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Can Moroccan Atlas lithospheric thinning and volcanism be induced by Edge-Driven Convection?

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ABSTRACT

The Moroccan lithosphere is characterized by an anomalously thinned area, located beneath the Atlas domains, which forms a singular narrow NE–SW directed strip overlain by Cenozoic alkaline volcanism. The origin of this thinning and volcanism is still a matter of debate. The proposed models invoke processes either related to the Mediterranean slab or mantle plumes. Herein, we propose an alternative Edge-Driven Convection (EDC) model involving small-scale convection at the boundary between the West-African craton and the Atlas lithosphere. Our comparison of the Atlas lithosphere velocity and volcanism episodes during the last 80 Ma points out that volcanism occurs when plate moves at velocities *c.*<1 cm a^{-1}, a velocity sufficiently low to trigger EDC. This is the first process that could explain the *c.* 20 Ma volcanism shutdown separating the two volcanic episodes of the Atlas. In addition, it may successfully account for the lithosphere thinning location and geometry and volcanism geochemistry.

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Introduction

The high topography (>4000 m) of the Moroccan Atlas intraplate mountains (NW Africa, Fig. 1) is due to the combination of significant lithospheric thinning and crustal shortening during Cenozoic times (Missenard *et al*., 2006). The thinned lithosphere forms a NE–SW directed narrow strip cross-cutting the E–W main structures of the Atlas belt, and is overlain by alkaline volcanism. The origin of this thinning and the associated volcanism still remains poorly understood. The vicinity of the northern Alboran slab and the western Canary Hotspot (Fig. 1A) led to contrasting models, invoking subduction-related and/or intraplate mantle processes, which do not fully account for the geological features of Morocco.

Herein, we propose an alternative Edge-Driven Convection model (EDC; Elder, 1976), which consider the neighbour West-African Craton rim (WAC; Fig. 1A).

Indeed, EDC is a small-scale convective instability forming at any step or discontinuous change in thickness of a thermal boundary layer such as the limit between thick cratonic lithospheres and thinner (oceanic or young continental) lithospheres. The convection is induced by the temperature contrast at the vertical wall separating the cold craton from the warmer asthenosphere (King and Anderson, 1998). Decompression in the upwelling part of the convection cell is thought to be sufficient to trigger partial melting (King and Anderson, 1995; Farrington *et al*., 2010). However, as EDC is a relatively weak instability, fast relative motion between the lithosphere (craton and thin lithosphere) and the underlying asthenospheric mantle may produce a shear-coupling that completely overwhelms EDC (King and Anderson, 1998; Shahnas and Pysklywec, 2004; Farrington *et al*., 2010).

In this article, we discuss the feasibility of EDC in the context of the Moroccan Atlas domains (Fig. 1B). To estimate the Moroccan lithosphere–asthenosphere relative motion, we calculate the absolute Atlas lithosphere velocities in a fixed Hotspot reference frame during the last 80 Ma. We evidence for the first time that volcanism occurs when plate moves at low velocities *c.* <1 cm a^{-1}, whereas it stops at higher velocities. This constitutes an argument in favour of EDC at the northern boundary of the WAC. Finally, we detail how this model could successfully account for the geological characteristics of the Atlas.

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Lithosphere structure and volcanism of Morocco

The Moroccan Atlas lithosphere is anomalously thin (Seber *et al*., 1996; Teixell *et al*., 2005; Zeyen *et al*., 2005; Fullea Urchulutegui *et al*., 2006, 2010; Missenard *et al*., 2006): the Lithosphere–Asthenosphere Boundary (LAB) is 60–70 km deep below the Middle Atlas, Central High Atlas and Anti-Atlas, while it reaches depths of 120–140 km beneath the Meseta (Fig. 1B). This thinning is restricted within a NE–SW strip (~150 km wide by 1000 km long) cross-cutting the Atlas belts and the main N–S hercynian or E–W cenozoic crustal sutures (Missenard *et al*., 2006; Fullea Urchulutegui *et al*., 2010).

Volcanic activity took place in the three main geological domains of Morocco (Rif, Atlas, Sahara) during Cenozoic (Fig. 1). The northernmost magmatism, related to the Rif subduction system, includes Gourougou, Guilliz volcanic centres and Oujda (Fig. 1B; Chalouan *et al*., 2008). It is composed of calcalkaline or transitional to alkaline lavas (e.g. Maury *et al*., 2000; Coulon *et al*., 2002).

In the southern Atlas and Sahara domains (Fig. 1A), volcanism exclusively displays an alkaline intraplate chemical affinity (e.g. Mokhtari and Velde, 1988; Rachdi, 1995; El Azzouzi *et al*., 1999, 2010; Wagner *et al*., 2003). It comprises the Taourirt

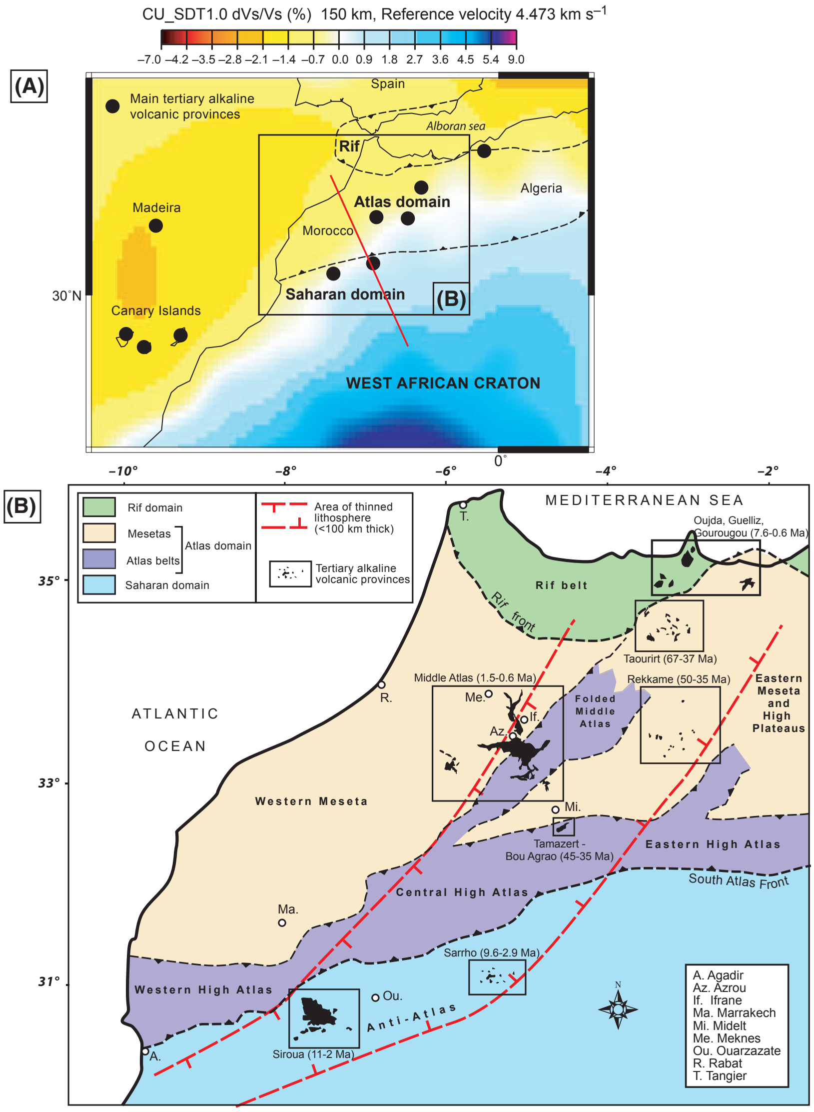

Fig. 1 (A) North-West Africa map showing the 3D shear-wave velocity tomographic model based on surface wave diffraction tomography. Map generated from the CUB model of N. Shapiro (http://ciei.colorado.edu/˜nshapiro/MODEL/). See Ritzwoller *et al.* (2002) and Shapiro and Ritzwoller (2002) for surface wave diffraction tomography and data processing. Colour scale shows the shear velocity as percentage perturbation relative to the reference velocity values of 4.473 km s^{-1} at a depth of 150 km. The most important geological structures and domains around the WAC are reported: (i) to the North, the Rif-Tell domain including the Maghreb margin (North Algeria) that belongs to the Mediterranean subduction system, (ii) to the South, the intraplate Atlas domains. The southern part of the covered area corresponds to the West-African Craton, close to the Saharian domain of Morocco. Red line: cross-section, Fig. 3. (B) Details of the Moroccan Atlas systems (Anti-atlas, High Atlas, Middle Atlas) and location of the Cenozoic alkaline volcanism outcrops. Periods of volcanic activity are compiled from various sources (see Table 1 for references). It is noteworthy that volcanism developed above the anomalously thinned lithosphere zone evidenced by Missenard *et al.* (2006) and Fullea Urchulutegui *et al.* (2010) and also called the Moroccan Hot Line (Frizon de Lamotte *et al.*, 2009). In this elongated zone (light grey), the lithosphere is < 100 km thick, inducing at least 1000 m of surface doming. As underlined by Liégeois *et al.* (2005), such a regional structure is too narrow and shallow to be seen in tomographic models (A), which only show the large scale structure of the lithosphere–asthenosphere.

district (south of the Rif Front), the Rekkame field, the large Middle-Atlas volcanic field, the Tamazert complex (High Atlas belt) and the Sahro volcanic field (or 'Saghro') and Siroua volcanic edifice (or 'Sirwa'), both located in the Anti-Atlas belt (Fig. 1B, Table 1).

Targets and methods

We focused our study to the anomalously thin lithosphere strip of Morocco (Fig. 1B) which includes the volcanic provinces of the Atlas and Sahara domains (Fig. 1B and Table 1).

The thicknesses change between the WAC (> 200 km) and the Atlas lithosphere (~120 km) constitutes an ideal configuration for EDC. However, a slow relative motion between the lithosphere and the asthenosphere is also required. As the degree of coupling between the lithosphere and underlying mantle remains unknown and, according to King and Anderson (1998), it is unlikely that the entire upper mantle is moving together with the lithospheric plate, we made the assumption (as Farrington *et al.*, 2010) that absolute plate motion velocities can reflect the relative motion between the continental lithosphere (craton and thinner lithosphere) and the asthenosphere. Thus, we calculated the Atlas lithosphere velocities, as well as the volume of volcanic products emitted, for the last 80 Ma.

Plate velocities were calculated by spherical trigonometry using palaeopoles and rotation data from four independent studies of plate motions reconstructions (Morgan, 1983; Duncan and Richards, 1991; Garfunkel, 1992; Müller *et al.*, 1993). Our results correspond to the absolute motion velocities, in a hotspot absolute motion frame, of a point located at 32°N 5°W (i.e. in the Moroccan Central High Atlas, Fig. 1B) since 80 Ma. We also included velocities computed from Madeira Islands and seamounts ages (Fig. 1A; Geldmacher *et al.*, 2005).

The computation of the volcanic products volumes first required a precise digitization of each volcanic edifice or field cited above (from Morocco 1/1 000 000 to 1/50 000 geological maps). Then, we extracted

Table 1 Main characteristics (locations, ages and lithologies) of the Cenozoic alkaline volcanic provinces of Morocco.

Area (location Fig. 1B)	Taourirt	Rekkame field	Middle-Atlas volcanic field	Tamazert complex High Atlas	Saghro (or `Sahro') field Anti-Atlas	Siroua (or `Sirwa') volcano Anti-Atlas
Ages	Palaeocene–Eocene (67–37 Ma)	Palaeocene–Eocene (50-35 Ma) rarely Pleistocene (*c.* 1.4 Ma)	Quaternary (1.5–0.6 Ma)	Eocene (45–35 Ma)	Miocene to Pliocene (9.6–2.9 Ma)	Miocene to Pliocene (11–2 Ma)
Lithologies	Alkaline lamprophyre (camptonite and monchiquite including carbonatite enclaves), dykes, sills and breccia pipes, plus rarer olivine nephelinite lava flows and nepheline syenite intrusions	Numerous basaltic edifices	Azrou field: basaltic flows and volcanic centres Oulmès field: strongly alkaline lavas (basanite, nephelinite and phonolite)	Elongated intrusion with pyroxenite, nepheline syenite and carbonatite, associated with dykes including lamprophyres	Series of thin (<100 m) phonolitic lavas and tuffs lying on lacustrine Pliocene sediments, as well as necks and diatremes	Lavas and tuffs, mainly alkaline–peralkaline trachyte and phonolite with some mugearite and benmoreite and rare mafic rocks
References	Mokhtari and Velde (1988), Wagner *et al.* (2003)	Rachdi *et al.* (1997)	Harmand and Cantagrel (1984), Rachdi (1995), El Azzouzi *et al.* (1999, 2010)	Agard (1973), Bouabdli *et al.* (1988), Bernard-Griffiths *et al.* (1991), Mourtada *et al.* (1997)	Berrahma *et al.* (1993), De Sitter *et al.* (1952)	Berrahma and Delaloye (1989)

the altitudes from the SRTM30 elevation dataset (USGS EROS data centre). We digitized the contour of the basement/volcano contacts for each edifice. The contours altitudes were then extrapolated using a minimum curvature method with Surfer software to reconstitute the basal surfaces.

Volumes were obtained by subtracting the computed volcano basal surface from the present topography (Table 2). Finally, we calculated the volcanic production rates using the published timing of volcanic activities (Table 1).

Results

Computed ages, areas, volumes and rates of emission for each volcanic province are summarized in Table 2. Cumulative volcanic emission rates and Atlas lithosphere absolute velocities since the last 80 Ma are presented in Fig. 2. Although some discrepancies do exist between the five velocity models (in particular those of Müller *et al.*, 1993 relative to the others), the general pattern is close. Two periods of relatively high velocity are identified: one before 60 Ma (up to 3 cm a^{-1}; Duncan and Richards, 1991), and the other between 35 and 15 Ma (up to *c.* 2 cm a^{-1}; Geldmacher *et al.*, 2005). The data are particularly consistent at two specific times where all velocities decrease below 1 cm a^{-1} (Fig. 2): one between 80 and 60 Ma (speeds divided at least by two for each models), the second since 15 Ma (also confirmed by Atlantic seamount ages study; O'Connor *et al.*, 1999).

The remarkable feature for the first time evidenced in this study is that most of the volcanism occurs when the absolute motion velocity is the lowest (< *c.* 1 cm a^{-1}; Fig. 2), whereas periods of volcanic gap almost systematically correspond to highest plate velocities (> 1 cm a^{-1}).

Discussion

Previous models for Morocco lithosphere thinning and associated volcanism

Subduction process

Teixell *et al.* (2005) speculate that the Moroccan alkaline volcanism and lithospheric thinning could originate

Table 2 Area, volume and volcanic emission rates computed for Morocco alkaline-type volcanism of the Atlas and Sahara domains. See Table 1 for age ranges references and explanations in the text for calculation.

Province	Location	Min. Age (Ma)	Max Age (Ma)	Area (km^2)	Volume (km^3)	Emission rates ($km^3\ Ma^{-1}$)
Taourirt	North Morocco	37	67	121	2.42	0.08
Rekkame	Eastern Meseta	35	50	21	0.84	0.06
Tamazert – Bou Agrao	High Atlas	35	45	32	1.60	0.16
Siroua	Anti-Atlas	2	11	600	65	7.22
Sagrho	Anti-Atlas	2.9	9.6	28	5.60	0.84
Middle-Atlas field	Atlas domain	0.6	1.5	874	2.62	2.91

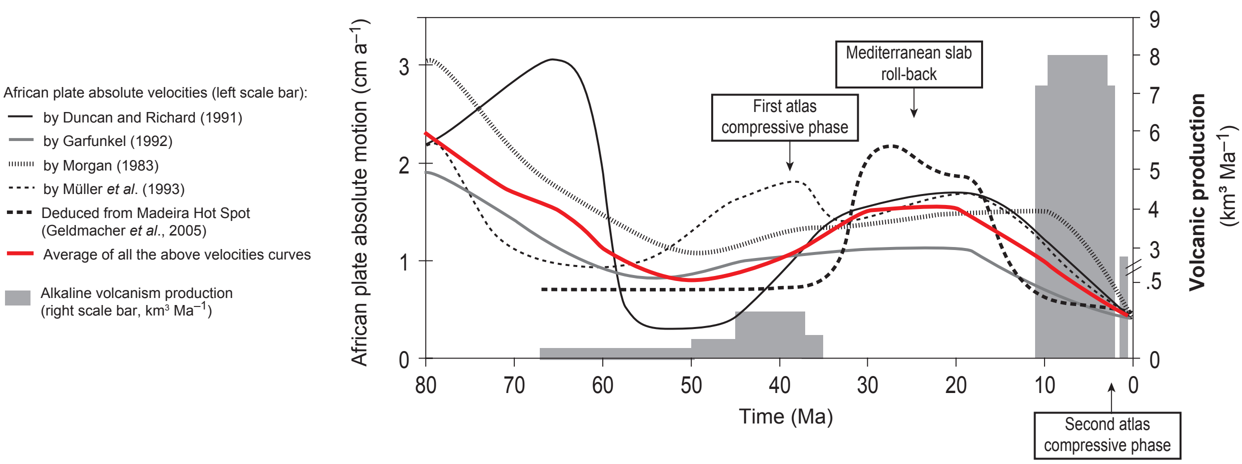

Fig. 2 Atlas lithosphere absolute motion (cm a^{-1}) in a fixed hotspot frame compared with volcanic production since the last 80 Ma ($km^3\ Ma^{-1}$). The red curve represents the average velocity of the five models used in this study. The current speed of 4.5 mm a^{-1} is from Nuvel1 model. The two main periods of volcanic activity in the Atlas and Sahara domains coincide with absolute plate velocities lower than *c.* 1 cm a^{-1}. The important difference of volcanic production between the two main phases of activity could be at least partly due to a major erosion event affecting the oldest volcanics during Middle to Late Miocene (Barbero *et al.*, 2007; Missenard *et al.*, 2008; Balestrieri *et al.*, 2009).

from lateral flow of asthenospheric mantle at the tip of the Mediterranean (Eo-Alpine or Alboran) slabs, as it has been proposed for Sicily alkaline volcanism (Gvirtzman and Nur, 1999; Cadoux *et al.*, 2007).

Thermal erosion by upwelling hot mantle is a suitable mechanism to thin the lithosphere, but the relationship between slab-induced flows and the particular location and geometry of the Moroccan thinning and associated volcanism remains unclear.

Delamination model with or without Canary mantle plume material flow

Mantle plume material flowing through a lithospheric corridor (created by delamination), from the Canary to the Atlas (Duggen *et al.*, 2009) could account for the location and geochemistry of the volcanism. Delamination of the Atlas lithosphere could be supported by the occurrence of intermediate depth seismicity (Ramdani, 1998) and might explain the volcanism geochemistry without requiring mantle plume material (e.g. Pearce *et al.*, 1990; Platt and England, 1993). However:

1 such seismicity is not evidenced in the Anti-Atlas, where lithosphere is thin (< 70 km thick);
2 the estimated shortening across the Atlas domain is < 20 km (Teixell *et al.*, 2005; Frizon de Lamotte *et al.*, 2009), which is insufficient to generate lithospheric thickening and subsequent delamination (e.g. Fullea Urchulutegui *et al.*, 2010);
3 the thinning developed independently of the geological main domains and E–W structures of the Atlas (Missenard *et al.*, 2006). This particularity seems inconsistent with the delamination model, such process being expected to be controlled by crustal structures;
4 the age inferred by Ramdani (1998) for the delamination event, between 25 and 15 Ma, can only account for the second main volcanism episode (< 13 Ma; Fig. 2).

The Atlas corridor invoked by Duggen *et al.* (2009), necessary for Canary plume material to flow north-eastward, was thus not present during the first volcanism period (67–35 Ma). Consequently, this latter cannot be issued from Canary mantle plume material. Besides, as underlined by Berger *et al.* (2009), the 'Canary-like' geochemical compositions are not restricted to areas above the lithospheric thinning in Morocco (e.g. in Algeria, Soudan, Lybia and Egypt; Liégeois *et al.*, 2005; Lustrino and Wilson, 2007; Lucassen *et al.*, 2008).

'Baby-plume' or convection cells

Fullea Urchulutegui *et al.* (2010) suggest the involvement of a deep mantle reservoir extending from the Canary Islands to the Western Mediterranean (Hoernle *et al.*, 1995; Goes *et al.*, 1999): the hot material would flows upward through a 'baby-plumes' or via convection cells. Nevertheless, the existence of such a widespread deep reservoir is far from being unanimously approved (e.g. Foulger *et al.*, 2005). Then, neither the convection cells nor the 'baby-plume' provide satisfying explanation for the elongated geometry of the lithospheric thinning and the volcanism periodicity. In addition, the lack of extensional structures in the thinned lithosphere area is inconsistent with the 'baby-plume' hypothesis, as extension is frequently associated to plume/lithosphere interactions (D'Acremont *et al.*, 2003; Burov *et al.*, 2007).

This review shows that none of the models currently proposed in the literature can account for all the geological particularities of the Atlas.

We argue hereafter why the EDC could be a good alternative model.

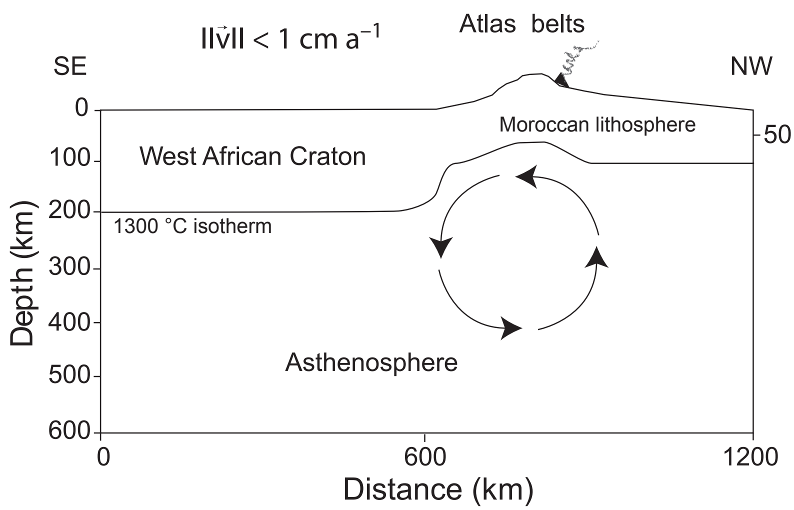

Fig. 3 Edge-driven convection model applied to Morocco: schematic NW–SE cross-section (see red line, Fig. 1) illustrating the development of an edge-driven convection cell at the boundary between the West-African Craton and the Moroccan Lithosphere. The temperature contrast between the cold WAC wall and the hot asthenosphere, combined with slow Africa plate motion (<1 cm a^{-1}), constitute ideal conditions for EDC to initiate. The sublithopsheric convection cell triggers thermal erosion of the overlying lithosphere as well as partial melting of the mantle allowing volcanic activity.

Edge-Driven Convection: an alternative model

The boundary between the thick cold WAC and the thinner Moroccan lithosphere is an ideal location for small-scale convection development. This hypothesis is supported by tomographic images showing fast seismic velocities anomalies beneath the WAC, extending to depth 300–400 km in narrow linear bands which King and Ritsema (2000) interpret as downwelling limbs of a small-scale convection cell associated with cratonic roots under Africa, consistent with EDC.

The correlation between plate velocities and volcanism activity demonstrated in Fig. 2 represents an additional argument supporting the occurrence of EDC processes. We show that during the last 80 Ma, magmatism occurred in Morocco when the Atlas lithosphere absolute motion slowed down below a speed of about 1 cm a^{-1}. Interestingly, this corresponds to the critical speed proposed by King and Anderson (1998) below which thermal buoyancy convection can develop. We show that periods of faster plate motion (>1 cm a^{-1}) coincides with absence of magmatic activity. The EDC could be thus the first model explaining the striking 20 Ma volcanic shutdown observed between the two main magmatic episodes (Fig. 2).

An asthenospheric convection roll acting parallel to the craton rim (Fig. 3) would perfectly explain the location and elongated geometry of the Atlas lithosphere thinning (Fig. 1 B). Indeed, this convection could induce thermal erosion of the base of the continental lithosphere. The incorporation of thermally eroded metasomatized lithosphere into the asthenosphere (Raffone *et al.*, 2009) might account for the geochemically enriched OIB-like character of the volcanic rocks.

Importantly, EDC can explain the lack of extension in the Atlas. Indeed, in the EDC model, the asthenospheric flow is directed towards the craton in the upper part of the cell (Elder, 1976; King and Anderson, 1998; Fig. 3). We might thus expect slight compression strains in the upper plate that could generate the crustal diffuse seismicity observed above the lithospheric thinning (see fig. 8 in Missenard *et al.*, 2006).

A possible scenario

The onset of the Africa–Europe collision at beginning of the Palaeocene (Jolivet and Faccenna, 2000) is probably at the origin of the drastic velocity decrease of the African plate (Fig. 2), which allowed EDC to develop at the northern edge of the WAC from Palaeocene to Eocene. Decompression in the upper part of the convection cell triggered sufficient partial melting of the subcontinental mantle to fed volcanic activity during *c.* 30 Ma.

At ~35 Ma, volcanic activity ceased with the acceleration of the African plate that was most probably driven by the northernmost Alboran slab roll back (Jolivet and Faccenna, 2000).

We interpret the successive velocity decrease as a consequence of the end of slab roll back process in the Alboran Sea, and the return to a strong Africa–Europe coupling.

As the Atlas lithosphere slowed down again below 1 cm a^{-1}, EDC restarted and induced the second Mio-Quaternary magmatism episode. The initiation of this new period of EDC is marked by a significant denudation event affecting the relief above the thin lithosphere (Barbero *et al.*, 2007; Missenard *et al.*, 2008; Balestrieri *et al*., 2009). This important erosion phase is likely to have partly removed the products of the first magmatic episode; this could explain the small preserved volumes compared with the youngest (< 13 Ma) volcanic edifices.

Thermal erosion of the Moroccan lithosphere above the EDC roll led to the present channel-like LAB topography that contributes to the uplift of the Atlas (Missenard *et al*., 2006).

Taking into account the distance between the WAC rim and the extent of the Cenozoic alkaline volcanic provinces of Morocco, we estimate that this convection roll could be about 600 km wide (Figs 1 and 3), a width similar to the one observed by King (2007) in North Atlantic or Reusch *et al*. (2010) in Central Africa.

Conclusions

We show that EDC is an alternative model that cannot be excluded at present time. The relationship between African plate motion velocity and volcanism occurrence pointed out in this study (Fig. 2) constitutes an argument in favour of this process. It can account for the Atlas lithosphere thinning location and shape, magmatism location, periodicity and geochemistry and lack of extensional structures. This model also explains why the thinning is independent of the inherited crustal structures: it is controlled by the craton rim direction (Fig. 1).

To definitely validate the EDC model, future researches should carry out a multidisciplinary study including: (1) geochemistry of the volcanic rocks to better constrain the sources of the volcanism near the craton rim; and (2) seismology to precisely determine the thermal and tectonic structure at the WAC-Atlas lithospheres boundary. The parameters deduced from these studies are crucial to perform realistic numerical modellings to test convection cells at WAC edge.

For the first time here, the Atlas volcanism is considered as peri-cratonic volcanism. It is noteworthy that the EDC is increasingly investigated as a potential process at the origin of volcanism of pericratonic regions worldwide (e.g. Shahnas and Pysklywec, 2004; Knesel *et al*., 2011).

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