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Timing, duration and role of magmatism in wide rift systems: Insights from the Jiaodong Peninsula (China, East Asia)

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In East Asia, widespread extensional sedimentary basins together with the close association of Metamorphic Core Complexes and magmatism are prominent features of the large-scale wide rift system developed during late Mesozoic times. This region thus appears as a proper place to study continental extension as well as questions about the link between continental extension and magmatism. This paper primarily provides pioneer exhumation time-constraints on the Linglong MCC (Jiaodong Peninsula) including cooling and deformation ages. MCC cooling at mid-crustal levels occurred at ca. 143 Ma. Besides, last ductile deformation occurred at ca. 134 Ma while final exhumation stages, under brittle conditions, occurred as late as ca. 128 Ma. Continuous crustal stretching was then recorded by the emplacement of a synkinematic pluton in the upper crust at ca. 128 Ma that cooled fast below an intracrustal shear zone crossing the ductile–brittle transition at ca. 123 Ma. The ca. 120–118 Ma age cluster is ascribed to the fast cooling of undeformed plutons marking the end of extension that lasted, in the area, over a minimum period of ca. 30 My. Combining other MCC exhumation constraints and the onset of subsidence in the sedimentary basins, total duration of late Mesozoic extension in East Asia could be estimated at ca. 60 My, related with a rather long process for extension from 160 to at least 100 Ma. East Asian continental extension is heterogeneously distributed in space and time as revealed by fundamental differences between two end-member classes of migmatite-cored MCC already described in other wide rift systems. Extension seems to have first favoured partial melting which subsequently, in turn, maintained continental extension.

1. Introduction

Continental extension is one of the most remarkable geodynamic processes affecting the lithosphere and attracts considerable attention of the geosciences community (e.g. England, 1983; Buck, 1991; Corti et al., 2003). Basically, continental lithosphere can be stretched following two principal modes of extension: (1) narrow rift and (2) wide rift systems (Buck, 1991; Brun, 1999; Corti et al., 2003). Narrow rifts display rather localised deformation within the continental lithosphere and correspond to continental rifts that may lead to continent break-up in more mature stages (Brun, 1999). Conversely, wide rifts concern very large strained areas (~1000 km wide) and comprise, among other structures, metamorphic core complexes (MCCs; Brun, 1999). Areas such as the Basin and Range (North America) and Aegean (Mediterranean Sea) regions, illustrate well the wide rift mode of extension (Buck, 1991; Corti et al., 2003, see references therein). Since the past three decades, field work (e.g. Davis and Coney, 1979; Crittenden et al., 1980; Lister et al., 1984; Lister and Davis, 1989; Gautier et al., 1993; Jolivet and Brun, 2010), as well as analogue and numerical modelling (e.g. Brun et al., 1994; Tirel et al., 2006, 2008) highly improved our knowledge and comprehension on the modes of extension in such domains. In particular, theories on the geodynamic causes generating wide rift systems, including subducting lithospheric slab movements, have been well developed (e.g. Rosenbaum et al., 2008; Jolivet et al., 2009a; Jolivet and Brun, 2010). Yet, in spite of the increasing amount of both geological data and mechanical models, two major points dealing with extension mechanisms are still discussed: (1) the timing and duration of deformation processes, and more particularly of MCCs development (e.g. Gautier et al., 1999; Sullivan and Snoke, 2007) and (2) the genetic link between regional-scale extension and magmatism in a broad sense (e.g. Crittenden et al., 1980; Reynolds and Rehrig, 1980; Coney and Harms, 1984; Lynch and Morgan, 1987; Lister and Davis, 1989; Tomassi

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et al., 1994; Gautier et al., 1999; Corti et al., 2003; Tirel et al., 2008; Péron-Pinvidic et al., 2009; Rey et al., 2009a,b).

East Asia has been marked by large-scale continental extension during late Mesozoic (e.g. Menzies et al., 1993; Ren et al., 2002; Meng, 2003; Lin and Wang, 2006; Zhai et al., 2007; Charles et al., 2011a, 2012) and thus constitutes a third example of wide rift system. As no major Cenozoic extensional tectonics superimposed on most of the late Mesozoic extensional system, numerous and various extension markers are still well preserved. Widespread late Mesozoic extensional sedimentary basins are amongst the most studied structures in East Asia owing to their coal and/or hydrocarbon potentialities (e.g. Liu, 1986; Watson et al., 1987; Ren et al., 2002; Zhang et al., 2010a; Li et al., 2012a). Besides, late Mesozoic magmatic rocks cover large areas over East Asia (e.g. Wang, et al., 1998; Li, 2000; Wu et al., 2000, 2005a,b, 2007; Zhang et al., 2010b). To the northeast of China, a pioneer and landmark geochronological study coupled with an age compilation has pointed out a "giant igneous event" settled between 130 and 120 Ma, leading to consider a coeval intense lithospheric thinning (Wu et al., 2005a). However, influence of magmatism on tectonic evolution remains rarely discussed for the late Mesozoic extension of East Asia. More recently, several MCCs have been recognised from Transbaikalia to the Jiaodong Peninsula, 2000 km apart (Fig. 1; e.g. Sklyarov et al., 1994; Davis et al., 1996; Webb et al., 1999; Darby et al., 2004; Liu et al., 2005; Lin and Wang, 2006; Donskaya et al., 2008; Daoudene et al., 2009; Charles et al., 2011a, 2012). While structure and kinematics of these MCCs are well-studied, the timing and duration of their development are often poorly constrained (Fig. 1). Accordingly, the precise timing and total duration of extensional process are also rarely estimated.

This paper focusses on the Jiaodong Peninsula (East China, Figs. 1 and 2) which experienced late Mesozoic NW–SE extensional tectonics (Charles et al., 2011a). Indeed, the common occurrence of MCCs, extensional shear zones, synkinematic and late isotropic granitic intrusions can be observed within a narrow zone and such a configuration constitutes a proper place to estimate the timing and duration of extensional tectonics. This paper primarily aims at bringing the first exhumation time-constraints for the Linglong MCC. Thus, conventional $^{40}Ar/^{39}Ar$ analyses were undertaken on both isotropic and deformed strained rocks where the synkinematic characters of successive mineral generations are texturally and chemically settled. Dating either other strained objects related to the same event and post-tectonic markers, this study also places constraints on the total duration of extensional tectonics recorded in the Jiaodong Peninsula. Coupled with a new geochronological compilation of extension markers throughout the East Asia, these new data allow discussing the timing and the total duration of the continental extension history in this large-scale wide rift system. Moreover, relationships between wide rift system development and magmatism are discussed in light of the "giant igneous event" that occurred in East Asia during late Mesozoic times. The evolution of the East Asia wide rift system is also compared to other highly stretched areas throughout the world (i.e. Basin & Range and Aegean regions).

2. Large-scale geological context and anatomy of the Jiaodong Peninsula

The East Asia wide rift system extends from South China to the Baikal Lake south-northwardly, and from the Japanese Islands to the Gobi desert east–westwardly. It forms a north-trending ~1500 km wide extensional band (Fig. 1; e.g. Davis et al., 1996; Ren et al., 2002; Meng, 2003; Liu et al., 2005; Lin and Wang, 2006; Zhai et al., 2007; Daoudene et al., 2009, in press; Charles, 2010; Charles et al., 2011a,b, 2012).

Late Mesozoic extensional basins are prominent geological and physiographical features of east-central Asia. Thanks to coal and oil exploration, these basins have been extensively studied in China (e.g. Liu, 1986; Watson et al., 1987). Sedimentation is characterised by coarse-grained continental deposits with calc-alkaline volcanic rocks that yielded a ca. 155 Ma age for the onset of sedimentation in the Songliao, Erlian, Hailar, Yingen or East Gobi basins (see references in Ren et al., 2002; Meng, 2003; Zhang et al., 2010a, 2011; Li et al., 2012a). Besides, the extensional character of the basins framework is attested by their overall half-graben geometry as displayed on seismic profiles. These are bounded by NE–SW trending normal faults and locally marked by growth-structures in the sedimentation (Chen et al., 1999; Ren et al., 2002; Lin et al., 2003; Meng, 2003). Tectonic subsidence lasted until 120–110 Ma, followed by a regional weak post-rift thermal subsidence (Ren et al., 2002; Meng, 2003). Nevertheless, in the Songliao basin (Fig. 1), thermal subsidence was more important since it promoted deposits up to 6000 m from ~120 to ~70 Ma (Meng, 2003; Li et al., 2012a).

MCCs are the most prominent features of intense and localised extension into continental crust, and some of them have been described throughout East Asia such as: the Yagan–Onch Hayrhan MCC (Mongolia; Webb et al., 1999), the South Liaodong MCC, the Linglong MCC and the Gudaoling MCC (North China; Yin and Nie, 1996; Liu et al., 2005; Charles et al., 2011a, 2012), the Lüshan MCC (South China; Lin et al., 2000), the Buteel–Burgutoy and Ereendavaa MCCs (Mongolia; Mazukabzov et al., 2006; Donskaya et al., 2008; Daoudene et al., 2009) or the Zagan MCC (Russia; Donskaya et al., 2008). Kinematic analyses of the exhumation of these MCCs reveal a common overall NW–SE extensional tectonics throughout East Asia. Timing of the exhumation has already been studied for most of the MCCs (e.g. Davis et al., 1996; Webb et al., 1999; Yang et al., 2007; Lin et al., 2008) and ages, generally interpreted as cooling ages, all cluster at ca. 130–120 Ma (e.g. Lin and Wang, 2006; Daoudene et al., in press; Lin et al., 2013).

Magmatic rocks are also particularly abundant throughout East Asia either as plutonic intrusions or as intercalated volcanic lavas within sedimentary basins. Emplacement ages for both plutonic and volcanic rocks are generally well documented and precisely constrained by HT thermochronological tools (e.g. Wang et al., 1998, 2006; Li, 2000; Wu et al., 2005a,b, 2007; Zhang et al., 2010b; Yang et al., 2012). Considering the apparent age clustering of plutonic rocks, Wu et al. (2005a) proposed the occurrence of a "giant igneous event" at around 130–120 Ma. However, a possible genetic link between this magmatic paroxysm and extension peak is still unclear.

The Jiaodong Peninsula is located in the eastern block of the North China Craton (see NCC on Fig. 1; Mattauer et al., 1985; Faure et al., 2003; Zhao et al., 2005; Zhang et al., 2009; Zhai and Santosh, 2011; Li et al., 2012b; Tam et al., 2012). Four main lithological groups are recognised throughout the Jiaodong Peninsula (Fig. 2a): (1) Late Archaean gneisses, granulites, amphibolites and micaschists belonging to the Jiaodong Group (Tang et al., 2007; Jahn et al., 2008; Zhou et al., 2008); (2) Palaeoproterozoic mafic to felsic volcanic and sedimentary rocks metamorphosed to amphibolite-granulite facies (Jinshan and Fengzishan Groups; Wang, 1995; Tam et al., 2011; see Li et al., 2012b for details); (3) Late Jurassic and Early Cretaceous plutonic and metamorphic rocks (e.g. Luanjiahe, Kunyushan, Guojialing, Weideshan, Aishan and Haiyang massifs); and (4) Cretaceous volcano-sedimentary rocks of the Jiaolai basin (SBGMR, 1991). Late Mesozoic times were characterised by two distinct pulses in the magmatic activity (*s.l.*) at 160–150 Ma and especially at 130–120 Ma (Wang et al., 1998; Goss et al., 2010; Zhang et al., 2010b; Yang et al., 2012). The complex interplay among heat advection, deformation and fluid circulations is thus responsible for the genesis of giant gold deposits (e.g. Zhou and Lü, 2000; Yang et al., 2003; Li et al., 2008; Miao et al., 2012).

The Linglong complex is a NNE–SSW oriented massif located in the Pingdu–Laizhou–Zhaoyuan area (Fig. 2a). It is of ~60 km in length and ~30 km in width. Following Charles et al. (2011a), the Linglong complex can be divided into two main structural elements (Fig. 2b): (1) the Linglong MCC, which is intruded to the north by (2) the Guojialing synkinematic intrusion roofed by a main extensional shear zone.