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Intra-oceanic arc growth driven by magmatic and tectonic processes recorded in the Neoproterozoic Bougmane arc complex (Anti-Atlas, Morocco)

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1. Introduction

Intra-oceanic arc systems (IOAS) are key-geological markers of past and modern plate tectonics and are viewed as major contributors to the growth of the post-Archaean continental crust (e.g., Taylor and McLennan, 1985; Rudnick, 1995; Condie, 1997; Gazel et al., 2015). The building and growth of IOAS are marked by the thickening of its crustal section driven by successive magmatic inputs, as well as the vertical stratification of its petrological structure and geochemical composition (Tatsumi et al., 2008; Stern, 2010; DeBari and Greene, 2011). Snapshots of such mature arcs have been acquired via indirect geophysical investigations in modern environments (Izu–Bonin–Marianna or Aleutian arcs; Tatsumi et al., 2008; Calvert, 2011) and are relatively consistent with an evolutionary stage of exceptionally preserved paleo-arc sections (Talkeetna, Kohistan and Tilemsi-Amalaoulaou accreted arcs; Behn and Kelemen, 2006; Garrido et al., 2007; Burg, 2011; DeBari and Greene, 2011; Berger et al., 2011). The main consequences of arc stratification are thought to be only driven by the accumulation of several mantle-derived magmatic pulses (e.g., Kelemen et al., 2003; Nikolaeva et al., 2008) and related intra-crustal differentiation processes (*i.e.* fractional crystallization and anatexis of infracrustal mafic rocks; *e.g.* Debari and Coleman, 1989; Miller and Christensen, 1994; Müntener and Hermann, 2001; Müntener and Ulmer, 2006; Garrido et al., 2006).

Thickening of the arc crust often lead to "garnetisation" of the lower crust which strongly affects the gravitational stability of the arc. There are two proposed endmember processes responsible for the growth of garnet, even on similar complexes and outcrops. (i) According to experimental data and field observations, garnet can form after crystallization at high pressure ($>$ 1 GPa) from a hydrous basaltic to andesitic magma and segregation in the deep root (Müntener and Ulmer, 2006; Jagoutz et al., 2013). (ii) Garnet can also form during dehydration and dehydration-melting of amphibole-bearing lower crustal mafic rocks in

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response to the emplacement and underplating of hornblendite, pyroxenites and gabbroic bodies (Wolf and Wyllie, 1994; Garrido et al., 2006; Berger et al., 2009, 2011).

Another possible cause of crustal thickening could be intra-oceanic tectonic activity. During subduction, the upper plate stress state depends largely on the dip of the subducting slab (Uyeda, 1983; Lallemand et al., 2005; Heuret et al., 2007; Royden and Husson, 2009). The stress regime can thus shift from extensional to compressional and *vice versa* in response to modifications of subduction zone dynamics (Lallemand, 2014), as also supported by analogue (Boutelier et al., 2003; Heuret et al., 2007) and numerical geodynamic modelling (Baitsch-Ghirardello et al., 2014). Although thickening of modern oceanic arcs in response to compressional upper plate stress state has not been reported yet, observations in the fossil arc records, especially for continental active margins showed that syn-subduction shortening in the upper plate can effectively lead to the thickening of the arc system (Baby et al., 1997; Haschke and Günther, 2003). Discrete phases of shortening can thus alternate with phases of magmatic accretion referred as flare-ups (e.g., DeCelles et al., 2009; Paterson and Ducea, 2015) which are well known in continental arcs but less so in their oceanic counterparts.

Petrological, structural and geophysical studies on active and Mesozoic accreted oceanic arcs reveal that growth of the arc system is mainly driven by magmatic processes rather than tectonic activity (e.g., Yoshino and Okudaira, 2004; Jicha et al., 2006; DeBari and Greene, 2011; Jicha and Jagoutz, 2015). However, direct structural and petrological observations in oceanic arc lower crust require access to exposed sections and only two Mesozoic occurrences are well characterized. Many intra-oceanic arc complexes are exposed in the Pan-African belt of West and North African continent (Dostal et al., 1994; Thomas et al., 2004; Berger et al., 2011; Triantafyllou et al., 2016), providing a unique opportunity to compare Neoproterozoic arc growth processes with Phanerozoic and active IOAS. The main purpose of this study is to investigate the crustal processes that drive the construction of IOAS during the Pan-African orogeny. This paper proposes that the Bougmane complex formed in an IOAS which reached a mature stage via a combination of intra-oceanic magmatic and tectonic processes. These results suggest that mechanisms of Neoproterozoic oceanic arc growth may slightly differ from those governing the building of Phanerozoic arcs.

2. Geological outline and previous works

The Bougmane complex belongs to the Central Anti-Atlas orogenic belt (South Morocco) and crops out in the southern side of the Bou Azzer inlier (Fig. 1a and b). That particular area forms a 70 × 10 km window where the Neoproterozoic basement and Pan-African structures are exposed. This basement is surrounded and locally overlain by unconformable Ediacaran volcano-clastic deposits of the Ouarzazate Supergroup and late Ediacaran to Early Cambrian siliciclastic sediments (Leblanc, 1981). The Bou Azzer inlier itself consists of several stacked tectonic units interpreted as dismembered parts of a Neoproterozoic oceanic supra-subduction zone system (e.g., Saquaque et al., 1989; Bousquet et al., 2008). These units were accreted and moulded onto the northern boundary of the West African Craton (WAC), highlighted by the WNW-ESE striking Anti-Atlas Major Fault (AAMF; Fig. 1a). Based on lithology, geochronology and tectonics, the Bou Azzer inlier can be subdivided as follow:

The oldest unit forms a discontinuous band of *mafic to felsic orthogneisses* in the southern boundary of the tectonic window. This assemblage is exposed in several complexes (D'Lemos et al., 2006; Blein et al., 2014) that are from east to west: Bougmane, Tazigzaout, Oumlil and Bou Azzer Mine complexes (Fig. 1b). These rocks were originally interpreted as the Eburnean basement of the WAC due to their intense deformation in comparison to other Proterozoic rocks in the Zenaga inlier (Choubert, 1963; Leblanc, 1981; Saquaque et al., 1992). However, recent geochronological data (U-Pb dating on zircons) confirmed their Neoproterozoic ages around 755–750 Ma (D'Lemos et al., 2006; Blein et al., 2014). These rocks were then intruded by mafic to felsic magmas dated from 710 to 690 Ma (D'Lemos et al., 2006; El Hadi et al., 2010; Blein et al., 2014; this study). According to Nd isotopic signature (ε_{Nd} from +4.9 to +6.0), all the rocks from the Tazigzaout complex were formed in oceanic settings (D'Lemos et al., 2006).

An ophiolitic assemblage is exposed in the core of the inlier. It is mainly made up of ultramafic rocks (serpentinites and few chromite pods), but also mafic meta-cumulates, meta-basaltic sheeted dykes and pillow lavas in a smaller extent (Leblanc, 1975, 1981). The geochemical signature points to an emplacement in a supra-subduction zone (SSZ) setting (Bodinier et al., 1984; Naidoo et al., 1991; Ahmed et al., 2005; Hodel et al., 2017). Precise radiometric dating of an igneous event forming this oceanic crust has not been performed yet. However, by comparison with the Sirwa window and using local relative geochronology, the igneous events can be bracketed between 760 and 660 Ma (Thomas et al., 2004; El Hadi et al., 2010; Blein et al., 2014). According to the tectonic model sketched by Bousquet et al. (2008) and El Hadi et al. (2010), significant thrust and tectonic stacking occurred between the ophiolitic remnants to the north and the old orthogneissic units to the south during Pan-African orogeny. However, the timing of this tectonic episode is still poorly constrained even if it is generally interpreted as synchronous to the obduction stage of oceanic relics onto the WAC margin (Bousquet et al., 2008).

Intrusive syn-kinematic dioritic to granodioritic plutons cut across both gneissic and ophiolitic units (Fig. 1b). Their emplacement was dated (U-Pb on zircons) between 660 and 640 Ma (Inglis et al., 2004; El Hadi et al., 2010; Walsh et al., 2012; Blein et al., 2014) and show arc-like geochemical fingerprints (Beraaouz et al., 2004). Beraaouz et al. (2004) suggest that some of these dioritic plutons have an adakitic affinity. Their isotopic signature (εNd: +4.2 to +8.1; Mrini, 1993; Beraaouz et al., 2004) argue for an intra-oceanic emplacement.

The whole subduction-related igneous pile is also intercalated with diverse deep oceanic deposits which consist in reworked sedimentary and volcano-sedimentary deposits (Leblanc, 1975; Leblanc and Billaud, 1978) and later unconformably and partially overlain by molassic deposits from the Tiddiline formation (Hefferan et al., 1992).

The Bougmane complex studied in this paper is located in the southern central part of the Bou Azzer inlier (Fig. 1b). It is made of gabbroic, granodioritic to granitic orthogneisses, described as a "leptyno-amphibolitic complex" in recent mapping survey and recently dated at 745 ± 5 Ma by U-Pb on protolithic zircon (Admou et al., 2013). Localized shear zones are suspected to have affected this complex under middle to low pressure-temperature (P-T) conditions (Rahimi et al., 1998). These host gneisses are associated with a metagabbroic unit dated at 697 ± 8 Ma (U-Pb on zircons) and interpreted as a dismembered element of the ophiolitic assemblage being tectonically extruded to the south (El Hadi et al., 2010, 2011). To the north of the complex, the gneissic units are intruded by granodioritic and tonalitic elongated plutons that have been dated at 702 ± 5 Ma with inheritance of older zircon crystallized at 743 ± 9 Ma (*cf.* supplementary data in Admou et al., 2013). These intrusions have attributed to the same igneous event represented by the Bougmane intrusive granodiorite by Admou et al. (2013) based on their similar mineralogical content. The geological significance of the Bougmane units remains unclear and deserves more detailed petrological studies to decipher the processes contributing to the build-up of supra-subduction oceanic systems.

3. Field relations and samples description

The Bougmane complex is mainly composed of two NW-SE trending units: (i) *a banded gneiss unit* intimately related to (ii) *an undeformed to weakly deformed plutonic unit* (Fig. 2). It is limited to the NE by a dextral strike-slip fault making the contact with augen granitic gneiss, and to