Lithospheric thinning associated with formation of a metamorphic core complex and subsequent formation of the Iranian plateau

Fariba Kargaranbafghi, *Dept. Geography and Geology, University of Salzburg, Salzburg, Austria, and Dept. of Geology, University of Yazd, Yazd, Iran, fkargaran@yazd.ac.ir; and* ***Franz Neubauer,*** *Dept. Geography and Geology, University of Salzburg, Salzburg, Austria, Franz.Neubauer@sbg.ac.at*

ABSTRACT

The formation of metamorphic core complexes is not well understood, which is why these large geological structures are still interesting subjects. They seem to have been formed by erosion of upper crustal rocks and exhumation of mid-crustal rocks. However, it is not clear how the lower crust and underlying mantle have responded. Many core complexes in the western United States are underlain by a flat Moho discontinuity, and some others possess a crustal root. Here, we present evidence of the Chapedony metamorphic core complex in the Central Iranian plateau. We show that the overall lithosphere and continental crust were thinned beneath regions of surface extension. The core complex is located within a continental rift and was exhumed at a rate of ~0.75–1.3 km/m.y. during the main phase of oceanic subduction of the Arabian plate beneath the Central Iranian block between ca. 49 and 30 Ma. The thinning of the underlying lithosphere appears to have been compensated by hot asthenosphere, as indicated by low seismic velocities in the Central Iranian block. We conclude that the development of the core complex involved lithospheric removal associated with extension and upwelling of hot asthenosphere, although we are aware of the fact that the structure could have been substantially modified by subsequent processes like slab break-off and associated uplift of the Central Iranian plateau.

INTRODUCTION

The Central Iranian plateau plays a key role in the study of the youngest continental collision on Earth, namely the oblique Arabia-Eurasia collision (Guest et al., 2007; Priestley et al., 2012). It provides, therefore, exciting opportunities to study large-scale orogenic processes that are overprinted and obscured in other, older parts of the Alpine-Zagros-Himalayan mountain chain. The combination of convergence with both shortening and extension is an interesting feature of the youngest continental collision. Understanding these complexities requires the recognition of important lateral variations in crustal and upper mantle structure (Wortel and Spakman, 2000). We describe, in a kinematic sense,

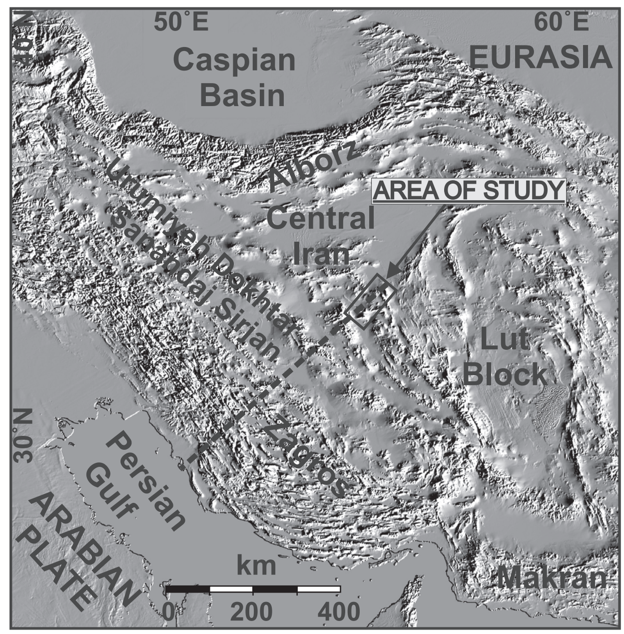

Figure 1. Digital elevation model of the Arabia-Eurasia convergence zone. Rectangle shows the position of the study area (Fig. 2); black dashed line shows the location of the lithospheric-scale cross section (Fig. 4) from the Arabian plate through the Central Iranian plateau.

the Zagros fold-thrust belt and Central Iranian block (Fig. 1) as part of the plate boundary zone, involving convergence and migrating subduction zones accompanied by extension and following collision. The overall surface structure of the Central Iranian plateau, which represents the uplifted part of the Central Iranian block at elevations of ~1.5 km, is characterized by large-wavelength folds with Cenozoic sedimentary basins and adjacent ridges with basement exposures (Guest et al., 2007; Kargaranbafghi et al., 2011; Morley et al., 2009). The development of the Central Iranian basin within the Central Iranian block probably began in a continental rift setting during Eocene to early Oligocene times (Jackson et al., 1990; Guest et al., 2007; Berberian and Berberian, 1981; Takin, 1972; Allen et al., 2003; Vincent et al., 2005), and the Central Iranian basin underwent inversion during the Early Miocene to Pliocene (Jackson et al., 1990; Guest et al., 2007; Morley et al., 2009; François et al., 2014a). The uplift of the Central Iranian plateau has been associated with slab break-off

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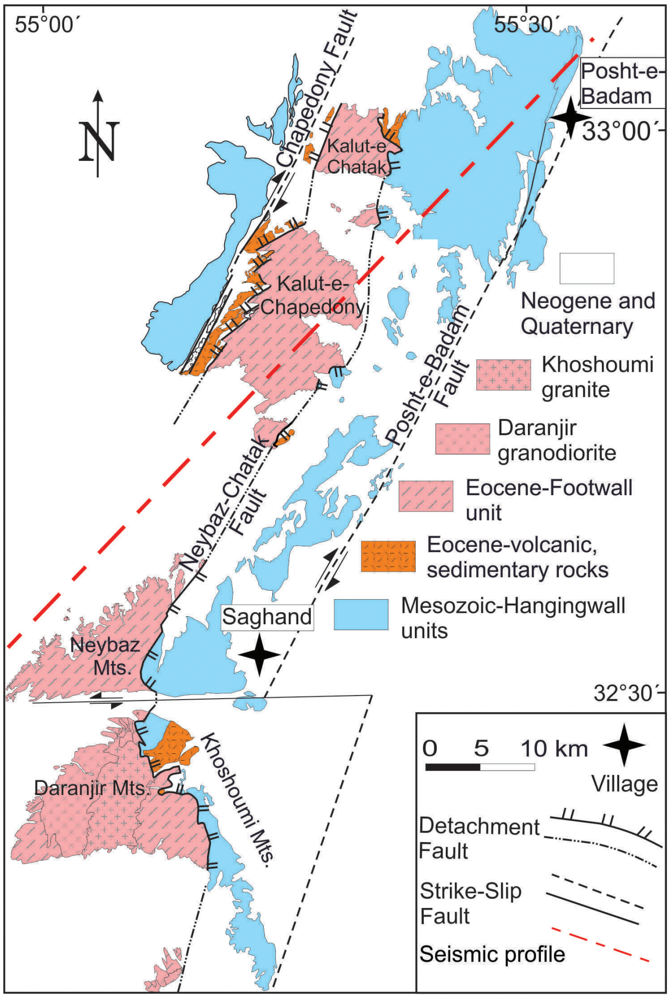

Figure 2. Simplified map of the footwall and hanging-wall of the metamorphic core complex.

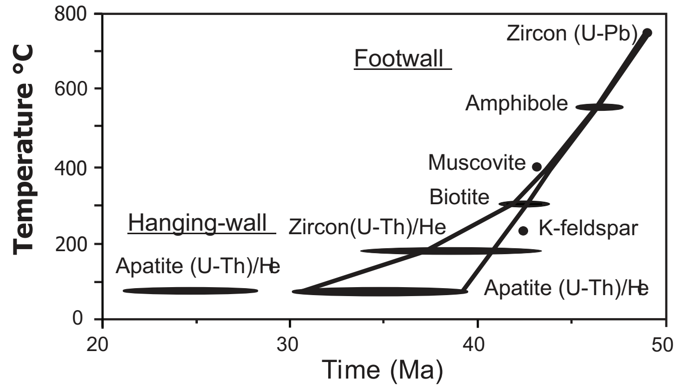

Figure 3. Chapedony Metamorphic Core Complex cooling path (modified from Kargaranbafghi et al., 2012a).

and heating of the base of the lithosphere and its subsequent thinning (e.g., Hafkenscheid et al., 2006; Bottrill et al., 2012; Jimenez-Munt et al., 2012; Mohammadi et al., 2013; François et al., 2014b). Slab break-off was recently estimated to have occurred ca. 10 ± 5 Ma (Agard et al., 2011).

CHAPEDONY METAMORPHIC CORE COMPLEX

The Chapedony metamorphic core complex (CMCC) is located in the Saghand area in the southwestern Central Iranian block (Fig. 1). The CMCC has an ESE-WNW extent of ~20 km and a NNE-SSW extent of ~100 km (Fig. 2). It exposes migmatites and is intruded by granite and granodiorite with U-Pb zircon ages ranging from 47 to 44 Ma (Ramezani and Tucker, 2003). Along the Neybaz-Chatak fault, a ductile low-angle normal shear zone, rocks of the CMCC are juxtaposed to overlying Mesozoic metamorphic and sedimentary units in the hanging wall. Kinematics along the Neybaz-Chatak fault indicate to the NE transport during the Eocene (Kargaranbafghi et al., 2012b).

Kargaranbafghi et al. (2012a, 2012b) reported *P-T* estimates of peak metamorphic conditions of 4 kbar and 750 °C within the CMCC. New and existing (U-Th)/He ages of zircon and apatite indicate that the complex had cooled to <50 °C by 30 Ma (Kargaranbafghi et al., 2012a). All geochronologic ages are consistent with a period of rapid cooling from 750 °C (migmatite formation, based on U-Pb zircon ages; Ramezani and Tucker, 2003) through ~300 °C ($^{40}Ar/^{39}Ar$ biotite ages; Verdel et al., 2007; Kargaranbafghi et al., 2012a, 2012b) to 50 °C by 30 Ma within <20 million years (Fig. 3). The data presuppose cooling at a rate of ~45–80 °C/ m.y. Using the mentioned mineral thermobarometry (Kargaranbafghi et al., 2012a, 2012b) to constrain the initial depth (12 km), we calculated that the CMCC underwent tectonic unroofing and erosional exhumation at an average rate of ~0.75 –1.3 km/m.y.

A seismic receiver function study indicates that the crustal thickness is ~45 km thick between the Persian Gulf coast and the High Zagros. After that, it thickens rapidly to ~70 km within a narrow zone beneath the Sanandaj-Sirjan Zone, before thinning to ~42 km beneath the Urumiyeh-Dokhtar volcanic magmatic arc. At the southern rim of Central Iran, the crust thins to 32–42 km beneath the CMCC (Kaviani, 2004; Kaviani et al., 2007; Paul et al., 2006; Priestley et al., 2012) (Fig. 4). These observations show that the CMCC is located above an area of crustal thinning. The average Moho upwarp is 7–17 km (Kaviani et al., 2007), close to the amount of upper crust tectonically removed over the CMCC in the period between 49 and 30 Ma (Fig. 4). An estimate of the

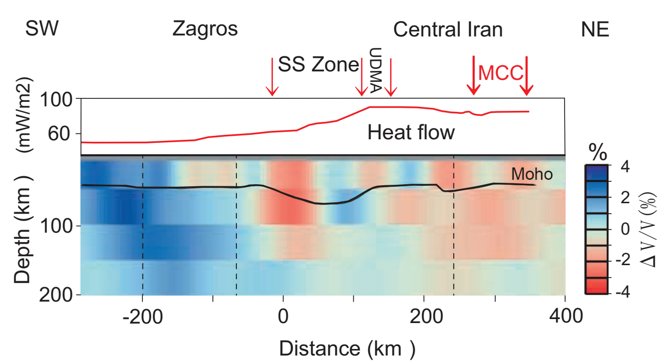

Figure 4. Depth cross section along the Arabian plate through the Central Iranian plateau (Kaviani et al., 2007). The profile in the 3-D model of P-wave velocity perturbations resulting from the inversion of residuals. Black solid line—Moho depth; red solid line—heat flow (Fernandez et al., 2003). MCC—metamorphic core complexes; UDMA—Urumiyeh-Dokhtar Magmatic Arc.

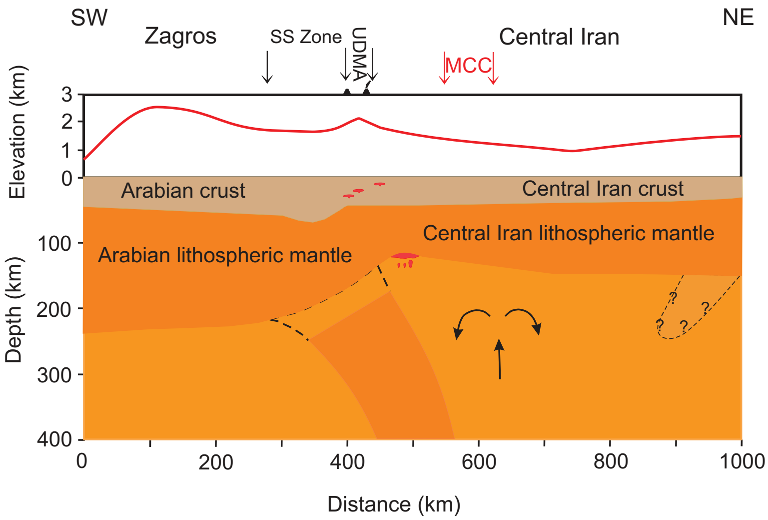

Figure 5. Model for the formation of the Iranian plateau. Interpretive cartoon cross section illustrating one possible scenario for the Central Iranian plateau. The subduction of lithosphere is tentatively inferred from seismic tomography images (Hafkenscheid et al., 2006) and confirmed by numerical modeling (Kaislaniemi et al., 2014). MCC—metamorphic core complexes; SS—Sanandaj-Sirja zone; UDMA—Urumiyeh-Dokhtar Magmatic Arc.

crustal and lithospheric thickness and heat flow before the exhumation of the CMCC can be made by adopting a thickness of 45–55 km and a temperature of 750 °C for the base of the crust before 49 Ma. These values are consistent with the metamorphic pressure-temperature-time studies on the CMCC (Kargaranbafghi et al., 2012a, 2012b) and with seismic estimates of the crustal thickness underneath the CMCC today (Kaviani et al., 2007; Paul et al., 2006).

CRUSTAL AND MANTLE LITHOSPHERIC STRUCTURE

The CMCC is located on a basement ridge within the region of crustal thinning and underwent surface uplift rather than subsidence. Mantle buoyancy isostatically supports regionally positive elevations in the Saghand region. The mantle decompression made this region susceptible to flow and further convective erosion of the mantle lithosphere beneath the CMCC. Priestley et al. (2012) and Lü et al. (2012) report a NE-trending fast direction of shear waves within the mantle lithosphere consistent with the Eocene NE-ward flow of crustal rocks within the CMCC (Kargaranbafghi et al., 2012b). Uplift continued forming topographic culminations reaching 1200–2100 m above sea level. The observed crustal thinning of ~7–17 km in the CMCC should produce 1.5–3 km of subsidence (Abers et al., 2002) that is isostatically balanced, because the mantle lithosphere thins in concert with the crust. The basin surrounding the CMCC is the surface expression of extension (Fig. 1). By the late-middle Miocene, ~3–4 km of post-Eocene evaporites, carbonates, and shales had accumulated in one of these successor basins (Jackson et al., 1990; Morley et al., 2009).

Variations in Moho depth beneath the CMCC explain variations in lower-crustal thickness through lower-crustal flow (Verdel et al., 2011). Furthermore, some flow of the lower crust may be needed to explain subsidence and the heat flow of the basins adjacent to the Saghand area. Heat-flow measurements across the Central Iranian block average ~85 mWm^{-2} (Fernandez et al., 2003) (Fig. 4), likely indicating ongoing thermal erosion of the lithospheric base.

GEODYNAMIC REGIME

A significant change in the tectonic regime is typically marked by a change in the composition of the associated magmatism (Turner et al., 1993). Before collision, subduction of the oceanic crust was accompanied by calc-alkaline arc magmatism in the Urumiyeh-Dokhtar Magmatic Arc, as is also the case in the high Himalaya (Turner et al., 1993). Crust-derived leucogranites were subsequently emplaced within the CMCC during the Eocene (Ramezani and Tucker, 2003) as a result of decompression associated with the onset of rapid exhumation. However, intense coeval volcanism occurred all over the Iranian plateau and is interpreted to represent a magmatic flare of crustal origin due to the remelting of crustal material (Verdel et al., 2011). A few scattered upper Oligocene to Quaternary volcanic rocks occur in the Central Iranian plateau (Berberian and Berberian, 1981; Milton, 1977) but not in the surroundings of the CMCC. The Oligo-Miocene regional plutonic activity of southwestern Central Iran cut through the Eocene-Oligocene volcanic rocks (Berberian and Berberian, 1981). The low $^{87}Sr/^{86}Sr$ initial ratio obtained for this complex (0.70524–0.70573) suggests an upper mantle or oceanic crust origin (Berberian and Berberian, 1981). The appearance of mantle-derived volcanism on the plateau marks a change in the tectonic regime and requires a thermal explanation. Young volcanism at the surface and high heat flow values in the region suggest that this zone of low velocities and high attenuation in the uppermost mantle represents asthenospheric material. We conclude that, in Central Iran, the only plausible means of attaining temperatures high enough for melting within the lithospheric mantle is by thinning, a mechanism consistent with recent seismic observations and modeling (e.g., Kaviani et al., 2009; Manaman et al., 2011; Zamani et al., 2013; Kaislaniemi et al., 2014). The surface uplift of the Central Iranian plateau is, therefore, likely associated with heating of the lithospheric base induced by break-off of the subducted lithosphere (François et al., 2014a, 2014b; Bottrill et al., 2012). Although no young volcanics are known in the surroundings of the CMCC, this process potentially could have slightly modified the lithospheric base of the area underneath the CMCC.

Although the geodynamic setting is entirely different, similarities exist between the CMCC in Central Iran and the metamorphic core complexes (MCCs) in Papua New Guinea, which may explain the juxtaposed thinning of crust and mantle lithosphere that is contrary in the MCCs of the western U.S. and the Aegean regions, which have relatively flat Mohos (Abers et al., 2002; Myers and Beck, 1994; Tirel et al., 2009).

CONCLUSIONS

The CMCC is a typical example of a metamorphic core complex formed by syn-orogenic extension: a contractional orogen, formed in Late Cretaceous to early Cenozoic times, which underwent rapid exhumation during the middle to late Eocene. The crust was probably thermally weakened before extension took place in the Eocene. Temperatures of 650–750 °C at depths equivalent to 3.5–4 kbar (~60 °C/km) would produce an unrealistic Moho temperature of >1200 °C for a conductive geotherm (Costa and Rey, 1995). Instead, advective heat transport probably occurred in the deeper parts of the continental crust to maintain the temperature of the lower crust between 750 and 1000 °C. The crustal root was partially melted, and the base of the mantle lithosphere was likely transformed into asthenosphere, either by thermal relaxation (Gaudemer et al., 1988) or by gravitational detachment (Houseman et al., 1981).

The geological evidence suggests that thinning, extension, and exhumation began in the middle Eocene (ca. 49 Ma), and extension continued through to earliest Oligocene (33 Ma). The final cooling (<50 °C) of the CMCC occurred earlier than in the hanging-wall unit (Kargaranbafghi et al., 2012a). This suggests that the hanging wall was exhumed during a second process after the main collision between the Arabian plate and the Central Iranian block. This took place during the late Oligocene and early Miocene, around the same time that the Red Sea started to open ca. 21–25 Ma (Omar and Steckler, 1995) and at the time of slab break-off (Hafkenscheid et al., 2006), although recent estimates suggest slab break-off at 10 ± 5 Ma (Agard et al., 2011). We propose a model for the Iranian plateau uplift subsequent to exhumation of the CMCC (Fig. 5) that is similar to the model for the northern Tibetan Plateau (Tilmann and Ni, 2003). We suggest that downwelling lithospheric material would inevitably drag neighboring asthenospheric material with it, a model recently confirmed through numerical modeling by Kaislaniemi et al. (2014). Tentative evidence for northeastward-directed subduction with associated downward convection along the northern margin of the Iranian plateau (Hafkenscheid et al., 2006) would have resulted in a deficit of asthenosphere. This must be counterbalanced by a focused upward-directed return flow. Such an upward flow would provide an explanation for the low-velocity body imaged by Kaviani et al. (2007) and provide a mechanism for heating the crust and gradual erosion of remaining mantle lithosphere beneath the Central Iranian plateau.

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