Tectonophysics 650 (2015) 34–52

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Short wavelength lateral variability of lithospheric mantle beneath the Middle Atlas (Morocco) as recorded by mantle xenoliths

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ARTICLE INFO

Article history:
Received 31 July 2014
Received in revised form 7 November 2014
Accepted 23 November 2014
Available online 2 December 2014

Keywords:
Lithospheric mantle
Middle Atlas (Morocco)
Lithospheric thinning
Melt–rock interactions
Decompression melting
Strain localization

ABSTRACT

The Middle Atlas is a region where xenolith-bearing volcanism roughly coincides with the maximum of lithospheric thinning beneath continental Morocco. It is therefore a key area to study the mechanisms of lithospheric thinning and constrain the component of mantle buoyancy that is required to explain the Moroccan topography. Samples from the two main xenolith localities, the Bou Ibalghatene and Tafraoute maars, have been investigated for their mineralogy, microstructures, crystallographic preferred orientation, and whole-rock and mineral compositions. While Bou Ibalghatene belongs to the main Middle Atlas volcanic field, in the 'tabular' Middle Atlas, Tafraoute is situated about 45 km away, on the North Middle Atlas Fault that separates the 'folded' Middle Atlas, to the South-East, from the 'tabular' Middle Atlas, to the North-West. Both xenolith suites record infiltration of sub-lithospheric melts that are akin to the Middle Atlas volcanism but were differentiated to variable degrees as a result of interactions with lithospheric mantle. However, while the Bou Ibalghatene mantle was densely traversed by high melt fractions, mostly focused in melt conduits, the Tafraoute suite records heterogeneous infiltration of smaller melt fractions that migrated diffusively, by intergranular porous flow. As a consequence the lithospheric mantle beneath Bou Ibalghaten was strongly modified by melt–rock interactions in the Cenozoic whereas the Tafraoute mantle preserves the record of extensional lithospheric thinning, most likely related to Mesozoic rifting. The two xenolith suites illustrate distinct mechanisms of lithospheric thinning: extensional thinning in Tafraoute, where hydrous incongruent melting triggered by decompression probably played a key role in favouring strain localisation, vs. thermal erosion in Bou Ibalghatene, favoured and guided by a dense network of melt conduits. Our results lend support to the suggestion that lithospheric thinning beneath the Atlas mountains results from the combination of different mechanisms and occurred in a piecewise fashion at a short wavelength scale.

1. Introduction

At the triple junction between the Atlantic Ocean, the Western Mediterranean and the West African Craton, Morocco is characterized by a rugged topography including the highest reliefs in northern Africa. There is however a consensus to consider that the Moroccan topography is only partly explained by crustal thickening in response to near- to far-field effects of the convergence between African and European plates. The Atlas mountain ranges were mostly structured in the Cenozoic by inversion of Mesozoic continental rifts related to the opening of the Atlantic and the Alpine Tethys (Frizon de Lamotte et al., 2008 and references therein). However, tectonic shortening did not exceed 10–30%, even in the central High Atlas where the elevation exceeds 4000 m (Beauchamp et al., 1999; Gomez et al., 1998; Teixell et al., 2003, 2009). Moreover, the Anti-Atlas and the eastern Moroccan Meseta, including the 'tabular' Middle Atlas, although virtually unaffected by Cenozoic deformation, were uplifted to above 3000 and nearly 2000 m, respectively. A significant component of mantle buoyancy is therefore required to explain the Atlas reliefs, as also supported by evidence for abnormally thin lithospheric mantle based on gravity, heat-flux, receiver functions, topography and crustal thickness data (Ayarza et al., 2005; Fullea et al., 2006, 2010; Miller and Becker, 2014; Missenard et al., 2006; Teixell et al., 2005), as well as seismological tomography (Bezada et al., 2014; Palomeras et al., 2014). Further evidence for asthenospheric upwelling arises from recent volcanic activity involving generation of sublithospheric melts at 60–120 km depth (e.g. Duggen et al., 2003, 2009; Frizon de Lamotte et al., 2008).

In detail, geophysical studies converge on the existence of a roughly SW–NE trending corridor of thinned lithosphere, 200–500 km wide, where the asthenosphere–lithosphere boundary raises to 90–50 km

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http://dx.doi.org/10.1016/j.tecto.2014.11.020
0040-1951/

(Bezada et al., 2014; Fullea et al., 2010; Jiménez-Munt et al., 2011; Missenard et al., 2006; Teixell et al., 2005; Zeyen and Fernandez, 1994). The corridor (the 'Moroccan Hot Line' of Frizon de Lamotte et al., 2009) extends from the Atlantic margin to the Eastern Rif through the central high-Atlas and the eastern Meseta, and concentrates most of the Moroccan Cenozoic volcanism. Several hypotheses have been put forward regarding the origin of lithospheric thinning beneath Morocco and the geodynamic significance of the Moroccan Hot Line. Debated issues notably addressed the pattern of mantle flow, with models involving upwelling of instable north-African upper mantle (Lustrino and Wilson, 2007), lateral spreading of a Canarian mantle plume (Duggen et al., 2009), toroidal/lateral mantle flow triggered by slab retreat and/or lithosphere delamination in the Alboran back-arc domain (Faccenna and Becker, 2010), or edge-driven convection related to the convergence between Africa and Europe (Kaislaniemi and van Hunen, 2014; Missenard and Cadoux, 2012). The proposed mechanisms of lithospheric thinning vary between two extremes: (1) relational-scale delamination of lithospheric mantle as a result of compressive lithosphere thickening (Duggen et al., 2009) and (2) thermal erosion of lower lithosphere by upwelling upper mantle, possibly reusing Mesozoic rift structures (Berger et al., 2009; Raffone et al., 2009). Between these extremes, to account for the complex topography of the lithosphere–asthenosphere boundary, Bezada et al. (2014) suggested a model involving piecewise lithosphere delamination due to tectonic shortening and loading by high-pressure magmatic segregates, combined with local upwelling of hot mantle and thermal erosion.

Mantle xenoliths allow direct observation of lithospheric mantle and provide insights into the mechanisms of lithospheric thinning. Processes such as eclogite loading and thermal erosion can be assessed, and the xenolith studies also provide clues to understand the role of deformation and fluid-rock processes in the convective erosion of the lithosphere. The most conspicuous xenolith localities in Morocco are concentrated in the 'tabular' Middle Atlas, where intra-plate Cenozoic volcanism coincides with nearly 2000 m uplifting of the undeformed Mesozoic cover and – roughly – with the maximum of lithospheric thinning beneath continental Morocco (Bezada et al., 2014; Fullea et al., 2010; Miller and Becker, 2014). However, previous xenolith studies focused on a single locality — the Bou Ibalghatene maar, in the central part of the volcanic district (Lenaz et al., 2014; Natali et al., 2013; Raffone et al., 2009; Wittig et al., 2010a,b). There, the mantle xenoliths were affected by extensive reactions with silicate and carbonate melts, a feature which is not observed to a similar degree in the other xenolith localities. The Bou Ibalghatene xenoliths may represent a restricted area of focused melt flow that is not representative of the whole Middle Atlas lithospheric mantle. In addition to representative peridotites from Bou Ibalghatene, analysed for comparison, this study deals with mantle xenoliths from the Tafraoute maar, located 45 km to the North-East of Bou Ibalghatene and distal to the main volcanic district. The maar is situated on the NE–SW North Middle Atlas Fault, a major transpressive fault separating the 'folded' Middle Atlas, to the South-East, from the 'tabular' Middle Atlas, to the North-West. The samples have been investigated for their mineralogy, microstructures, crystallographic preferred orientation (EBSD-SEM), and bulk rock and mineral compositions (XRF, EPMA and LA-ICP-MS).

2. Geological setting

The Middle Atlas volcanic province lies on a Mesozoic limestone plateau that represents the easternmost and most elevated part of the Moroccan Meseta, and is sometimes referred to as the 'tabular' Middle Atlas (Fig. 1). The tabular Middle Atlas is separated from the folded Middle Atlas belt to the southeast by a NE-trending, southeast dipping transpressive thrust fault, the 'North Middle Atlas Fault'. Geophysical imaging suggests that this area coincides with the maximum of lithospheric thinning beneath continental Morocco (Bezada et al., 2014; Fullea et al., 2010). The plateau is crosscut and bounded by NE–SW trending major faults of Variscan age that were reactivated during the Alpine orogeny (Frizon de Lamotte et al., 2008). The highest elevations (nearly 2000 m) and the maximum of volcanic activity are observed on the Azrou–Timahdite plateau, bounded by the Tizi-N'Tretten Fault to the North-West and the North Middle Atlas Fault to the South-East.

The Middle Atlas volcanic province is the largest (~1000 km^2) and youngest (16 to 0.6 Ma) volcanic field in Morocco (El Azzouzi et al., 2010). About one hundred well-preserved strombolian cones and maars define a ~120 km long, N160–170°E trending alignment (Fig. 1). Each volcano emitted one single lava flow of nephelinite, basanite or alkali basalt (El Azzouzi et al., 1999, 2010). In spite of the relatively large number of emission points, the volume of lava flows is rather small (about 10 km^3) and the lack of true differentiated lava excludes the presence of magmatic chambers. Mantle xenoliths may be found in several volcanic centres and lava flows but they are more frequent in two localities: the Bou Ibalghatene and Tafraoute maars.

The Bou Ibalghatene maar is located in the centre of the main volcanic field (33°20′12.91″N; 5°03′07.42″W — Fig. 1). The volcanic structure is 3.5 km long and nearly 1.5 km wide. It is composed of two contiguous explosion craters bounded by two anastomosed half-rings of phreatomagmatic tufs. The Bou Ibalghatene mantle xenoliths were previously described by Raffone et al. (2009). We collected a new set of samples, among which 27 peridotites were examined in thin sections and 9 processed with the same methods as the Tafraoute suite, for comparison.

The Tafraoute maar is located 45 km to the North-East of Bou Ibalghatene, away from the main volcanic field (33°20′12.91″N; 5°03′07.42″W — Fig. 1). It is situated near the Aït Bouzziyane and Tafraoute villages, at the foot of a cliff formed by a slickenside of the North Middle Atlas Fault (Fig. 1). The volcanic edifice is about 2 km long and 500 m wide, oriented NE–SW, parallel to the North Middle Atlas Fault. It is composed of an elliptical explosion crater bounded by a semicircular phreatomagmatic tuff ring. The xenoliths are mostly found in the upper part of the tuf ring, on its SE flank. They are rounded, generally devoid of lava crust and bigger, on average, that in the other Middle Atlas localities (up to 30 cm in diameter). Mantle xenoliths include both peridotites and spinel or garnet pyroxenites, and are associated with garnet- and kyanite-bearing granulite xenoliths from the lower crust. 150 mantle xenoliths were collected for this study, among which 40 peridotites and spinel pyroxenites were examined in thin sections and 12 selected for detailed investigations.

3. Petrography and sample selection

The Bou Ibalghatene mantle xenoliths show a wide range of modal compositions including spinel lherzolites, harzburgites, dunites, wehrlites, olivine-spinel websterites, and spinel websterites (Fig. 2). According to Raffone et al. (2009), about 65% of the Bou Ibalghatene peridotites also contain secondary amphibole ± phlogopite. In contrast, the Tafraoute suite is dominated by fertile spinel lherzolites (12.5–15% clinopyroxene); harzburgites are subordinate while dunites and wehrlites are virtually absent. The suite also comprises olivine–spinel websterites and garnet clinopyroxenites, and further differs from the Bou Ibalghatene suite by the lack of amphibole and phlogopite, except for very rare exceptions. In both localities, the peridotites are equilibrated in the spinel peridotite facies. Spinel is most often interstitial and aligned along foliation in samples that are foliated. However, several peridotites from Tafraoute contain symplectites of orthopyroxene + clinopyroxene + spinel (Fig. 3a) that likely represent destabilization products of former garnets (Morishita and Arai, 2003; Nicolas et al., 1987; Shimizu et al., 2008).

About half of the Tafraoute samples also contain interstitial micro-granular aggregates, 0.1 to 1 μm in grain size, forming a network of anastomosed micro-veins (<100 μm in width) predominantly developed at olivine–olivine grain boundaries. The micro-veins are locally