON *et al.* (2002). Cette rupture de panneau plongeant se produit sous le NE de l'Algérie vers 20 Ma et migre vers l'Ouest (et vers l'Est dans une moindre mesure) jusqu'à 8 Ma, soit à une vitesse d'environ 7-8 cm/an. Elle est en outre synchrone de la période d'extension d'arrière-arc orientée EW en mer d'Alboran (JOLIVET *et al.*, 2006).

La comparaison des compositions isotopiques du Pb obtenues sur les minéralisations à Pb-Zn au cours de ce travail, avec celles de gisements sud-andalou (Rodalquilar) et tunisien (oued Belif), confirme l'opposition entre ces deux processus géodynamiques. En effet, les compositions isotopiques du Pb à Melilla-Nador se rapprochent davantage de celles de l'oued Belif, tout en révélant une contribution mantellique plus importante dans leur source qu'à Rodalquilar. Ceci apporte donc une évidence supplémentaire que le système trans-Alboran reflète un environnement géodynamique fondamentalement différent de celui de la Marge Maghrébine. Ainsi, et bien qu'ils ne soient séparés que par la mer d'Alboran, le district de Melilla-Nador est toujours sous influence de la rupture de panneau plongeant tandis que le district de Rodalquilar est strictement lié à la subduction sous la mer d'Alboran.

Migration of Neogene magmatism and associated mineralizations, reflecting slab tearing in the western Mediterranean

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Abstract

Introduction

Slab detachments and slab tearing belong to the normal evolution of subduction zones, especially where slabs are laterally constrained and the subduction zone highly non-cylindrical (Wortel and Spakman, 2000; Govers and Wortel, 2005). The consequences of slab tearing on surface deformation or vertical movements can be important because they imply changes in the regime of flow in the asthenospheric mantle (Faccenna and Becker, 2010). The Mediterranean region is one example where slab tears have been suggested by seismic tomographic models and possible influence of changing mantle flow on the crustal tectonic regime have been advocated (Carminati *et al.*, 1998; Faccenna et al., 2004; Spakman and Wortel, 2004). One of the most prominent of such tears is found below the northern margin of Africa, below the coast lines of Algeria and Morocco. Tomographic models shows that a deep slab is only present there below the Gibraltar arc and the southern tip of the Iberian peninsula whereas subduction of the north African margin and Ionian oceanic lithosphere is required to explain the observed compressional structures and metamorphic evolution of the Tell and the Rif. The present-day configuration of slabs in the central and western Mediterranean results from the fast retreat of a once continuous slab that was sinking in the asthenosphere below Corsica and Sardinia in the Oligocene and its tearing in several pieces; eastward retreat formed the Calabrian subduction zone and westward retreat formed the Gibraltar subduction.

The dynamics of slab tearing is far from being fully understood because we have little information on the average rheology of slabs, oceanic or continental. New information on the kinematic evolution during retreat providing estimates of the retreat velocity is thus required to better understand the dynamic of such complex systems. The evolution of the northern African margin and the Alboran region can provide such data. The geometry of the slab is quite well controlled by several recent tomographic models, the tectonic and kinematic evolution can be described in some details (Jolivet *et al.*, 2006; Faccenna *et al.*, 2004) and the magmatic evolution through time is also well known (Maury *et al.*, 2000 ; Duggen *et al.*, 2004, 2005, 2008). We use a compilation of data on magmatic rocks chemistry and ages, as well the distribution and chemistry of ore deposits, together with new kinematic reconstructions to describe the evolution of the tear from 20 Ma to the present and discuss its dynamics. A comparison of the tectonic timing in the Betic Cordillera and the Rif confirm the possible control of surface tectonics by the migration of a torn piece of lithospheric mantle beneath north Algeria and provides velocities of migration toward the west.

Geodynamic context

The Neogene geodynamic evolution of the western Mediterranean domain is controlled by two contemporaneous phenomena: (1) Africa-Eurasia convergence and northward subduction of the African plate, and (2) slab retreat and coeval back-arc basin opening (Le Pichon and Angelier, 1981; Horvath and Berkhmer, 1982; Dercourt *et al.*, 1986; Malinverno and Ryan, 1986; DE-Wey, 1988; La Pichon *et al.*, 1988; Royden, 1993; Carminati *et al.*, 1998; Jolivet and Facenna, 2000; Wortel and Spakman, 2000). Carminati *et al.* (1998a) suggested that slab retreat in the western Mediterranean was complicated by four detachment events. Five major features allow the identification of a slab breakoff process (Davies and Von Blanckenburg, 1995): (1) the combined presence of basaltic and lower crustal granitoid melts (bimodal magmatism), both with a mantle parentage, (2) rapid uplift and exhumation of deep crustal rocks, (3) development of a regional metamorphism, (4) development of extensional structure related to the change in potential energy of the orogen, and (5) abundant clastic sedimentation in intramontane adjacent basins.

Based on these features, Carminati *et al.* (1998a) propose that one of these events would have occurred beneath northern Africa during Langhian times (16-15 Ma). Maury *et al.* (2000) and Coulon *et al.* (2002) have then demonstrated that the magmatic evolution along the Mediterranean Maghreb margin is consistent with this model. Indeed, the margin presents a very low magma production rate with a progressive magmatic change from (1) a calc-alkaline subduction-related geochemical imprint and extensive crustal contamination, to (2) transitional basalts derived from the melting of the mantle in the boundary between the lithosphere and the upwelling asthenosphere, and finally (3) alkaline basalts generated through partial melting of an asthenospheric mantle. This magmatism started in Central Eastern Algeria at ca. 16 Ma, then propagated eastwards and westwards along the Mediterranean Maghreb margin (Maury *et al.*, 2000).

We now focus on the Gibraltar arc and the Mediterranean Maghreb margin. We discuss herein the migration of the magmatism and distribution of mineralizations in the light of nE-W paleogeographic reconstitutions by Do Couto *et al.* (in prep.).

Neogene kinematics and tectonic timing

At ca. 35 Ma, the subduction zone in western Mediterranean ran from Gibraltar to Liguria in their present-day positions (Carminati *et al.*, 1998; Frizon de Lamotte *et al.*, 2000; Facenna *et al.*, 2004). Back-arc extension started at ca. 32 Ma in the Liguro-Provençal basin and then propagated towards the Alboran basin, as the slab retreated towards the SE.

The Alboran region includes the Betics (southern Spain) and the Rif (northern Morocco) fold-and-thrusts belts, connected through the Gibraltar arc. The Alboran Sea is a narrow basin inbetween, constituted of thinned continental crust. In this area, the back-arc extension developed mostly during Burdigalian-Langhian times (Bourgeois *et al.*, 1992; Mauffret *et al.*, 1992). At that time the extension was roughly NNE-SSW (Crespo-Blanc, 1995; Jolivet *et al.*, 2003, 2006), driven by the southeastward slab retreat. By ca. 20 Ma, extension turned to E-W, as the whole Alboran domain was migrating from East to West, driven by westward roll-back, tearing and local detachments of the subducting plate (Morley, 1993; Lonergan and White, 1997; Duggen *et al.*, 2004, 2005, 2008; Spakman and Wortel, 2004). This particular tectonic setting is well-constrained by the exhumed metamorphic units in the Betics sierras – from bottom to top the Nevado-Filabride, Alpujarride and Malaguide complexes – and their neighbouring intramontane basins. Jolivet *et al.* (2006) proposed a five-steps tectonic scenario for the internal Betics: (1) 40-50 Ma: crustal thickening and nappe stacking under the N-S compression due to northward subduction of the African plate; (2) 30-20 Ma: N-S ductile stretching in the Alpujarride, under N-S extension related to a first southward slab retreat episode; (3) 20 Ma: transition from a southward slab retreat (N-S extension still active in the Alpujarrides) to a westward slab retreat (E-W ductile stretching recorded in the underlying Nevado-Filabride), provoking a widespread thermal overprint and local crustal anatexis (Platt and Whitehouse, 1999; Zeck and Whitehouse, 1999); (4) 20-8 Ma: westward slab retreat, exhumation of the metamorphic core complexes and inception of the basins. A top-to-the-west shearing prevailed during this exhumation, which final stages are recorded in the Nevado-Filabride complex and constrained by fission-tracks on zircons (11.9 ± 0.9 Ma) or apatite (8.9 ± 2.9 Ma) and U-Th/He cooling ages on apatite (8.7 ± 0.7 Ma) (Johnson *et al.*, 1997; Vazques *et al.*, 2011). NE-W paleostress analyses by Augier *et al.* (2013) suggest that most of the neighbouring intramontane basins initiated as extensional basins linked with the coeval exhumation of the Nevado-Filabride complex; (5) 8 Ma-Present: resuming of the compressional regime (N-S to NNW-SSE), producing tectonic inversion, basin uplift and a diffuse reverse faulting, strike-slip faulting and related folding. Strike-slip activity of the Trans-Alboran transcurrent zone has been recognized at least from the (uppermost Tortonian?) Early Messinian (Booth-Rea *et al.*, 2003; Masana *et al.*, 2004). The prolongation of these NE-SW faults in the intramontane basins reveals that the activity postdates the formation of these basins and was generated during the Early Messinian (Augier *et al.*, 2013).

Further east, the Algerian margin includes the oceanic Algerian basin and the Tell fold-and-thrust belt, eastern extension of the Rif orogen. Stretching of the Algerian basin began in the late Oligocene-early Miocene times (Dewey *et al.*, 1989; Rosenbaum and Lister, 2004), as the subduction front migrated eastward. Contemporary with this rifting stage, metamorphic core complexes exhumed in the Tellian Internal zone: in the Edough massif, ductile extension is represented by a top-to-the-WNW extensional shear which began at ca. 24 Ma and ended at 17-16 Ma (Monié *et al.*, 1992; Saadallah and Caby, 1996). At the end of the Burdigalian period (ca. 20-18 Ma), N-S extension ended as the Alpine collision truly began, overthrusting the Numidian flysch southward onto the Tellian zone (Wildi, 1983; Aris *et al.*, 1998; Khomsi *et al.*, 2009). In northern Tunisia, the Tellian nappes are dated from the Langhian (Rouvier, 1977). Since then, the northern African region has experienced an oblique compression regime responsible for the Tell orogen building, interrupted by short-lived returns to extensional conditions during the Late Miocene and Pliocene times (Bouaziz *et al.*, 2002).

The onset of the backarc compression and basin inversion begins in the Gibraltar arc after 8 Ma (Late Tortonian) and then propagates along the Mediterranean Maghreb margin towards the Calabrian arc. It is recorded in North Algeria at 7-5 Ma (Mauffret, 2007) by S-dipping, N-verging reverse faults concentrated at the transition between continental and oceanic domains. Some newly generated reverse faults verging toward the north may reflect the inception of a new subduction off Algeria (Billi *et al.*, 2011).

Magmatism migration

To discuss the migration of magmatism in the study area, we have compiled ages taken from the literature (Annexe VIII) and plot them in two Age *versus* Distance transects: (1) NE-SW Trans-Alboran (Fig. 1), and (2) W-E along the Mediterranean Maghreb margin (Fig. 2).

Figure 1 shows no particular trend except perhaps an outward migration from Cabo de Gata northward and southward in the recent period. Despite some poorly constrained ages older than 20 Ma in Spain and the Alboran Sea, the first Miocene magmatic occurrences are related to an anatectic event that produced leucogranites and cordierite bearing dacites (e.g. 18.5 Ma ± 1.6 Ma in Mar Menor; Duggen et al., 2004) and reset some Eocene Malaga dikes ages (not represented). Calc-alkaline magmatism became widespread in the Trans-Alboran region at ca. 16-15 Ma. The main alkaline occurrences set up after ca. 6 Ma. A study of these magmatic products around the Alboran Sea led Duggen *et al.* (2004) to describe four successive stages at the latitude of Morocco and Spain: (1) Early Oligocene tholeiitic to calc-alkaline Malaga dikes emplaced in a back-arc setting, (2) crustal anatexis during an Early Miocene thermal event that is observed also in the metamorphic evolution of the Betics, (3) Middle to Late Miocene tholeiitic to calc-alkaline volcanism in the Alboran Basin, and (4) Late Miocene to Lower Pliocene shoshonitic and Messinian to Pleistocene intra- plate-type volcanic activity, related to the removal of subcontinental lithosphere and resulting asthenospheric upwelling.

On the W-E transect (Fig. 2), calc-alkaline magmatism shows an age peak at ca. 20 Ma in Dellys (NE Algeria) and a subsequent westward migration with an evolution toward more alkaline composition with time. A similar migration with a slower velocity is recorded toward the east. In a previous study of the whole north African margin between Morocco and Tunisia, Maury *et al.* (2000) noticed that magmatism in the Mediterranean Maghreb margin started in NE Algeria at ca. 16 Ma and then propagated eastwards and westwards. The same authors also conclude that the Langhian-Serravalian magmatism shows characteristics typical of subduction-related magmatism but with surprisingly small volumes produced, which they see as a consequence of the slab detachment. One can add that the short duration of these magmatic episodes is also compatible with the rapid cessation of a normal subduction after slab breakoff. The K-rich alkaline magmas reflect the incorporation of crustal melts due to the thermal anomaly induced by slab breakoff. Moving to the west, its distribution shows a striking age shift from 20 to 8 Ma (*e.g.* 8.06 Ma ± 0.14 Ma in the Beni Bou Ifrour massif;

Lebret, 2014). Calc-alkaline magmas are replaced by transitional and then alkaline ones, an evolution compatible with a hot asthenospheric anomaly. The Ras Tarf complex however stands apart from this trend. From NE Algeria to Tunisia, calc-alkaline magmatism ages shift smoother from 20 Ma to 14 Ma. Eventually, transition from calc-alkaline to alkaline affinities occurred simultaneously on both extremes of the Mediterranean Maghreb margin at ca. 7 Ma.

Lead isotope compositions of ore deposits

Together with Neogene magmatism, numerous polymetallic deposits (Pb-Zn-Hg-Cu-Ag-Au) are scattered from the Alboran Sea surroundings to northern Tunisia (Fig. 3 + Annexe I). According to De Boorder *et al*. (1998), the development of Late Cenozoic orogenic mineralizations in the European Alpine Belt reflects an increase in heat flow and fluid flow, which can be connected to tearing and detachment of lithosphere slabs, and concomitant emplacement of hot asthenosphere at lower crustal levels. Discussing lead sources and comparing on a Western Mediterranean scale can thus provide another evidence of a slab breakoff process.

We performed isotopic studies on epithermal galenas from the Melilla-Nador peninsula (Table 1). Lead isotope results are plotted in Figure 4, together with (1) epithermal galenas from the well-known Cabo de Gata district in southeastern Spain (Arribas and Tosdal, 1994), (2) the Oued Belif hematite-rich breccia of the Nefza district in northeastern Tunisia (Decrée *et al.*, 2013), and (3) magmatic rocks from southeastern Spain to northeastern Tunisia (Arribas and Tosdal, 1994; Duggen *et al.*, 2004, 2005; Decrée *et al.*, 2013). The average crustal Pb growth curve of Stacey and Kramer (1975) and the Pb orogen curve of Doe and Zartman (1979) are also shown for reference.

Pb isotopic measures were performed at GEOTOP (UQAM, Montreal, Canada), using a Nu Plasma II MC-ICP-MS, with an Aridus II as system of introduction. Measured samples were carried out on hand-picked galenas and dissolved; all details of sample preparation and analytical procedure are reported in Belshaw *et al.* (1998). Replicate analyses of the NBS-981 Pb standard yielded a mean value of ^{206}Pb/^{204}Pb = 16.941 ± 0.000 (2 σD), ^{207}Pb/^{204}Pb = 15.505 ± 0.000 (2 σD) and ^{206}Pb/^{204}Pb = 36.731 ± 0.001 (2 σD) (n=6).

Considering the reference curves of Stacey and Kramer (1975) and Doe and Zartman (1979), studied galenas are rather radiogenic and show a very limited range of composition. Moreover, the Pb isotope compositions of galenas from Melilla-Nador Peninsula display no variation between the two localities, the Beni Bou Ifrour Massif and the Trois Fourches Cape, despite their different host-rock; this absence of variation seems to reflect a unique hydrothermal event with a common source throughout the whole peninsula. At this scale, the isotopic compositions field of galenas can be compared with those of lavas from the neighbouring Gourougou stratovolcanoe (Duggen *et al.,* 2005). These lavas define two distinct groups evolving from a Si-K-rich (7.58-4.8 Ma) to a Si-poor (6.3-3.73 Ma) geochemistry. Results suggest a direct genetic link between galenas and the Si–K-rich lava group (Figure 4).

Compared with the galenas from southeastern Spain ores and hematite-rich breccia from northeastern Tunisia, the Pb isotope compositions of galenas from Melilla-Nador Peninsula are similar to those of the Nefza district ore. Since all deposits have equivalent ages (9.2 Ma in Cabo de Gata, Arribas and Tosdal, 1994; 10.4 Ma in Oued Belif, Decrée *et al.*, 2013; ca. 7.8 Ma in Melilla-Nador peninsula, Lebret, 2014), this shows that the ores from the Mediterranean Maghreb margin exhibit a major mantellic contribution, which is consistent with the trend of the Moroccan volcanic rocks compared with the southeastern Spain ones (Duggen *et al.*, 2004, 2005, 2008). This brings further evidence that the Trans-Alboran system traces a different geodynamic environment than the Mediterranean Maghreb margin. Although they are only separated by the Alboran Sea, the Melilla-Nador peninsula district is still under the influence of the slab breakoff event, while the Rodalquilar district is related to the eastward subduction of Tethys oceanic lithosphere beneath the Alboran basin (Duggen *et al.*, 2004, 2005, 2008).

Reconstructions

In order to correlate the magmatic, mineralization and tectonic events we now plot these on paleogeographic reconstitutions (Do Couto *et al.*, in prep.; Fig. 5), and we discuss the evolution of magmatism for each significant stage from the Early Oligocene to the Present:

(A) In the Early Oligocene (30 Ma), a roughly NNE-SSW subduction was active as Africa converged toward Iberia along a N-S direction and N-S extension started in the internal zones of the Alboran domain. The first occurrence of magmatism is represented by the Malaga dyke field, which tholeiitic affinity demonstrates the link with a subduction zone (Torres-Roldán *et al*., 1986; Duggen *et al*., 2004).

(B) and (C) By 25 Ma, N-S back-arc extension was still active, without significant magmatism. It lasted until the Burdigalian (D) when extension in the western part rotated from N-S to E-W and disappeared in the eastern part. This event provoked a widespread thermal overprint (Platt and Whitehouse, 1999; Zeck and Whitehouse, 1999). The subsequent crustal anatexis produced the leucogranites and cordierite bearing dacites. At that time, the first occurrences of calc-alkaline magmatism is observed in NE Algeria; its particular bimodal calc-alkaline affinity reflects a slab breakoff beneath the African margin (Maury *et al.*, 2000).

(E) As E-W extension proceeded westwards, the slab breakoff-related magmatism spread along the Mediterranean Maghreb margin. Meanwhile, a Trans-Alboran calc-alkaline magmatism set up, resulting from the eastward subduction of Tethys oceanic lithosphere beneath the Alboran basin (Duggen *et al*., 2004, 2005, 2008).

(F) During the Serravalian, the effects of slab breakoff kept spreading along the Mediterranean Maghreb margin, reaching Tunisia and Oranie. The Trans-Alboran magmatism migrated westwards because of E-W extension, along with the Malaga dikes and products of crustal anatexis.

(G) In Tortonian times, magmatism was still active and widespread. As the E-W extension was about to stop, the Trans-Alboran volcanic centers finally acquired their present-day locations. Associated with the Cabo de Gata volcanism, polymetallic mineralizations emplaced in the Rodalquilar district and surroundings. Along the Mediterranean Maghreb margin, slab breakoff-related magmatism reached the NE Morocco (Trois Fourches). At the Tunisian end of the margin, polymetallic mineralizations emplaced in the Nefza district (Oued Belif hematite-rich breccia). The first occurrence of intraplate alkaline volcanism occurred at that time in the Atlas (Siroua).

(H) 2 Ma later, the E-W extension in the Alboran region finished. This period displayed the last calc-alkaline magmatic manifestations. In Trans-Alboran, they were limited to the Betics while the slab breakoff-related magmatism was restricted to the extremes of the Mediterranean Maghreb margin. On the Moroccan end of the margin, an epithermal event took place throughout the Melilla-Nador peninsula.

(I) In the Late Messinian, only a few patches of alkaline magmatism remained. Except for the intraplate magmatism of the Siroua complex, they were the ultimate manifestations of slab breakoff, as the asthenospheric upwelling proceeded and partial melting occurred in the sole asthenospheric mantle (Maury *et al.*, 2000). They set up in transtensive reactivation of crustal-scale fault zones inherited from the Variscan orogeny (Piqué *et al.*, 1998).

(J) From the Messinian to the Present, magmatic activity was represented by an intraplate alkaline volcanism, defining the NE-SW "Morocco Hot Line" from the Siroua to the Valencia trough (Michard *et al.*, 2008).

Discussion and conclusions

The analysis of the compiled data and the correlations with tectonic events shows that (1) E-W extension in the Alboran domain was coeval with the migration of magmatism from East to West between 20 and 8 Ma and (2) resumption of N-S compression around the Alboran Sea was contemporaneous with the end of this westward migration of magmatism after 8 Ma. The E-W extension can thus be attributed to the westward slab rollback after initiation of the tear. This westward slab retreat initiated an E-W extension that lasted 12 Ma until ca. 8 Ma along some 900 km at an average velocity of ~7-8 cm/yr, which is a reasonable figure for asthenospheric flow. This extension led to the exhumation of metamorphic core complexes – the Sierra Nevada, Sierra de Los Filabres and Sierra Alhamilla domes – which are elongated parallel to the direction of stretching, thus falling into the a-type dome category of Jolivet *et al.* (2004). Le Pourhiet *et al.* (2012) have shown that such dome can develop if a component of strike-slip shearing is added to extension. The presence of a-type domes thus reinforces the case for a lateral migration of a slab tear below the Alboran region.

At 8 Ma, N-S compression is recorded again in the Alboran region. This coincides with the end of magmatism migration: Moroccan magmatic centers in Oranie, Guilliz or the Melilla-Nador peninsula (Trois Fourches, Gourougou, Beni Bou Ifrour) indeed display superimpositions in time and space of potassic and ultrapotassic (transitional) calc-alkaline magmatism, and ultimate alkaline magmatism (Hernandez and Bellon, 1985; Hernandez *et al.*, 1987; El Bakkali *et al.*, 1998; Duggen *et al.*, 2004; 2005). This transition in time from calc-alkaline to alkaline affinities in the same region within a 2 Ma timespan shows that the magmatism is now dominated by the influx of hot asthenosphere rather than by subduction-related mantle melts. The end of the westward migration of magmatism is associated with the end of extension and the beginning of a new phase of dominant N-S compression due to the convergence of Africa and Eurasia. This shows that the tectonic regime in the Alboran Sea was under the control of the retreating slab before 8 Ma with dominant extensional tectonic. As soon as slab retreat stopped, the only remaining cause of deformation is the convergence of Africa and Eurasia that leads to this new compressional phase.

From Dellys to Northern Tunisia, most of the magmatism occurs in a short time window of ca. 15 Ma ± 2 Ma, with a slight rejuvenation towards the easternmost end. On this part of the Mediterranean Maghreb margin, compression is recorded in the Tellian nappes since the Late Burdigalian (20-18 Ma, NE Algeria) to the Langhian (Tunisia). This migration is related to the global eastward slab retreat in Central Mediterranean.

The Ras Tarf volcano however does not fit into this general W-E trend: as an equivalent to the Cabo de Gata volcanism (Hernandez and Bellon, 1985), it indeed belongs to the subduction-related Trans-Alboran magmatism.

The gap observed in Algerian magmatism between Miliana and the Oranie (Fig. 3) is either due to: (1) the absence of significant magmatism, (2) the lack of data due to poor field conditions or (3) an acceleration of the slab retreat between ca. 16-12 Ma. Tomographic data tend to invalidate the first hypothesis. We favor the third one, which is consistent with previous work (Lonergan and Platt, 1995; Lonergan and White, 1997; Jolivet and Facenna, 2000).

To conclude: the north African margin and the Alboran region during the Neogene have recorded the progressive development of a slab tear and the westward migration of a torn piece of slab from ca. 20 to 8 Ma. This period is almost exactly concordant with a first-order E-W extensional phase in the Alboran domain that led to the exhumation of a-type metamorphic core complexes and the formation of sedimentary basins, onshore and offshore Spain and Morocco. The most significant effects of the slab tear visible in the crust (see also Do Couto *et al.*, in prep.) are thus a westward migration of magmatism and a transition through time from calc-alkaline to alkaline volcanism and the formation of metamorphic domes elongated parallel to the direction of migration. The velocity of migration of the torn piece of slab in the asthenosphere can be estimated at around 7-8 cm/yr.

Acknowledgements

References

Figures

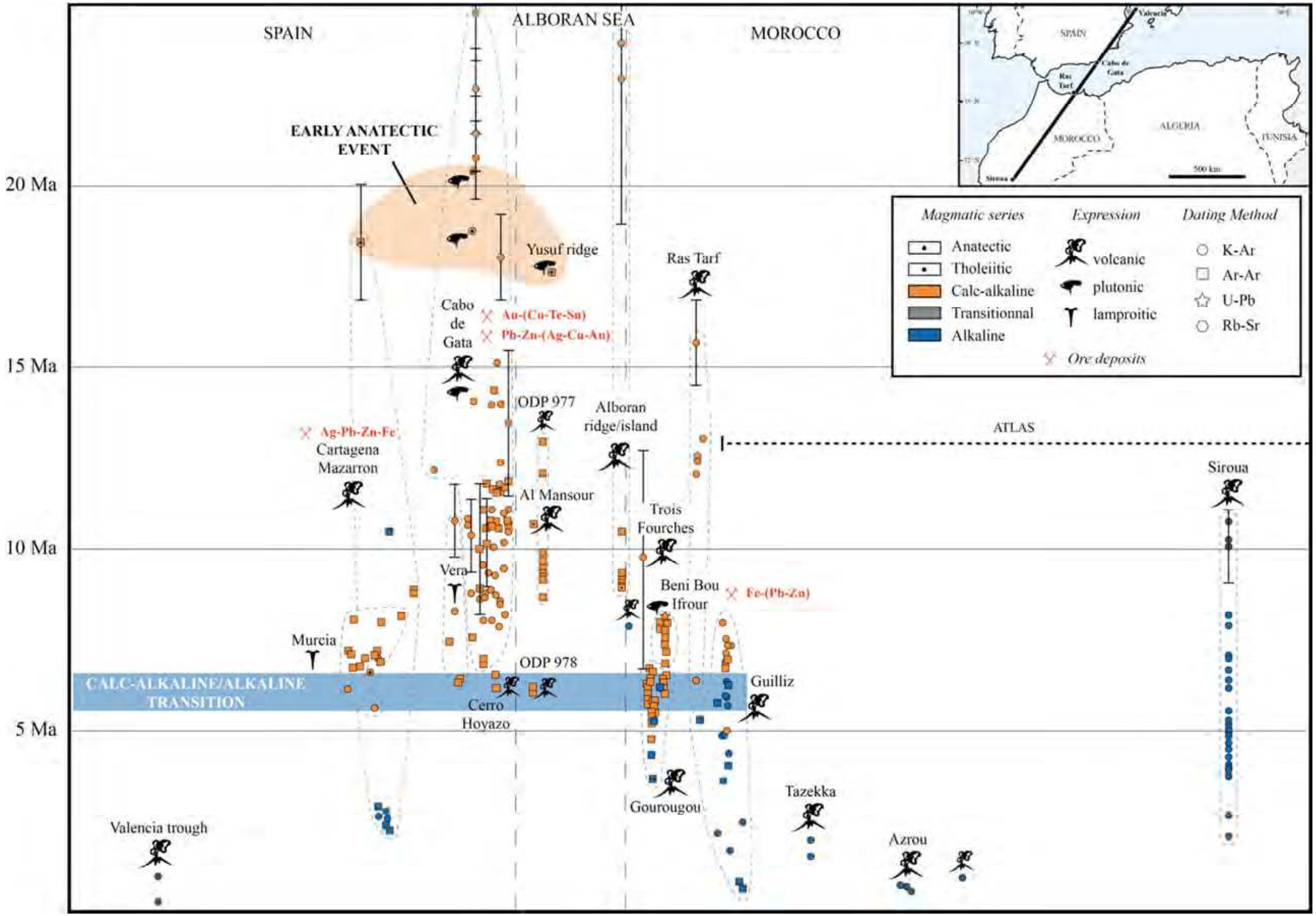

Fig. 1 : NE-SW Trans-Alboran Age *vs* Distance transect (200 km wide). Errors on ages are displayed only if they exceed 1 Ma.

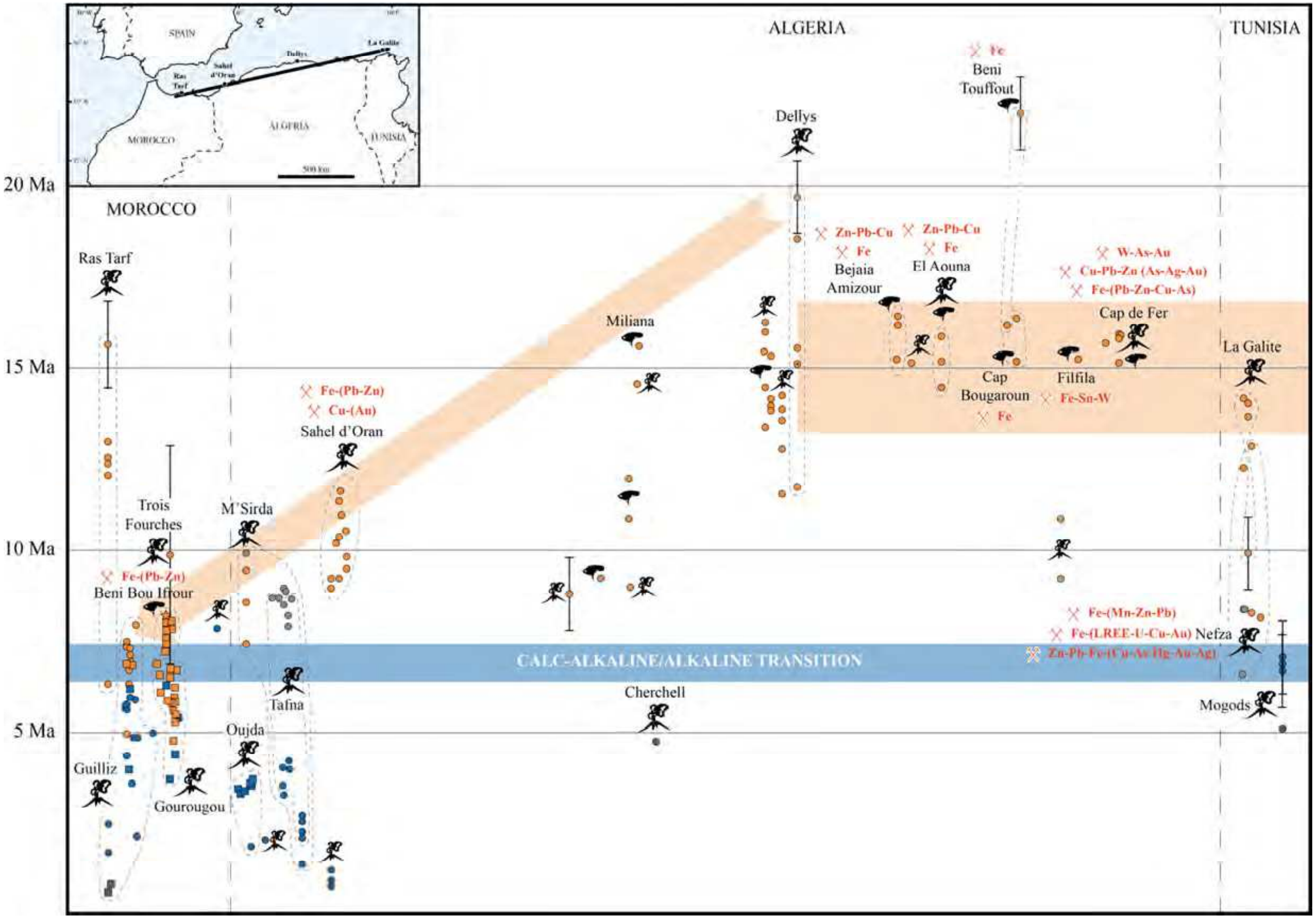

Fig. 2 : WE Age *vs* Distance transect along the north African margin (200 km wide ; Alboran Sea datings are not taken into account). Errors on ages are displayed only if they exceed 1 Ma.

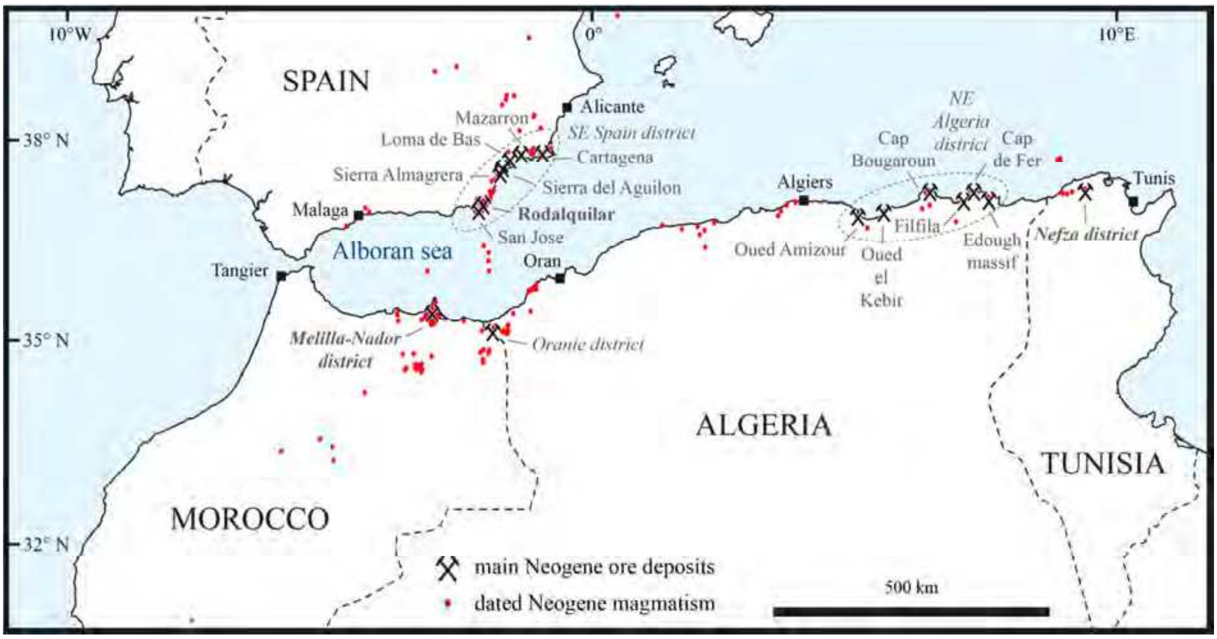

Fig. 3 : Distribution of dated Neogene magmatism and main Neogene ore deposits in the study area.

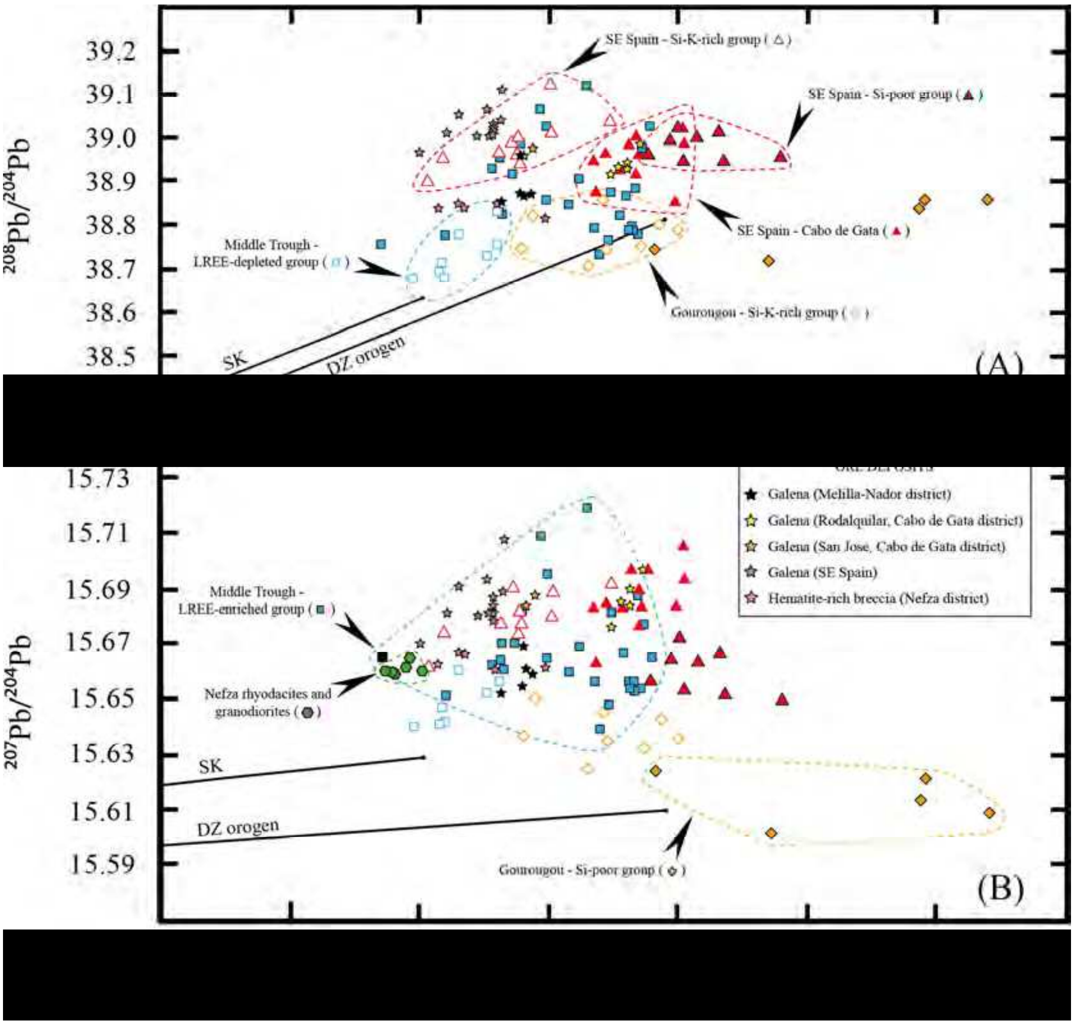

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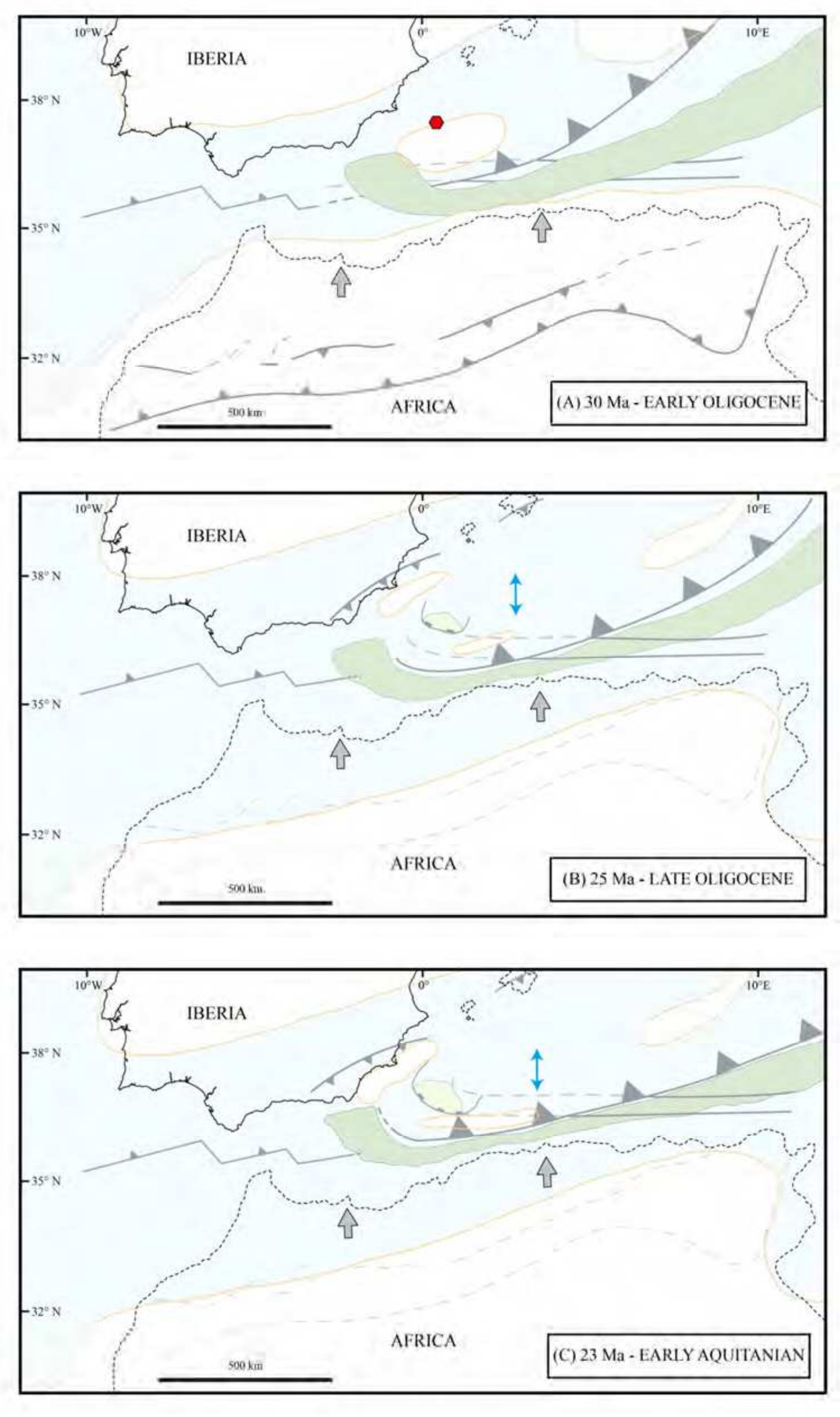
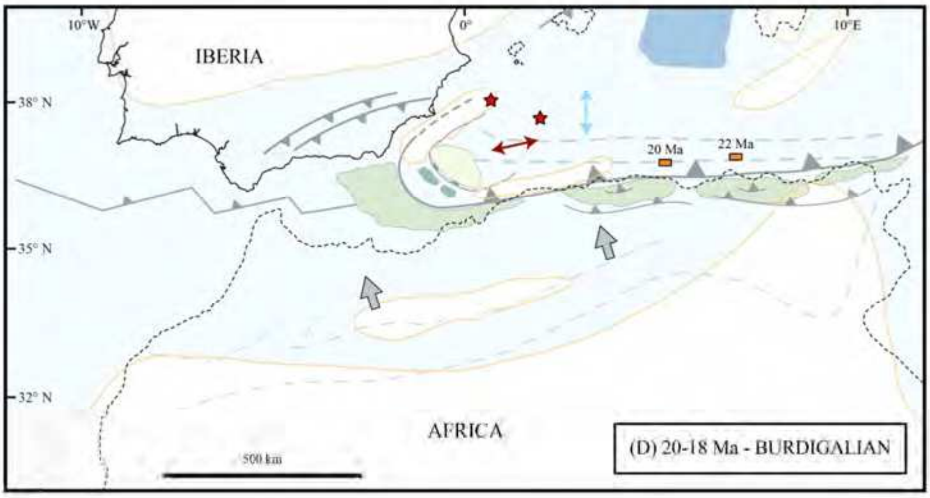
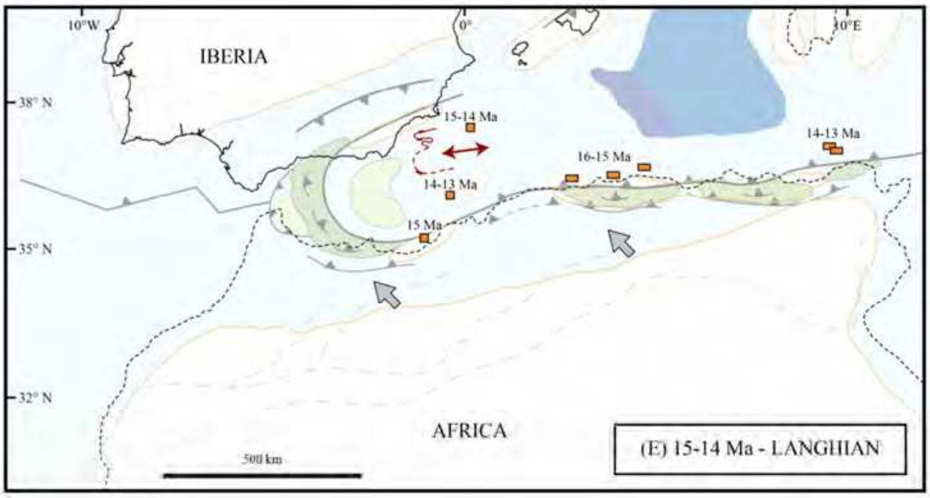
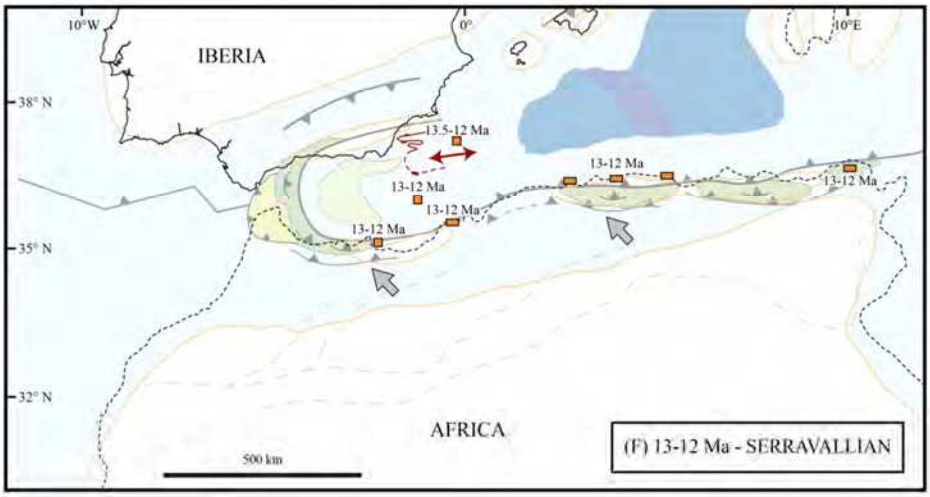
Fig. 4 : ^{208}Pb/^{204}Pb *vs* ^{206}Pb/^{204}Pb (A) and ^{207}Pb/^{204}Pb *vs* ^{206}Pb/^{204}Pb (B) diagrams of galenas and volcanic rocks from southeastern Spain, northeastern Morocco and northeastern Tunisia.

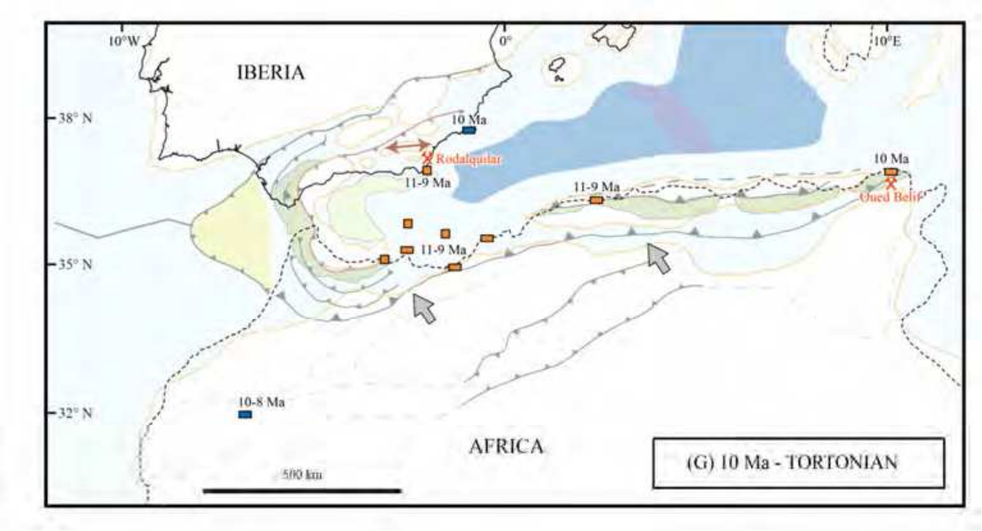
Fig. 5 : Paleogeographic reconstitutions of the western Mediterranean from the Early Oligocene to the Present (Damien Do Couto, 2014).

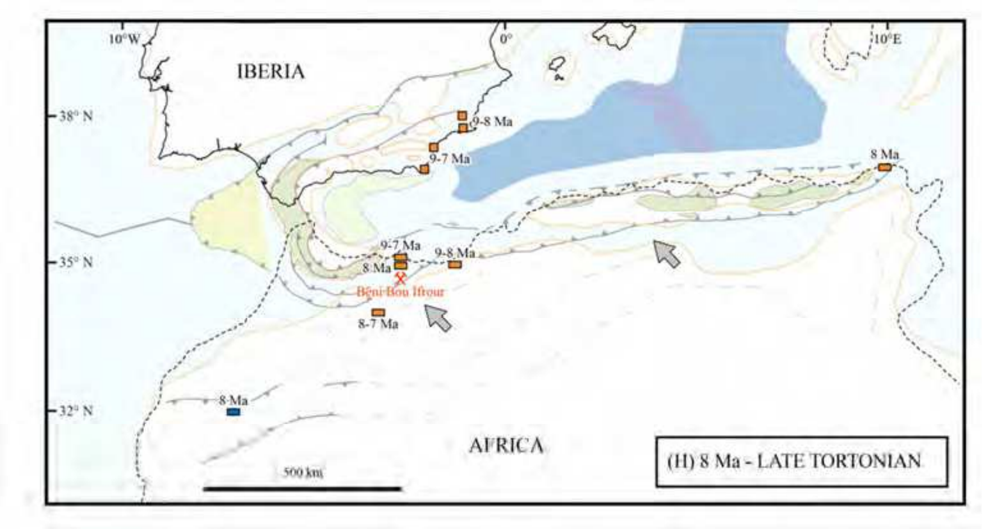


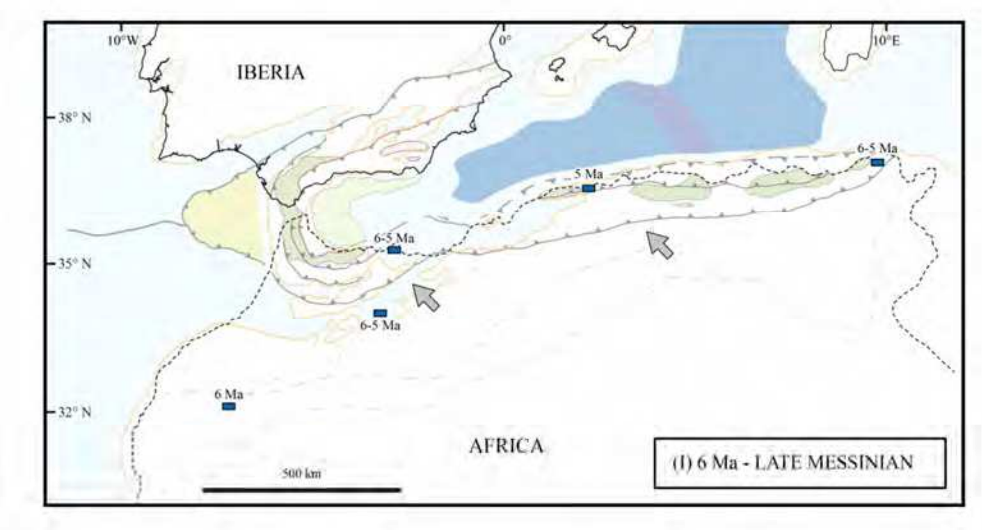

10°W
0°
10°E
IBERIA
38° N
35° N
32° N
20 Ma
22 Ma
AFRICA
500 km
(D) 20-18 Ma - BURDIGALIAN


10°W
0°
10°E
IBERIA
38° N
35° N
32° N
15-14 Ma
14-13 Ma
16-15 Ma
14-13 Ma
15 Ma
AFRICA
500 km
(E) 15-14 Ma - LANGHIAN


10°W
0°
10°E
IBERIA
38° N
35° N
32° N
13.5-12 Ma
13-12 Ma
13-12 Ma
13-12 Ma
13-12 Ma
13-12 Ma
AFRICA
500 km
(F) 13-12 Ma - SERRAVALLIAN


10°W
0°
10°E
IBERIA
38° N
35° N
32° N
10 Ma
Rodalquilar
11-9 Ma
11-9 Ma
10 Ma
Oued Belif
11-9 Ma
10-8 Ma
AFRICA
500 km
(G) 10 Ma - TORTONIAN


10°W
0°
10°E
IBERIA
38° N
35° N
32° N
9-8 Ma
9-7 Ma
8 Ma
9-7 Ma
8 Ma
9-8 Ma
Beni Bou Ifrour
8-7 Ma
8 Ma
AFRICA
500 km
(H) 8 Ma - LATE TORTONIAN


10°W
0°
10°E
IBERIA
38° N
35° N
32° N
6-5 Ma
5 Ma
6-5 Ma
6-5 Ma
6 Ma
AFRICA
500 km
(I) 6 Ma - LATE MESSINIAN

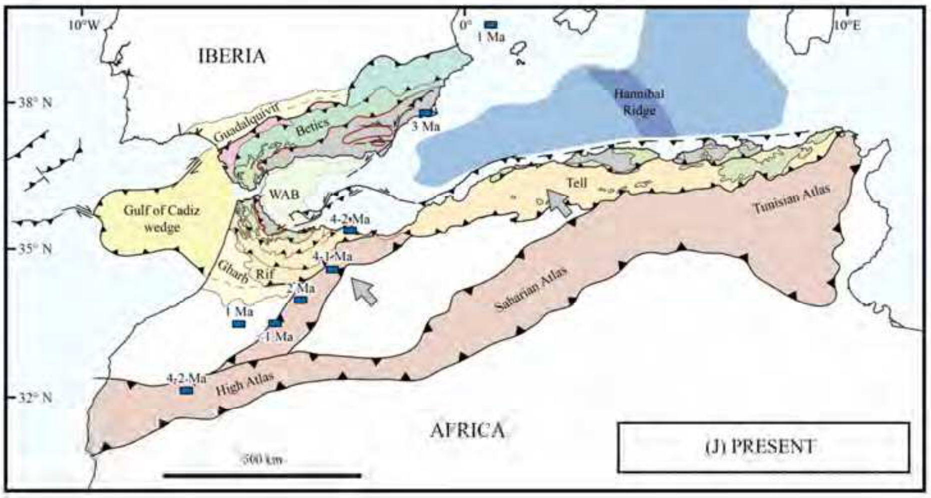


Table 1 : Lead Isotopic compositions of the Melilla-Nador peninsula galenas.

Sample	Localisation	Host-rock	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb
AFRA1f	Afra	Cretaceous schists	18,782	15,661	38,868
AFRA4	Afra	Cretaceous schists	18,764	15,652	38,850
AFRA6	Afra	Cretaceous schists	18,787	15,659	38,872
OUK35	SW Jbel Ouiksane	Cretaceous schists	18,779	15,669	38,958
FOU4	Mina Rosita	Paleozoic substratum	18,779	15,655	38,870