Geometric and temporal evolution of an extensional detachment fault, Hohhot metamorphic core complex, Inner Mongolia, China

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ABSTRACT

The Early Cretaceous Hohhot metamorphic core complex and its master Hohhot detachment fault are ~400 km west of Beijing in the Daqing Shan (Mountains) of Inner Mongolia. The complex developed across the east-trending Yinshan fold-and-thrust belt within <4 m.y. following cessation of thrusting ca. 125 Ma (see note added in proof in main text). Postcontractional extension was initiated within a mid-crustal zone of mylonitic and ductile shear that was in part controlled by Carboniferous(?) strata sandwiched between its Proterozoic and Archean crystalline basement and an overlying thrust sheet of similar crystalline rocks. The Hohhot detachment fault appears to have rooted into deep, kinematically active levels of the mid-crustal shear zone. Higher, inactive levels of the mylonitic section were transected by the fault and carried upward in its footwall. Geometries of the footwall mylonitic rocks indicate localized ramp-flat geometries of the fault within and across them. The crosscut top of the mylonitic sequence defines a mylonitic front that departs from the gently south dipping detachment fault and dips northward into its footwall. Early Cretaceous extension was widespread elsewhere in northern China, and was particularly pronounced in the Yunmeng Shan core complex north of Beijing. The gravitational collapse of orogenically thickened crust acting in concert with localized centers of deep-seated plutonism appear to have led to the development of isolated metamorphic core complexes within a broad region of more distributed extensional deformation.

Keywords: metamorphic core complex, detachment fault, northern China, Daqing Shan, Early Cretaceous, gravitational collapse.

INTRODUCTION

Geologic Setting

As first described by Darby et al. (2001), the Early Cretaceous Hohhot metamorphic core complex is ~400 km west of Beijing along the northeast corner of the Ordos plateau. With a minimum along-strike length of >120 km, the Hohhot core complex is a major structural component of the eastern Daqing Shan (shan is mountains). A major south-dipping, low-angle (15°–30°) normal fault, the Hohhot detachment fault, is along the southern flank of the east-trending Daqing Shan antiform (Fig. 1) and defines portions of the Daqing Shan mountain front. In contrast to the single detachment fault on the southern limb of the antiform, two stacked and synformally folded detachment faults are present on its northern flank (Figs. 1 and 2). The lower of the two detachments separates lower plate mylonitic rocks from overlying nonmylonitic crystalline rocks—primarily Proterozoic (ca. 2200–1880 Ma) and Permian (ca. 260–240 Ma) granitoid gneisses. The higher, more localized detachment carries a faulted, steeply dipping section of Early Cretaceous volcanic and sedimentary strata.

In the lower plate of the Hohhot detachment fault, mylonitic gneisses and their higher grade schistose to gneissic equivalents have a thickness east of Hohhot (Fig. 2) in excess of 4–5 km. These rocks, with Archean to Early Cretaceous protoliths, are characterized by a gently dipping foliation and northwest-southeast stretching lineation. Abundant kinematic indicators in the mylonitic sequence on both flanks of the Daqing Shan antiform demonstrate a consistent top-to-the-southeast relative displacement, a displacement sense shared by the detachment faults. We interpret the two northerly detachment faults as representing progressive stages in the structural evolution of the Hohhot detachment. The single Hohhot detachment to the south is the master fault, whereas the folded faults to the north are splays (lowermost the oldest) that were active for only part of the core complex development (Fig. 3). The reasons for the synextension fold hinges lying nearly perpendicular to the extension direction (Fig. 1), observed in other metamorphic core complexes as well (e.g., Howard and John, 1987; Lister and Davis, 1989), are controversial and not a topic of this discussion. We estimate a minimum displacement across the master fault and its northerly splays of >40 km, on the basis of the exposed width of the mylonitic footwall (Fig. 1) and the slip necessary to bring mid-crustal mylonitic rocks to the surface along a fault of low to moderate dip.

The outcrop pattern of the Hohhot detachment faults is also influenced by fold-like primary corrugations in the detachment fault that are oriented parallel to the northwest-southeast direction of metamorphic core complex extension (Fig. 1); similar antiformal and synformal corrugations are also well developed in the

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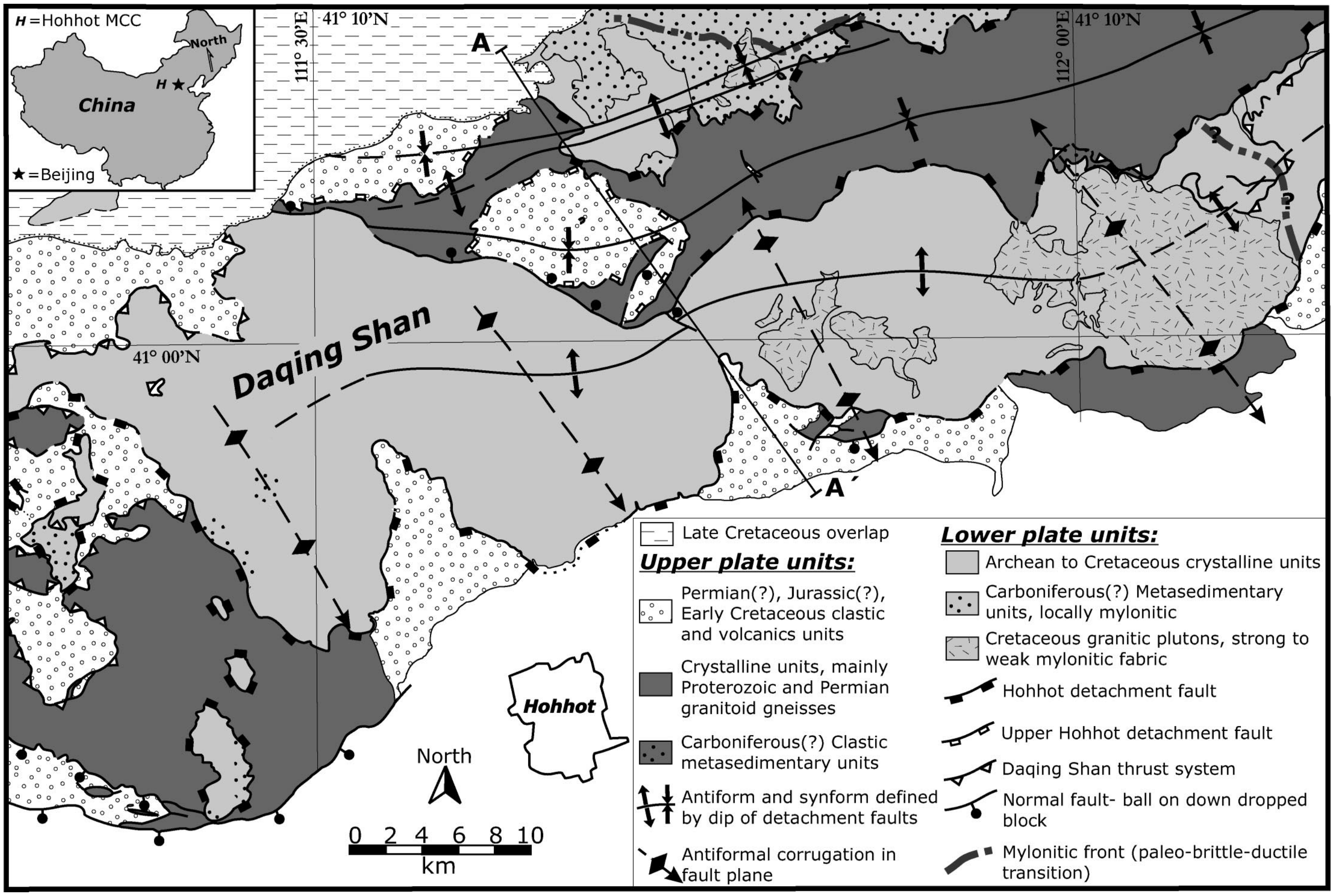

Figure 1. Simplified tectonic map of Hohhot metamorphic core complex (MCC) based on our mapping and that of Nei Mongol Bureau of Geology and Mineral Resources. Note multiple, folded detachment faults on north flank of Daqing Shan antiform. Extension direction is northwest-southwest, parallel to antiformal and synformal (not shown) primary corrugations of detachment faults; shear sense for both detachment faults and footwall mylonitic rocks was top-to-southeast.

metamorphic core complexes of the Lower Colorado River extensional terrane of the southwestern United States (John, 1987; Davis and Lister, 1988; Livaccari and Geissman, 2001).

Tectonic Significance of the Hohhot Metamorphic Core Complex

The Hohhot metamorphic core complex is noteworthy for several reasons that advance our understanding of the formation of metamorphic core complexes: (1) extension forming the Hohhot metamorphic core complex followed major contractional deformation in the Daqing Shan within 4 m.y. of thrust displacement involving Early Cretaceous strata—a temporal relationship that favors gravitational collapse of a tectonically thickened crust as the principal cause for core complex development; (2) several lines of evidence indicate that the Hohhot detachment fault propagated upward across a preexisting, but kinematically related mid-crustal mylonitic shear zone, the position of which was controlled in part by an older thrust fault that was below the Daqing Shan thrust; (3) areas in which major discordance exists between the master detachment fault and mylonitic foliation in its footwall can be explained by ramp-flat geometries of the fault within and across the mylonitic shear zone.

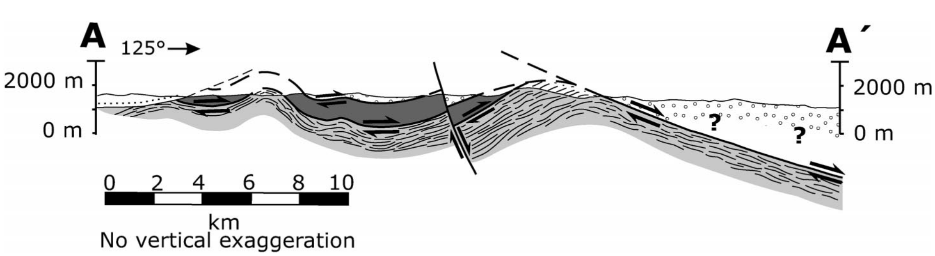

Figure 2. Simplified cross section of Hohhot core complex as we mapped and interpreted it. Fill patterns as in Figure 1. Geology at depth under Early Cretaceous clastic and volcanic sequence in southeastern portion of cross section is undefined. Total displacement on detachment system is >40 km. Dashed lines represent projection of since-eroded structure.

DAQING SHAN CHRONOLOGY OF CRETACEOUS DEFORMATION

Daqing Shan Thrust Fault

The Hohhot metamorphic core complex is superimposed on the east-trending Yinshan fold-and-thrust belt of Jurassic to Cretaceous age (Zhu, 1997; Zheng et al., 1998; Davis et al., 2001). To date, we and geologists from the Nei Mongol Bureau of Geology and Mineral Resources have recognized at least six major post-Carboniferous(?) thrust sheets in the Daqing Shan. The highest major thrust fault in the Daqing Shan portion of the Yinshan belt is the north-northwest–directed Daqing Shan

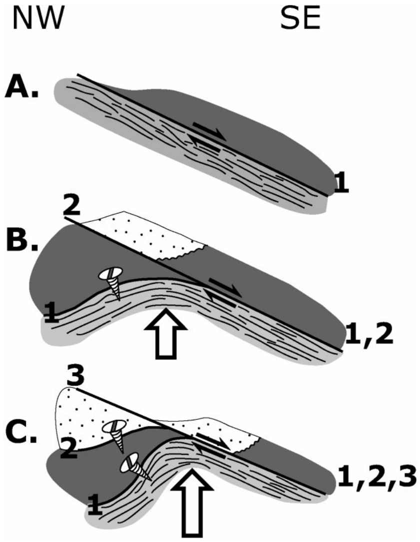

Figure 3. Evolution of Hohhot detachment fault system. Single Hohhot detachment along south flank of Daqing Shan is master fault, whereas synformally folded faults to north are splays (lowermost oldest) that were active for only part of core complex evolution. A: Initial displacement (1) on south-dipping detachment. B: Isostatically related(?) folding of detachment fault (1) and generation of planar splay (2) as detachment continues. C: Continued folding of detachments (1) and (2) and generation of second planar splay (3).

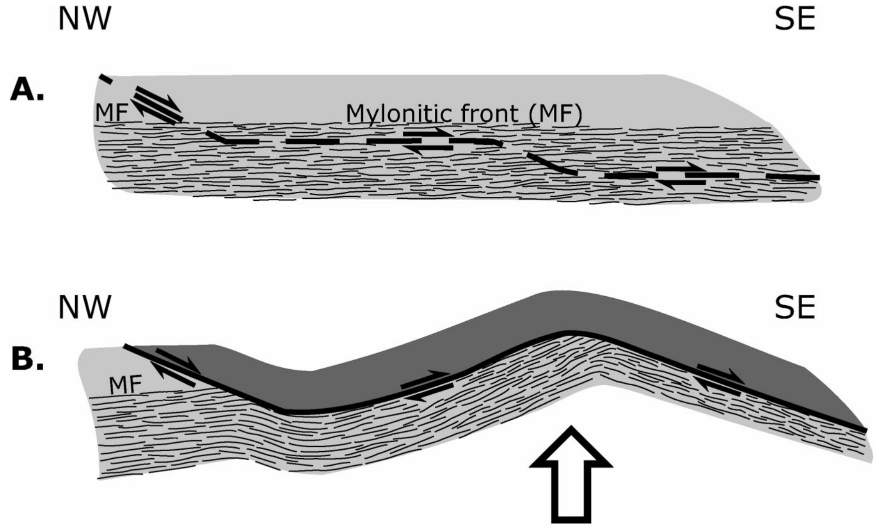

Figure 4. A: Ramp-flat geometry of Hohhot detachment fault in middle crust as determined from discordance between foliation of mylonitic sequence and younger, but kinematically related detachment fault. Mylonitic front is thermally controlled strain boundary below which quartz has undergone penetrative crystal-plastic deformation. B: Folded ramp-flat geometry of detachment fault. Fill patterns as in Figure 1. Note similarity to Figure 2.

thrust (Zheng et al., 1998). This fault, with a minimum 17 km displacement of Archean and Proterozoic crystalline rocks over late Paleozoic(?), Jurassic(?), and Early Cretaceous strata, is well exposed in areas west-northwest of Hohhot (Fig. 1). Siliceous volcanic rocks in its lower plate have yielded Early Cretaceous $^{40}Ar/^{39}Ar$ ages (127.2 $\pm$ 1.0 Ma, whole-rock isochron; 125.5 $\pm$ 0.7 Ma, single-crystal sanidine weighted mean). (*Note added in proof*: Summer 2002 fieldwork refutes a lower plate position for these volcanic rocks; the end of Daqing Shan thrusting [see later discussion] is thus not constrained by these dates.)

Hohhot Detachment Fault

The Hohhot detachment fault is below the Daqing Shan thrust west of Hohhot (Fig. 1), but farther north it cuts discordantly across the thrust and its upper- and lower-plate rocks. Allochthonous Cretaceous volcanic rocks similar to those in the lower plate of the thrust are widely exposed directly above the detachment fault and yield indistinguishable $^{40}Ar/^{39}Ar$ ages (125.2 $\pm$ 0.7 Ma, 125.7 $\pm$ 0.6 Ma, and 125.8 $\pm$ 0.6 Ma; sanidine single-crystal weighted means). Biotite and hornblende in footwall amphibolitic schists at one southern locality below the detachment give indistinguishable $^{40}Ar/^{39}Ar$ cooling ages of 121.4 $\pm$ 0.9 and 121.5 $\pm$ 1.3 Ma, respectively. Collectively, these age relationships indicate that displacement on the Daqing Shan thrust postdated ca. 125 Ma, and that the initiation of extension along the Hohhot detachment fault occurred prior to the rapid cooling of the southernmost exposures of its footwall ca. 121 Ma.

EVOLUTION OF THE HOHHOT DETACHMENT FAULT

It was originally proposed (e.g., Wernicke, 1981) that detachment-related mylonitic rocks form along deeper levels of the detachment faults before being transported upward in their footwalls. The Hohhot detachment fault, like the Whipple Mountains fault of earlier studies (Lister and Davis, 1989), is an important exception to this geometry. In the Daqing Shan, Early Cretaceous contraction was soon followed by extension-related translation of the brittle upper crust with respect to deeper, more ductile levels, thus forming the mylonitic sequence now found in the metamorphic core complex. The location of this sequence was partly controlled by the presence at mid-crustal levels of low-strength psammitic and pelitic Carboniferous(?) strata sandwiched between its underlying Archean–Proterozoic crystalline basement and a thick, previously unrecognized overlying thrust plate of crystalline basement units. The age of this northward-vergent thrusting has not yet been determined, but it clearly contributed to the crustal thickening that preceded core complex development. Ductile deformation of Carboniferous(?) quartz-bearing clastic rocks indicates that they had been tectonically buried to depths where temperatures exceeded 300–350 °C.

Upper, inactive structural levels of the mylonitic schists and gneisses were later transected by the Hohhot detachment fault and transported upward in its footwall. It is likely that the detachment flattened downward and rooted into deeper, kinematically active levels of the intracrustal shear zone represented by the mylonitic sequence. This conclusion is supported by two separate lines of evidence—a ramp-flat geometry of parts of the detachment fault, and a mylonitic front below northernmost areas of the detachment.

Ramp-Flat Geometry of the Hohhot Detachment

At most localities in the Hohhot metamorphic core complex, including both flanks of the Daqing Shan antiform (Fig. 1), the foliation in lower plate mylonitic schists and gneisses and underlying higher grade schists and gneisses is parallel or subparallel to the detachment fault. However, along the south flank of the Daqing Shan antiform in the vicinity of longitude 111°59′W, there is marked discordance between the south-dipping detachment fault (~15°) and the footwall mylonitic foliation that dips variably northward (~25° $\pm$ 10°; Fig. 2). In contrast, on the north flank of the antiform at this longitude both the detachment fault and footwall mylonitic fabrics dip gently northward (~10°–15°). We interpret these geometric relationships to be indicative of an original configuration at depth of the south-dipping detachment fault cutting upward across kinematically inert, subhorizontal mylonitic gneisses (Fig. 4A) and then flattening to become parallel to higher levels of the mylonitic section. Later antiformal folding of the detachment fault and its lower plate mylonitic rocks (Fig. 4B) produced the present patterns of southern discordance (reflective of a ramp) and northern concordance (a flat).

Daqing Shan Mylonitic Front

Mylonitic footwall rocks of the Hohhot detachment are exposed across a 25-km-wide tract of the Daqing Shan north of its southern range front. However, at the northern edge of this tract (latitude ∼41°09′N), a mylonitic section of Carboniferous(?) schists and phyllonites leaves the gently south dipping detachment fault and dips northward at low angles (∼15°–20°) into its footwall (Figs. 1, 2, and 4B). The upper limit of the mylonitic rocks is a mylonitic front (Davis and Lister, 1988), a thermally controlled strain boundary below which quartz has undergone penetrative crystal-plastic deformation. Here, the mylonitic front is a narrow gradational zone between highly foliated Carboniferous(?) schists and phyllonites that contain a northwest-southeast stretching lineation and low-grade Carboniferous(?) metasandstones and metaconglomerates; these latter rocks exhibit nonpenetrative deformation that includes localized cleavage development and bedding transposition. The main transition between the north-dipping mylonitic section and its higher, less transposed counterparts occurs across an interval ≤100 m thick. The departure of the mylonitic section away from the gently dipping detachment fault is best explained by an earlier ramping of that fault across the top of a deep, subhorizontal mylonitic sequence (Fig. 4A); the cutoff angle between the detachment fault and the mylonitic foliation is ∼25°–30°.

CONCLUSIONS

The onset of intraplate extension between 125 and 121 Ma, within <4 m.y. after the end of major Early Cretaceous contraction in the Daqing Shan, seems reasonably attributed to gravitational collapse of an orogenically thickened crust. The apparently highest thrust in the range, the Early Cretaceous Daqing Shan thrust, now is in the upper plate of the Hohhot detachment fault. Permian(?) conglomerates in the footwall of that thrust exhibit fault-related low greenschist–grade metamorphism and ductile deformation suggesting their deep tectonic burial. Gravitational collapse may also have been facilitated by the Early Cretaceous intrusion of granitic plutons (ca. 137–119 Ma; zircon U-Pb ages from George Gehrels, March 2002, written commun.) into crustal levels below the Hohhot detachment fault; none have been found above it.

Early Cretaceous extension was not limited to the Daqing Shan, but encompassed an area from the Yagan metamorphic core complex to the west (Zheng et al., 1991; Webb et al., 1999), the Yunmeng Shan to the east (Davis et al., 1996; 2001), and large portions of Mongolia to the north (Johnson et al., 2001; Ren et al., 2002). In the Yanshan belt north and northwest of Beijing, for example, widespread and possibly diachronous northwest-southeast crustal extension accompanied or occurred shortly after the end of major Jurassic–Cretaceous thrusting (≤127 Ma; Davis et al., 2001). The Yunmeng Shan metamorphic core complex, north of Beijing, is the most profound expression of this deformation (Davis et al., 1996, 2001), which elsewhere was generally characterized by half-graben formation. There is considerable petrologic opinion that Early Cretaceous extension in northern and eastern China was initiated by delamination of mafic lower crust and its underlying mantle lithosphere (e.g., Zhang et al., 2001).

Pronounced loci of late Mesozoic contraction-related thickening of the North China crust and localized deep-seated plutonism (both observed in the Daqing Shan and Yunmeng Shan) appear to have focused development of the isolated metamorphic core complexes of the Yinshan and Yanshan belts within a broad region of more distributed extensional deformation.

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