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Synthesis Paper

Formation of metamorphic core complexes in non-over-thickened continental crust: A case study of Liaodong Peninsula (East Asia)

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ABSTRACT

Pre-thickened hot orogenic crust is often considered a necessary condition for the formation of continental metamorphic core complexes (MCCs). However, the discovery of MCCs in the Liaodong Peninsula, where the crust has a normal thickness (~35 km), challenges the universality of this scenario. Therefore, we implement a series of 2-D numerical thermo-mechanical modeling experiments in which we investigate the conditions of MCC formation in normal crusts, as well as the relationships between the underlying mechanisms and the syn-rift basin evolution. In these experiments, we explore the impact of the lithostratigraphic and thermo-rheological structure of the crust. We also examine the lithosphere thickness, strain softening, extension rate, and surface erosion/sedimentation processes. The experiments demonstrate that high thermal gradients and crustal heterogeneities result only in a symmetric spreading dome, which is geometrically incompatible with the observations of the MCCs in the Liaodong Peninsula. According to our further findings, the strain softening should play a key role in the development of asymmetric strain localization and domal topography uplift, while synchronous surface erosion controls the polarity of the syn-rift basin. The synthetic model data are compatible with the geological observations and cooling history based on the thermo-chronology for the eastern part of the East Asia during the late Mesozoic to the early Cenozoic. The model-predicted P-T-t paths are essentially different from those inferred for the other known MCCs, confirming the exceptional character of the MCC formation in the wide rift system of the East Asia.

1. Introduction

The concept of the metamorphic core complex (MCC) was introduced during the late 1970s based on tectonic surveys in the Basin and Range Province (USA) (Coney, 1974; Coney and Harms, 1984; Davis and Coney, 1979; Proffett, 1977). MCCs develop in extensional settings characterized by significant amounts of crustal stretching and are regarded as distinctive structures, different from those associated with, for example, wide or narrow rifting (e.g., Buck, 1991). A typical MCC comprises the following: (1) a lower unit of metamorphic and/or plutonic rock exhumed from the lower crust into the upper crust; (2) a shallow unit of upper crustal rocks that do not undergo any metamorphic changes during extension; (3) a detachment structure localized between the lower and upper crustal units that corresponds to a shallow dipping and strongly sheared mylonitic zone, which absorbs much of the movement during the exhumation of the lower crust rocks; and (4) differently from "usual" rifts, the Moho below an MCC is nearly horizontal or only slightly uplifted(Buck, 1991; Coney and Harms, 1984; Davis and Coney, 1979; Lister and Davis, 1989; Wernicke, 1981). The upper units behave as brittle blocks and experience rather limited stretching during extension. High-angle normal faults rooted in the detachment typically develop within these domains, and their dynamics largely condition the deposition of sediments into the half-graben structures. The lower units, having low viscosity and flowing from the lower to upper crustal levels, display penetrative ductile deformation with foliations during extension. A dome is underlined by the bended shape of foliation envelope within the lower crust which carries imprints of the extensional shear zone localized along the detachment and on top of the dome.

Some well-known MCCs have been identified in the Aegean Sea domain (Gautier et al., 1990, 1993; Jolivet et al., 2013; Lister, 1984), West Antarctica (Richard et al., 1994), East Asia (Li, 2000; L.G. Wang et al., 1998; Wu et al., 2000, 2005a,b, 2007), the Norwegian Caledonides (Steltenpohl et al., 2004), and Iran (Verdel et al., 2007). A particular appellation of "Cordilleran style metamorphic core complexes" (Lister,

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1984; Liu et al., 2005; Verdel et al., 2007) is also widely applied to metamorphic features of the Cordilleran realm, although the related kinematic and thermo-mechanical conditions are not completely identical to those associated with the description of the conventional MCC. A remarkably common feature of most of the described MCCs is that they form in orogenically pre-thickened crust (crustal thickness >50 km, Moho temperatures >800 °C) (Buck, 1991; Tirel et al., 2008). This observation is therefore often treated as a crucial condition for the formation of MCCs, either during post-orogenic extensional collapse (North American Cordillera) (Foster and Raza, 2002; Gebelin et al., 2011; Mulch et al., 2007) or in back-arc extension settings during ongoing plate convergence (Aegean Sea) (Jolivet and Faccenna, 2000). MCC domes have also been identified in East Asia (EA) in relation to the large-scale continental extension that took place during Mesozoic times. There are strong debates about the thickness of the continental crust before extension in the East Asia. Previous shortening event is argued to drive the extension (Liu et al., 2005; Wang et al., 2011). However, the Songliao basin can provide direct evidence for the crustal thickness in Liaodong Peninsular before MCC exhumation from the shape of faults and the sequential cross-section restoration (Ge et al., 2012). While the major features and kinematics of these structures perfectly correspond to the canonical features of MCCs, no high-pressure metamorphism and no trace of the pre-existing crustal thickening or of a suture zone have been reported in the northeastern part of China (Charles, 2010; Gumiaux et al., 2012). Indeed, the latest event responsible for crustal thickening happened at the boundary between the North China Craton (NCC) and the South China block (SCB) during the Triassic, which represents a nearly 100-Ma time lag with the Meso-Cretaceous extension episode. It is therefore unreasonable to relate the MCC formation in the Liaodong Peninsula (EA) to this post-orogenic extension (Lin et al., 2013a). This atypical tectonic context of the MCCs in the Liaodong Peninsula raises the new question of whether it is possible for an MCC to develop in non-thickened continental crust.

Many analog and numerical experiments have been performed to understand the mechanisms of MCC formation, addressing a number of key conditions leading to MCC development (Brun, 1999; Burov et al., 2014; Huet et al., 2011a,b; Lavier et al., 1999; Tirel et al., 2008, 2013). Strain localization and weakening (Buck, 1993; Gessner et al., 2007; Lavier et al., 1999), a pre-existing density and/or weak rheological/compositional heterogeneities in the lower crust (e.g.,Brun, 1999; Brun and Sokoutis, 2007; Burov et al., 1994; Petit et al., 1997) are thought to be essential for rift localization and, in particular, for MCC formation (Brun, 1999; Brun and Sokoutis, 2007; Tirel et al., 2008). Later experiments that have tested the impact of the depth, length, and position of the compositional heterogeneity (Tirel et al., 2008) showed, however, that the presence of compositional heterogeneities is not essential for the occurrence of an MCC. The extensive parametric study by Tirel et al. (2008) demonstrated that in the case of an orogenic crust with a commonly inferred rheological structure, three conditions should be satisfied: (1) the initial temperature of the Moho must be greater than 800 °C, (2) the crustal thickness must be greater than 45 km, and (3) the initial effective viscosities of the lower crust and the underlying mantle should be lower than 10^{20}Pa and 10^{22} Pa, respectively. Rey et al. (2009) additionally demonstrated that the extension rate partitioning (with respect to the rift axis) may have a major effect on the asymmetry of the crustal detachment faults that characterize most MCCs. Thermal gradients due to collisional thermal heritage or asthenospheric heat sources are also considered in some of the previous studies showing the non-negligible impact on the P-T-t paths of the exhumed metamorphic material (Schenker et al., 2012). Even if the initial thermal gradient remains a first-order parameter for structural heritage, the rheological structure might strongly influence the conditions of MCC development. Huet et al. (2011a,b) showed, in particular, that an unusual "inverted" rheological structure resulting from orogenic nappe stacking may result in acceleration of the growth rate of the extensional instabilities, enabling MCC formation even in relatively cold crust (Moho temperature ~600 °C–700 °C). Finally, Tirel et al. (2013) developed a model where MCC forms as a result of stacking and exhumation of continental terrains in a back-arc extension context. Moreover, 3D models testing the impact of kinematic extensional boundary conditions demonstrate geometrical disparities between the extensional and transgressive domes, yet without major modifications in the mechanisms of formation of the detachment fault systems (Le Pourhiet et al., 2012). It is still noteworthy, however, that all previous mechanical and thermo-mechanical experiments are based on a common implicit assumption that the MCCs form as a result of the extensional collapse of a thickened crust, either in a post-orogenic intracontinental context or within the framework of subduction-driven burial and back-arc exhumation of crustal units (Tirel et al., 2013). Most of these studies were enlightened by the Aegean Sea either with thickened crust or fast extension rate. None of these geological settings directly correspond to the case of the Liaodong Peninsula.

In this study, we therefore examine the particular conditions for the thermal and mechanical evolution of MCCs in "normal" crustal thickness settings. With this goal, we implement a series of 2D thermo-mechanical numerical experiments assuming a normal 35-km-thick crust. We further try to elucidate some additional key factors of MCC formation, such as the extension rate, initial thermal gradient, strain softening, erosion/sedimentary rates, initial litho-rheological stratification of the crust, and lithospheric thickness. Finally, after incorporating all available geological and geophysical data, the models are applied to the natural case of the Liaodong Peninsula.

2. Geological settings

2.1. The wide rift system of the East Asia

East Asia mainly comprises the Central Asian Orogenic Belt (CAOB), the North China Craton (NCC), and the South China Block (Fig. 1a) (Charles et al., 2013; Wang et al., 2011). The NCC is an old and relatively small craton dated to approximately 1.85 Ga (Zhao et al., 2001) that locates in-between the CAOB and the SCB bordered by the Permain Solonker Suture Zone (Xiao et al., 2003; Yin and Nie, 1996) and Triassic Qinling–Dabie Orogen (Mattauer et al., 1985) separately. After the final amalgamation of these three tectonic units, the whole tectonic collage experienced an intensive reactivation. A pervasive extension event occurred over ~1500 km wide from South China up to the Baikal Lake. The geological features associated with the extension are characterized by the opening of large-scaled extensional basins and the emplacement of numerous plutonic and volcanic massifs in East Mongolia and East China (Fig. 1a). Mesozoic sedimentation is characterized by graben or half-graben such as in the region of Songliao, Yingen, Erlian, Hailar, and East Gobi (Graham et al., 2001; Meng, 2003; Ren et al., 2002). For the rather large intracontinental Songliao basin (~260 000 km^2), both paleontological (Li, 2001) and radiochronological (Chen et al., 1999; Wang et al., 2002) dating show that its opening began in the Late Jurassic in the north and progressed southwards until the latest Cretaceous. Several intensively deformed metamorphic domes and associated granitic intrusions underlying a large extensional shear zone have been identified during late Mesozoic, including Buteel and Zagan (South Lake Baikal, Donskaya et al., 2008; Sklyarov et al., 1997), Yagan-Onch Hayrhan (Southern CAOB, Webb et al., 1999), Hohhot, Louzidian, and Yumengshan (Northern NCC, Darby et al., 2001; Davis and Zheng, 1988; Wang et al., 2002, 2004), Linglong (Jiaodong Peninsula, Charles et al., 2011a,b), Yiwulüshan, Liaonan, and Gudaoling (Liaodong Peninsula, Charles et al., 2012; Lin et al., 2013a,b; Liu et al., 2005; Xu et al., 1994), Beidabie and Xiaoqinling (Qinling–Dabie Orogen, X.D. Wang et al., 1998; Zhang et al., 1997), Lushan and Hongzhen (South China, Lin et al., 2000; Zhu et al., 2010) MCCs. All these MCCs record common NW–SE crustal stretching, and they satisfy all the above-mentioned conditions to join the Cordilleran-type MCC's family. Coincident with the formation of MCC, the Yanshanian tectono-magmatic