DELAMINATION/THINNING OF SUB-CONTINENTAL LITHOSPHERIC MANTLE UNDER EASTERN CHINA: THE ROLE OF WATER AND MULTIPLE SUBDUCTION

B. F. WINDLEY*, S. MARUYAMA**, and W. J. XIAO***

ABSTRACT. We present a new model to explain one of the biggest tectonic problems of Earth Sciences today, namely, how and why did the Archean sub-continental lithospheric mantle under the Eastern Block of the North China Craton (NCC) delaminate or thin so drastically in the Cretaceous? The eastern NCC is surrounded by several sutures: to the north the south-dipping Solonker (Permo-Triassic formation age) and Mongol-Okhotsk suture (Jurassic formation age), to the south the north-dipping Dabie Shan and Song Ma sutures (Permo-Triassic formation age), and to the east the Pacific oceanic plate (200-100 Ma). Water was carried down under the eastern NCC by the hydrated Pacific plate for at least 100 Ma, and by oceanic plates subducted along the Solonker, Dabie Shan and Song Ma sutures for at least 250 Ma from the early Paleozoic to the Permo-Triassic, and by the Mongol-Okhotsk suture for at least 200 Ma until the Jurassic. Tomographic images show that the Pacific plate has ponded along the top of the mantle transition zone under the eastern NCC for over ca. 2000 km from the Japan trench. An addition of 0.2 weight percent H_2O lowered the solidus temperature of hydrous mantle peridotite by 150 °C, which led to extensive melting in the hydrous mantle transition zone, and to the rise of hydrous plumes into the overlying crust-mantle. By the time of formation of the Permo-Triassic sutures, the hydration caused by subduction of four oceanic plates had caused major garnetization of the Archean crustal root of the eastern NCC, and post-collisional thrusting in the Jurassic led to major crust/mantle thickening and this triggered collapse of the hydro-weakened garnet-enriched crustal root. During the extensional Cretaceous period, abundant mafic, adakitic and granitic intrusions and extensive gold mineralization were emplaced and metamorphic core complexes and sedimentary and foreland basins formed in and around the eastern NCC. Part of the root was chemically transformed and replaced by upwelling fertile asthenospheric material, which fed the extrusion of extensive alkali flood basalts in the Cenozoic.

Key words: Delamination, water in subduction, Permo-Triassic orogeny, East Asia, North China craton

INTRODUCTION

The existence of an asthenosphere, and therefore of plate tectonics as we know it, is possible only in a planet, like Earth, that has a water-bearing, convecting mantle (Bunge and others, 1996; Bercovici and Karato, 2003; Mierdel and others, 2007). In other words, plate tectonics would not exist on Earth without traces of hydroxyl groups in nominally anhydrous minerals (Regenauer-Lieb and others, 2001; Regenauer-Lieb and Kohl, 2003). Since the first synthesis of hydrous wadsleyite and ringwoodite, it is well accepted today that such mantle water is derived by dehydration of relatively well-hydrated subducted slabs and is introduced and concentrated in the mantle transition zone between 410 km and 660 km depth (Peacock, 1993; Inoue and others, 1995; Iwamori, 1998; Ohtani and others, 2004; Richard and others, 2006; Maruyama and Okamoto, 2007; Tonegawa and others, 2008). Subsequently, this transition zone water has a major influence on the inception and rise of plumes into mid-oceanic ridges (Bercovici and Karato, 2003), and on delamination and thinning of sub-continental lithosphere, the subject of this paper.

* Department of Geology, University of Leicester, Leicester LE1 7RH, United Kingdom; brian.windley@btinternet.com
** Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama 2-12-2, Tokyo 1528551, Japan; smaruyam@geo.titech.ac.jp
*** State Key Laboratory of Lithosphere Tectonic Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, P.R. China; wj-xiao@mail.iggcas.ac.cn

One of the major, international, unresolved tectonic conundrums of today concerns the delamination/thinning of sub-continental lithosphere under orogenic belts of different age. Selective removal of the mantle has major implications for the growth of the overlying continental crust. Lithospheric thinning or root/keel removal has occurred in different tectonic environments worldwide, and different mechanisms have been ascribed to account for them for example, a dense mountain root that transformed to negatively buoyant garnet-enriched lower crust in a thickened Andean-type crust, for example in California, USA (Ducea and Saleeby, 1997; Boyd and others, 2004; Jones and others, 2004), Oregon, USA (Hales and others, 2005), and in the Andes (Kay and Kay, 1993; Garzione and others, 2006), thermal weakening that led to attenuated lithosphere as a result of crustal thickening caused by continental plate convergence for example at Ronda in the Betic orogen, Spain (Tubía and others, 2004), and in South India, where the 1-Ga lithospheric root of the Dharwar craton has vanished (Griffin and others, 2009). However, eastern China arguably provides the best-documented example of this phenomenon that has stimulated an array of alternative models with the result that there is no viable or widely accepted explanatory mechanism (for example, Menzies and others, 2007). The main aim of this paper is to propose a new model, which accounts for the thinning or delamination of sub-continental mantle lithosphere below eastern China in terms of the dehydration of multiple subducted slabs, which integrates existing data on the physical-chemical properties of the hydrated mantle transition zone, and which provides a novel mechanism of tectonic forcing which triggered the thinning/delamination of a dense garnet-enriched crustal root.

GEOLOGICAL-TECTONIC BACKGROUND OF EASTERN CHINA

The Eastern Block of the North China Craton (fig. 1) is the best example worldwide of an Archean craton that has lost its lithospheric root, first documented by Griffin and others (1992); see also (Fan and Menzies, 1992; Menzies and others, 1993; Griffin and others, 1998; Fan and others, 2000; Gao and others, 2004; Kusky and others, 2007; Chu and others, 2009). The craton is bordered by Phanerozoic orogens, suture zones and faults. On the northern side, the Permo-Triassic Solonker suture marks the closure of the Paleo-Asian ocean and termination of the Central Asian Orogenic Belt. During closure of the ocean, southward subduction began in the early Paleozoic and continued until collision near the end-Permian (Xiao and others, 2003; Jian and others, 2010).

In the Yanshan orogen on the southern side of the suture in the northern part of the craton post-collisional Late Jurassic–Early Cretaceous thrusting was followed by extensive, largely granitic magmatism (at *ca.* 195-185 Ma and *ca.* 159-141 Ma, Yang, F.-Q., and others, 2007), metamorphic core complex formation (Davis and others, 2001), extensional structures, uplift, regional unconformities and sedimentary basins (Cope and Graham, 2007), and foreland basins formed from the Late Triassic to Cretaceous (Li and others, 2007).

On the southern side of the craton, the Qinling–Dabie Shan suture and orogen formed as a result of collision between the North China (Sino-Korean) and South China (Yangtze) cratons either by the end of the Permian (Metcalfe, 2002) or in the Late Triassic (Meng and Zhang, 2000). Subduction was to the north, with the result that the Dabie Shan orogen contains many UHP-HP eclogites and associated rocks containing diamond and coesite derived from the South China Craton (Wang and others, 1989; Liu and others, 2001). The presence of exsolution lamellae of clinopyroxene, rutile and apatite in eclogitic garnets suggests that subduction reached depths of more than 200 km (Ye and others, 2000). Post-collision thrusting took place on the northern side of Dabie Shan, partly in association with formation of the Hefei foreland basin, from the Late Triassic to at least the mid-Cretaceous (Li and others, 2007).
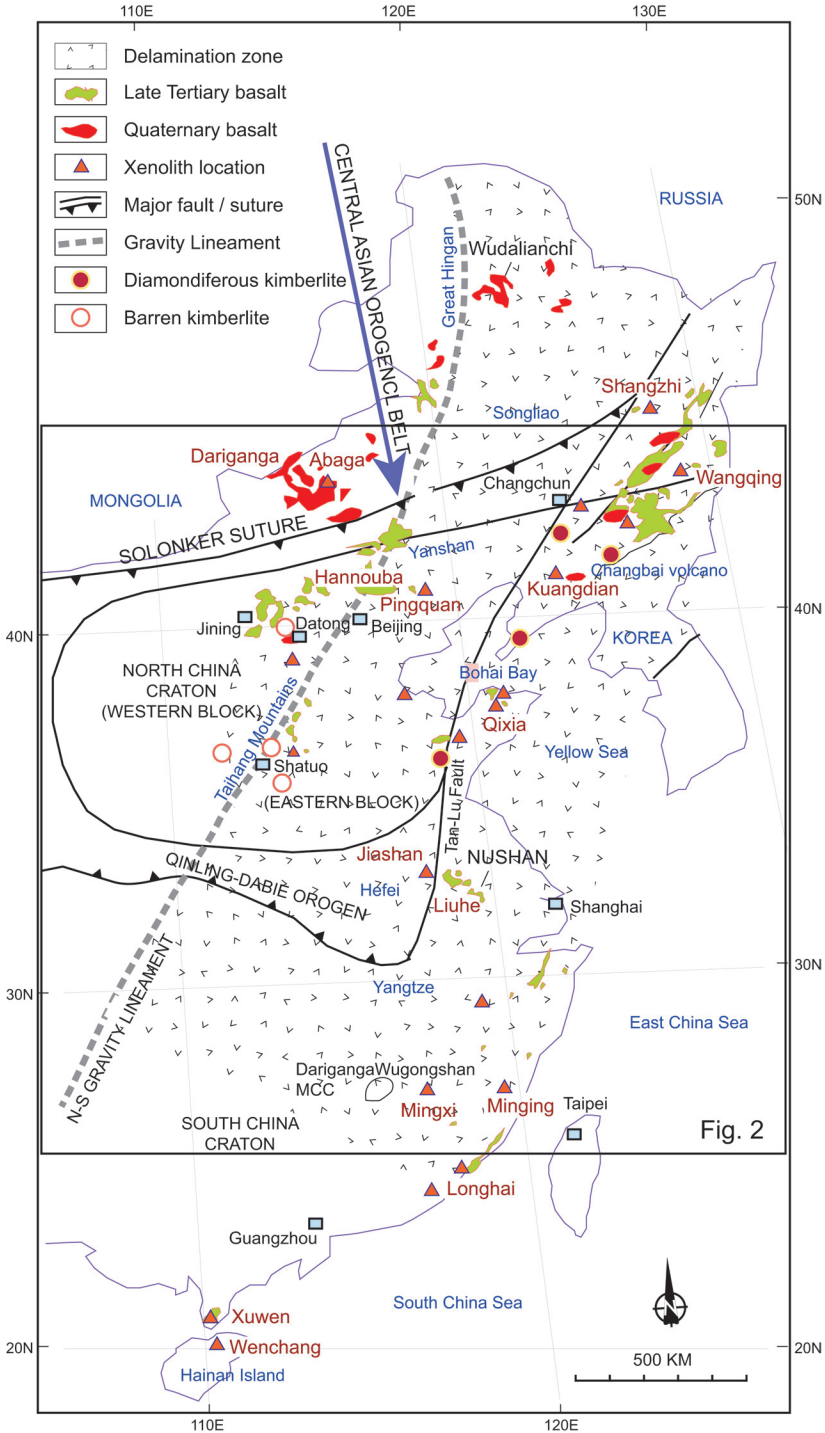
Fig. 1. Compilation map of eastern China showing the N-S gravity lineament to the east of which is the region underlain by thinned lithospheric mantle that includes the Eastern Block of the North China Craton and areas to the north, east and south. Also marked are the main areas with Late Tertiary and Quaternary basalts and the locations of xenoliths and kimberlites (for further details see fig. 2). Position of fig. 2 is marked.

Geophysical data suggest that the Dabie Shan orogen today has an average crustal thickness of 36 to 34 km (normal for an orogen) and that its root is only 6.5 km thick (Gao and others, 1998a; Wang and others, 2000); most of the root may have foundered into the underlying mantle (Huang and others, 2008).

Although the South China craton south of the Dabie Shan orogen has not been traditionally included in the major Mesozoic delamination belt, the recent data of Li and others (2009) demonstrate that the northern part did undergone coeval lithospheric extension and thinning; emplacement of dioritic and quartz dioritic plutons of adakitic affinity started at *ca.* 152 Ma and peaked at 141 to 132 Ma (Huang and others, 2008), and dacitic lavas were erupted and dikes of monzonite and gabbro-diorite were intruded in the period 130 to 113 Ma. The Tan-Lu fault—fig. 1 (Xu, 1993) displaced the Sulu orogen northwards by ~500 km from the Dabie orogen in the early Cretaceous. This major fault may have triggered the foundering of over-thickened lithosphere (Huang and others, 2008) and assisted Cenozoic replacement of pre-existing Archean lithospheric mantle (Zheng and others, 1998). On its western side, the North China Craton is overlain by the Ordos basin with which it has a thrust-reactivated margin (Darby and Ritts, 2002). Important in later discussions is the Mongol-Okhotsk suture and orogen in northern Mongolia and Transbaikalia that formed in the Jurassic to Cretaceous when the final ocean closed between the Siberian and Mongolian plates (Tomurtogoo and others, 2005).

The North China Craton consists of Archean Western and Eastern Blocks that were welded together by collision in the Paleoproterozoic to give rise to a NS-trending, Trans-North China orogen (Zhao, 2001). The Western and Eastern Blocks are very different in many respects (Griffin and others, 1998). Whereas the Western Block has a "normal" mantle and crust with no thinning, magmatic additions, or extensional structures since its stabilization at *ca.* 1.8 Ga (Zhao and others, 2000; Zhang, H.–F., and others, 2003), the Eastern Block has undergone major changes. Its lithospheric mantle was massively thinned, modified or removed in the Early Mesozoic, its crust was affected by many intrusions, extrusions, sedimentary basins and extensional structures in the Mesozoic and Cenozoic, and it is still seismically active. Hereafter this modified part of the Eastern Block will be referred to as the Eastern part of the NCC.

A major N-S gravity lineament (fig. 1) extends both north and south of the North China Craton across the whole of China; it coincides with the boundary between the Western and Eastern Blocks, it parallels the Pacific subduction margin for several thousand kilometers, passing along the eastern sides of the Great Hingan Mountains and Taihang Mountains, which are marked by 40 to 42 km thick crust (Li and others, 2006). The linear gravity gradient on figure 1 follows that of Ma (2002), which varies from ~200 to 250 km in width within which the gravity anomaly values drop by over 100 mgals from west to east; Griffin and others (1998) only marked its 40 to 45 km-wide western boundary as the lineament. Within the North China Craton the anomaly separates areas to the **west** that have high negative Bouguer anomalies, low heat flow, high mantle seismic velocities (8.3-8.1 km/sec), 200 to 150 km thick lithosphere, a 45 to 40 km-thick crust, and present-day mountainous surface topography, from areas to the **east** that have zero to slightly positive gravity anomalies, high heat flow, lower mantle seismic velocities of 7.7 to 7.6 km/sec, a lithosphere that is 90 to 60 km thick, a crust that thins from 42 to 28 km thick, and flat-plain surface topography (Lin and others, 2005). The low relief in the eastern North China Craton can be best explained by post-delamination thermal subsidence, which can cause 1.3 km of net surface lowering within 100 m.y. regardless of the state of relief and elevation (Avigad and Gvirtzman, 2009). The crust/lithosphere-thinned eastern part of the craton (within the gravity lineament) is noted for its abundant earthquakes: more than 100 with magnitudes greater than 5.0 in the Beijing region alone in the last 1000 years, some

reaching magnitude 8.0 (Gu, 1983, in Huang and Zhao, 2004). The minimum crustal thickness of 26 km is beneath the Bohai Sea (Lin and others, 2005). The Tan-Lu fault parallels the lineament, being never far from the value of 0.0 mgals. Xu (2007) suggested that the gravity lineament was most likely caused by diachronous lithospheric thinning of the North China Craton. Widespread Mesozoic and Cenozoic igneous intrusions and extrusions, sedimentary basins and metamorphic core complexes occur within and to the east of the gravity lineament, rather than to its west. Osmium isotopic data of peridotite xenoliths indicate that the lithospheric mantle beneath the Western Block was stabilized in the early Precambrian and that the crust-mantle there is coupled, which contrasts with the decoupled nature below the Eastern Block (Xu, X., and others, 2008; Xu, Y.-G., and others, 2008). The fast polarizaton direction of P-waves in the mantle below the Eastern Block trends SE and is deflected at the boundary with the Western Block, which implies that northwestward mantle flow played an important role in the reactivation of the Eastern Block (Zhao and Zheng, 2005).

Off the North China Craton to the north, the lithosphere of the Central Asian Orogenic Belt below the Songliao Basin has been symmetrically thinned from 120 km to <80 km (Zhang and others, 2000), and the crust has been thinned from 36 km to <32 km (Li and others, 2006). On the western side of the Songliao basin, the Great Hingan Range contains Mesozoic basalts, andesites, dacites and rhyolites that were erupted during the Early Cretaceous with an age peak at ~125 Ma, coincident with the time of lithospheric thinning in the Eastern Block of the North China Craton. Because of its almost N-S alignment Zhang and others (2008) related this magmatism to subduction of the parallel Pacific plate.

XENOLITHS IN KIMBERLITES AND BASALTS

Xenoliths in kimberlites and basalts that have intruded and extruded through the North China Craton provide the critical evidence for loss of Archean lithosphere and thus for models of delamination and thinning.

Ordovician diamondiferous kimberlites in the Eastern Block of the craton (fig. 2) contain Archean xenoliths (Griffin and others, 1992; Gao and others, 2002) of garnet peridotite that indicate that the Paleozoic lithospheric mantle had a very low conductive, cold, refractory cratonic geotherm (<40 mW/m^{-2}), and that the lithosphere was thick (~200 km) (Menzies and others, 1993; Griffin and others, 1998; Zheng and others, 1998, 2004). A lithospheric thickness of about 200 km is supported by geothermobarometry of minerals and assemblages included in diamonds (for example, Wang and Gasparik, 2001). The early Paleozoic lithospheric mantle consisted of highly refractory, major element-depleted, buoyant harzburgites and clinopyroxene-poor lherzolites (Zhang and others, 2002) with an enriched Sr-Nd isotopic composition (Chu and others, 2009).

In contrast, Mesozoic and Cenozoic kimberlites contain mantle xenoliths and Cenozoic basalts (fig. 2) contain xenoliths of spinel peridotite (Peng and others, 1986; Song and others, 1990; Basu and others, 1991; Xu and others, 1998; Chu and others, 2009). Geophysical data suggest that the present lithosphere is thin (only 90 km, and as little as 60 km beneath the Bohai Sea) and hot (geotherms up to 60-80 mW/m^{-2}) (Fan and others, 2000; Zheng and others, 1998, 2004, 2005). For example, the Nushan alkali basalt volcano (fig. 1) erupted in the mid-Pleistocene at 0.53 to 0.73 Ma through a 30 km thick crust with a 100 km thick lithosphere (Xu and others, 1998).

It is widely accepted that the Eastern Block of the North China Craton has undergone large-scale lithospheric thinning that led to the removal of about ~120 km of lithospheric root in the Mesozoic (Griffin and others, 1998; Fan and others, 2000; Deng and others, 2004). The thinning process also gave rise to compositional changes from a cold thick and refractory Paleozoic lithospheric mantle to a hot, thin and fertile
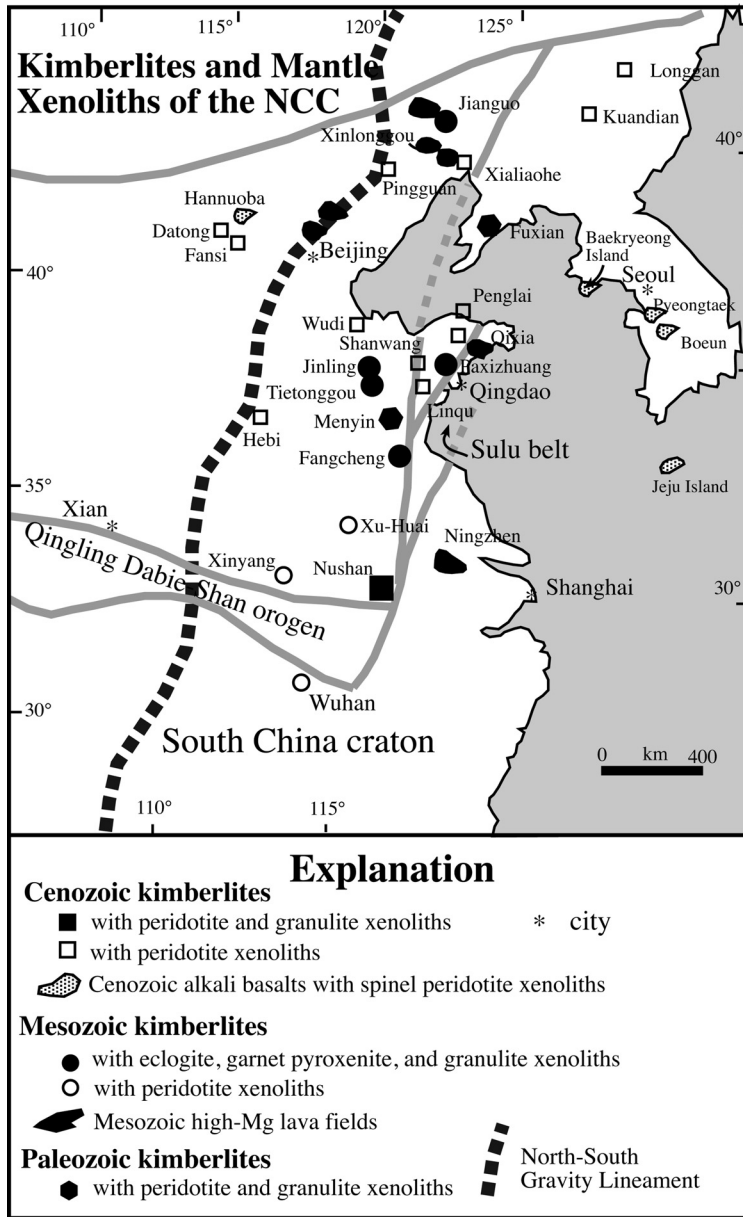
Fig. 2. Map of eastern China showing the distribution of Cenozoic, Mesozoic and Paleozoic kimberlites and their different types of xenoliths (modified after Menzies and others, 1993; Griffin and others, 1998; Zheng and others, 1998, 2004). MCC = Metamorphic Core Complexes. For position in eastern China see fig. 1.

Cenozoic lithosphere (Fan and others, 2000; Zhang, 2007) that has a Sr-Nd isotope composition similar to that of the depleted mantle (Chu and others, 2009). The temperature at the Moho increased from ~400°C in the Paleozoic to 700 to 800 °C at present in some areas (Liu, 1987; Griffin and others, 1998).
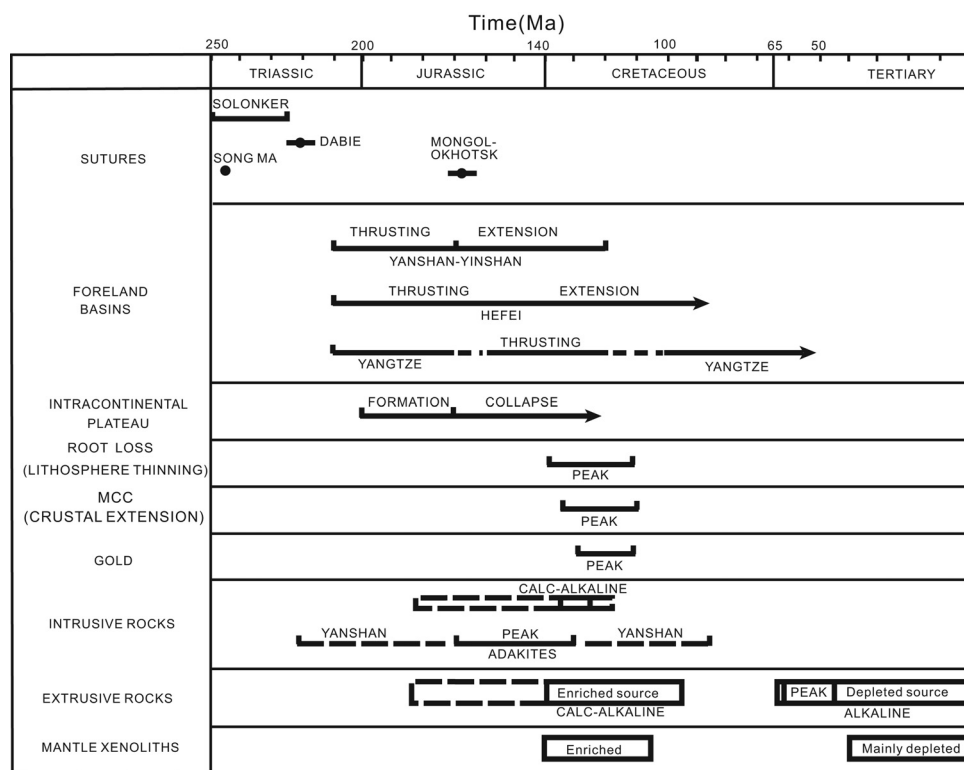
Fig. 3. A history of key events for the eastern North China Craton. Modified and expanded from Menzies and others (2007). MCC – metamorphic core complex.

Spinel peridotite xenoliths from Cenozoic volcanoes in the Dariganga lava plateau that straddles the Chinese-Mongolian border (fig. 1) situated in the Central Asian Orogenic Belt, lack volatile-bearing minerals, but the water contents of nominally anhydrous minerals have not yet been determined; they record partial melting of the upper mantle metasomatized by oxidized fluids (Wiechert and others, 1997).

MESOZOIC MAGMATISM

The North China Craton is unique amongst the early Precambrian cratons of the world in having been intruded and extruded by a wide variety of magmatic rocks in Jurassic-Cretaceous (Yanshanian) time. The geochemical characteristics of these rocks provide key information on the composition of their crustal or mantle protoliths.

The most abundant Mesozoic igneous rocks in the Eastern Block range from monzogabbro, through monzonite to monzogranite, and locally to syenite; monzonitic rocks predominate (Chen and others, 2007, and references therein). Their principal geochemical signatures include high-K, calc-alkaline to shoshonitic affinities, high Sr-Ba abundances, and high Sr/Y, La/Yb, and highly enriched Sr-Nd isotopic compositions with $\varepsilon_{Nd}(t)$ ranging from -8 to -20 and I_{Sr} from 0.7053 to 0.710. Zircon SHRIMP ages range from 180 Ma to 120 Ma but concentrate in the range 135 to 127 Ma—fig. 3 (Wu and others, 2005). Chen and others (2007) concluded that upwelling hot asthenospheric mantle triggered partial melting of enriched subcontinental lithospheric mantle generating voluminous mafic magmas that underplated and partially melted the lower crust, producing granitic melts.
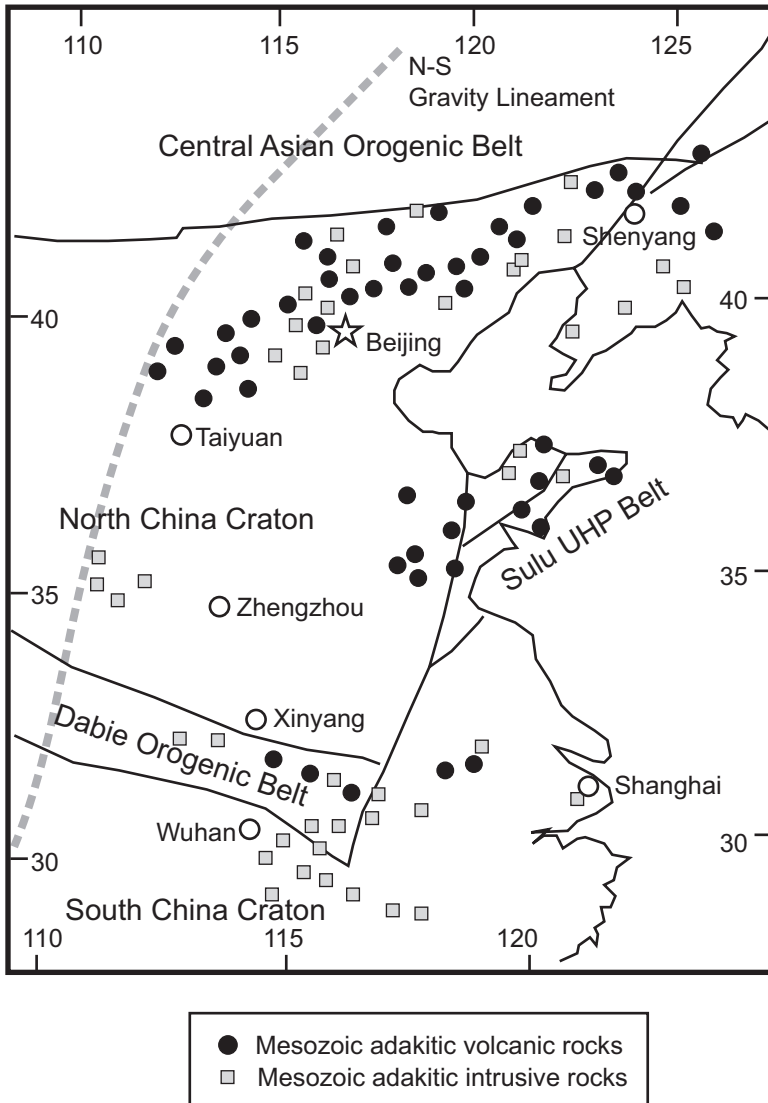
Fig. 4. Map of eastern China showing the distribution of Mesozoic adakitic volcanic and intrusive rocks both within the Eastern Block of the North China Craton and to the east and southeast of it. Partly after Xu and others (2006b) and Zhai and others (2007).

Adakites are distinctive rocks that are distributed in the Eastern Block of the craton, and in the thinned areas to the east and south (fig. 4). In general, the adakites are characterized by LREE enrichment, HREE depletion, high Al_2O_3, MgO, Sr, and low contents of Y and Yb. Zhai and others (2007) called the adakites "high-Sr granitoids." Some adakites are produced by slab melting in subduction zones, but some, like those in eastern China, by the melting of delaminated lower crust (Zhai and others, 2007). According to the latter process, when the continental crust has been thickened, for example, by thrusting, the thickened Archean lower crust becomes eclogitic, separates and sinks into the mantle, comes into contact with relatively hot

mantle, which initiates melting and the production of adakites; or put more simply, the adakites were derived by partial melting of Archean lower crustal eclogite (Gao and others, 2004; Xu and others, 2008).

The eastern Chinese adakites formed under high-pressure (>1.5 GPa) melt conditions (Davis, 2003), as required for adakites that form at the base of continental crust that has been tectonically thickened, leaving a dense eclogitic residue, according to Kay and Kay (2002). This relationship is confirmed by the presence of 136 ± 3 Ma adakitic rocks a few kilometers east of the Tan-Lu fault, which were most likely derived by the partial melting of delaminated lower crust at pressures equivalent to a crustal thickness of >50 km (that is ~1.5 GPa), possibly leaving a rutile-bearing eclogitic residue (Wang and others, 2006). The geochemistry of nearby adakites at Ningzhen (fig. 2) indicates that garnet was stable as a residual phase during partial melting, implying that the crustal thickness exceeded 40 km in the Early Cretaceous (Xu and others, 2002). However, the present thickness of the crust in the area is only 30 km; therefore it can be reasonably concluded that the crust has been thinned by at least ~10 to 20 km since the Early Cretaceous. In the Eastern Block of the craton, high-Mg, dioritic-monzodioritic, 132 to 131 Ma adakites contain xenoliths of eclogite, garnet clinopyroxenite and garnet amphibolite (Xu and others, 2006a); geochemical data suggest that the high-Mg adakitic magma resulted from partial melting of delaminated lower continental crust of early Precambrian age (1700-1800 and 2400-2550 Ma inherited zircons) that interacted with hot mantle. Huang and others (2008) reported compositionally similar adakitic rocks in the Dabie Shan orogen that formed by similar tectonic-chemical processes.

The Yanshan belt underwent intense thrust deformation, which culminated at c. 170 Ma, and extension began after c. 159 Ma (Hu and others, 2010), or after 127 Ma (Davis and others, 1998, 2001; Davis, 2003). Adakitic magmas were generated in the Yanshan belt from *ca.* 190 Ma to *ca.* 80 Ma (fig. 3); the peak of such magmatism largely coincides with the period of extensional deformation from 170 Ma to 130 Ma (fig. 3). However, some confusion arises because of compilation of data from different areas. For example, Cope and Graham (2007) concluded that the largely adakitic magmatism in the Yanshan region occurred at *ca.* 219 to 130 Ma. According to Yang and Li (2008) 177 Ma high-Mg# adakites (with arc-like Sr-Nd-Pb isotopic compositions) were produced by partial melting of Paleozoic oceanic crust subducted beneath the northern margin of the North China Craton along the Solonker suture (Xiao and others, 2003). But many adakitic rocks from the Eastern Block belong to the high-potassium calc-alkaline series and do not have the trace element features of adakites that formed as a result of oceanic slab melting (Davis, 2003). In contrast, they are petrochemically similar to adakites in tectonically thickened crust in the Andes (Kay and Kay, 2002) and Tibet (Chung and others, 2003). This is consistent with the idea of Zhang, Q., and others (2001) of the presence of an intracontinental plateau in eastern China (see later).

Regional extension took place throughout the Yanshan-Dabie belts and in the delaminated Eastern Block of the craton at ~170 to 100 Ma. In some areas widespread igneous rocks, many mafic in composition (fig. 5A), range from lamprophyre dikes (Chen and Zhai, 2003), moderate Mg# gabbros (Xu and others, 2004b), dolerite dikes and diorites to A-type granites that have U-Pb ages of 135 ± 2.7 to 117 ± 7 Ma (Wu and others, 2005), 156.3 ± 4.8 to 157.4 ± 5.7 (Li and others, 2004), and 210 ± 1 Ma (Yang, J.-H., and others, 2007), and a late syenite at 113 ± 2 Ma (Yang, F.-Q., and others, 2007a). They were intruded in what Wu and others (2005) described as a "giant igneous event" in an extensional setting that includes metamorphic core complexes (139-109 Ma)—fig. 3; the last authors concluded that the magmatic generation was related to coeval lithospheric delamination that resulted from Kula-Pacific plate
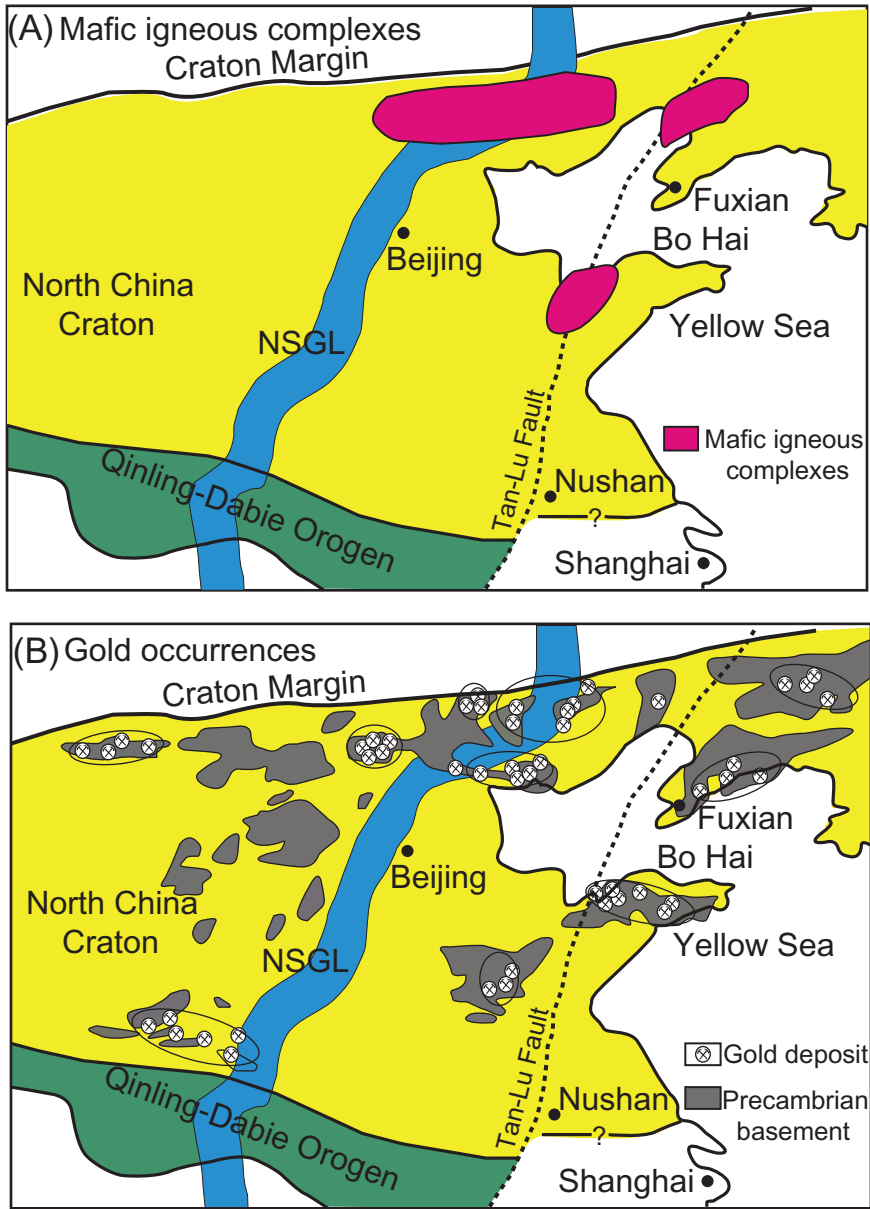
Fig. 5. Maps showing (A) the main areas with Mesozoic mafic igneous rocks in the North China Craton, after Menzies and others (2007) and Zhang (2007); they wrap around the area underlain by spinel facies mantle compositions (fig. 4B), and (B) the distribution of gold deposits and main gold districts that are concentrated near the margins of the eastern North China Craton. NSGL: N-S Gravity Lineament. Modified after Yang and others (2003).

subduction, possibly aided by major superplume activity associated with global-scale mantle upwelling, but not many other authors have invoked a plume/superplume model. Early Cretaceous calc-alkaline basalts and associated shoshonite lavas, CaFe-carbonatite dikes, and gabbro/diabase dikes were interpreted to be the result of

northward subduction of the South China craton (Zhang and Sun, 2002). A 132 Ma complex containing syenite, gabbroic diorite-monzonite, and monzonite was generated by hybridization between mafic magma derived from enriched sub-continental lithospheric mantle and lower crust (Chen and others, 2008).

There is recent evidence that the mantle lithosphere below the center of the eastern part of the craton has been less modified by lithospheric changes than the margins. Whereas Mesozoic mafic volcanism is predominant in the northern and southern margins (fig. 5A), mafic magmatism in the interior produced gabbroic to dioritic intrusive complexes. Zhang (2007) attributed this variation to the fact that dehydration melting of surrounding subducted oceanic plates produced silicic melts that reacted with lithospheric peridotites to generate more fertile lithospheric mantle. However, these effects were less marked in the center of the Eastern Block of the craton farthest from the subducting margins.

The late Mesozoic Shatuo gabbro, emplaced just west of the N-S gravity lineament, contains zoned olivine xenocrysts, the cores of which have high Mg# (92-94), similar to those of olivine xenocrysts (92-95) from Paleozoic kimberlites in eastern China (Ying and others, 2010), and to those from high-Mg, highly refractory mantle peridotites entrained in Mesozoic and Cenozoic basalts (Zheng and others, 2001). These olivines are different from the less magnesian (Mg# <91) olivines in Mesozoic fertile mantle peridotites in the delaminated eastern part of the NCC. (Xu, 2001, and references therein). These contrasting features of the lithospheric mantle led Ying and others (2010) to conclude that large-scale lithospheric removal had not taken place just west of the gravity lineament.

<center>CENOZOIC MAGMATISM</center>

Cenozoic basaltic lavas and volcanoes are widespread around and in the eastern part of the NCC (fig. 1). Early Tertiary basalts are mainly tholeiites with minor alkali basalts with a depleted mantle signature, which suggested to Xu and others (2004a) that the lithosphere was <60 km thick, whereas Late Tertiary and Quaternary basalts are alkaline to peralkaline (fig. 3), suggesting that the lithosphere was relatively thick (>80 km). The trend of increasing alkalinity with time was attributed to declining degrees of partial melting and increasing depth of the source region, as upwelled asthenosphere converted to lithosphere, that is, there was lithosphere thickening.

The mineral compositions of xenoliths from basalts at Hannuoba (fig. 1) indicate that the Moho depth increased from 30 km in the pre-Cenozoic to 42 km today possibly as a result of basaltic underplating (Chen and others, 2001). From a comparative geochemical study of basalts at Hannuoba and nearby Datong near the western side of the gravity lineament (fig. 1), Xu and others (2005) proposed that the lithosphere thickness changed from ~100 km in the Miocene to ~70 km in the Quaternary. The NS-trending Shanxi Graben is situated just to the west of the Taihang Mountains and the gravity lineament (fig. 1). The reverse geochemical trend is observed in Cenozoic basalts in the graben, where alkaline basalts are succeeded by tholeiitic basalts; this change is interpreted to reflect progressive lithosphere thinning as a result of continuous upwelling of asthenosphere (Xu and others, 2004a).

The water contents of clinopyroxene, orthopyroxene and olivine in xenoliths from mantle peridotites and lower crustal granulites in Cenozoic volcano basalts at Hannouba (fig. 1) indicate that the distribution of water in the lowermost crust and the uppermost mantle beneath the North China Craton is laterally and vertically heterogeneous. This fact, together with the temperature and mineralogy, likely affected the rheological strength of the deep continental lithosphere, and calculated viscosity profiles confirm that the strength of the deep crust relative to the underlying mantle is stronger at Hannuoba and weaker at Nushan—fig. 1 (Yang and others, 2008).

Lithospheric thinning also took place in the eastern Central Asian Orogenic Belt north of the North China Craton. From a study of Cenozoic alkali basalts, Yan and Zhao (2008) showed that the lithospheric thickness in the off-craton setting has changed from ~120 km at Wudalianchi eastwards to ~75 km in the Jiangpohu area (fig. 1), which they ascribed to the influence of the subducting Pacific plate; mantle P-wave tomography supports this idea (Zhao, 2004). Okamura and others (2005) suggested that the Cenozoic magmatism in the delaminated zone culminated with extension and sea-floor spreading at 25 to 18 Ma that formed the Sea of Japan.

Also off the North China Craton and to the west of the gravity lineament is the Dariganga cinder cone field that straddles the Mongolian-Chinese border (fig. 1), and which is the largest area/volume (20,000 km^2) of Quaternary plateau lavas in central-east Asia (Barry and others, 2007). Chen, L., and others (2009) used teleseismic S-receiver functions to demonstrate that lithospheric thinning has taken place, at least locally farther south, to the west of the gravity gradient, and much farther west in the North China Craton than previously thought. Dariganga has not entered into the literature of the delamination/thinning under eastern China; could it be that a finger of sub-continental asthenopheric melt (Barry and others, 2007) rose up through a localized zone of lithospheric thinning west of the gravity lineament? This suggestion would be consistent with the tomographic image of Zhao (2004, fig. 16a), which shows that the cold, subduction-derived, stagnant slab in the mantle transition zone does not stop at the gravity lineament, but continues farther west as a much-thinned slab; this could have provided metasomatizing fluids that channelled a finger-like hole through the upper mantle (Wiechert and others, 1997).

SEDIMENTARY BASINS

Sedimentary basins, especially those with associated magmatic activity, provide key information on the structural history of the crust and lithosphere. The Yanshan-Yinshan and Hefei foreland basins are situated on the northern and southern margins of the eastern part of the craton, respectively (fig. 1). The amounts of coarse clastic sediment suggest that topography was higher on the southern than the northern margin of the craton. Dated volcanic rocks indicate that thinning began in the mid-Jurassic in the Yanshan basin and in the Early Cretaceous in the Hefei basin (Huang, F., and others, 2007), and culminated with widespread extensional events at 145 Ma and 132 Ma, respectively (Li and others, 2007).

The Yanshan-Yinshan foreland basin is over 1200 km long, is dominated by coarse red bed clastic sediments, and is associated with a major thrust belt. South-directed thrusts demonstrate compression from north to south, and with development of km-scale nappes (He and others, 1998). We correlate these thrusts and foreland basin with post-collisional tectonics following formation of the Himalayan-scale Solonker suture from the end-Permian to mid-Triassic (Xiao and others, 2003, 2009). The eastern Yanshan thrust belt contains a record of rapid uplift, erosion and foreland deposition coeval with thrusting events in the Late Triassic and Early Jurassic, which culminated in the mid-Jurassic (*ca.* 170 Ma) (fig. 3), by which time there was high topographic relief that led at the end of the mid-Jurassic to extensional gravity-induced collapse and landslides with blocks over 4 km long (Hu and others, 2010); another block also ascribed to gravitational collapse is 5 km wide (Cope and Graham, 2007). Confirmation of previous high topography in the Yanshan region comes from the presence of high Sr and low Y in Upper Jurassic volcanic rocks (Li and others, 2001) suggesting that the crust was previously thickened (Hu and others, 2010).

The Hefei foreland basin, located within a major fold-and-thrust belt, contains up to 7000 m of Mesozoic fluvial-lacustrine sedimentary rocks, the sedimentary thickness being greatest near the Dabie Shan orogen from where the sediments were derived (Okay and Sengör, 1992; Liu, S. and others, 2003). The many EW-trending, N-verging,

Triassic thrusts in the basin are constrained by a seismic section, which demonstrates an increase in intensity of thrusts towards the south indicating control by uplift of the Dabie mountains. Negative inversion in the Early Cretaceous (fig. 3) led to higher intensity of extensional faults in the north, but higher intensity in the south thereafter (Xu and others, 2007). In the Hefei basin there was a 25 Ma hiatus in magmatism from ~110 Ma to ~85 Ma (fig. 3); the occurrence of 85 to 65 Ma flood basalts, whose trace element chemistry indicates an asthenospheric derivation, demonstrates that lithospheric thinning reached a minimum of 65 km in the Late Cretaceous (Zhang, 2007). Lithospheric thickening began in the earliest Cenozoic and today the thickness is ~110 km (Yuan, 1996a).

Because lithospheric thinning also took place to the south of the Dabie Shan orogen in the northern part of the South China Craton (Li and others, 2009) it is important to consider the Middle Yangtze foreland basin (fig. 6) (Liu, S., and others, 2005), situated within a major fold-and-thrust belt (Dong and others, 2004), which received sediments from the core of the Dabie Shan orogen from Late Triassic through Middle Jurassic time, and again in the Cretaceous to Early Tertiary—fig. 3 (Liu, S., and others, 2003). Beginning in latest Jurassic time, and continuing through the Early Tertiary, rift basins developed, first locally on the northern side of the Dabie Shan orogen, and then increasingly across the whole belt from the Hehei to Middle Yangtze basins, and their lithic compositions show that by Late Cretaceous time deep crustal levels were exposed at the surface across the entire core of the Dabie Shan orogen (Liu, S., and others, 2003).

The off-craton, Late Jurassic Songliao Basin (fig. 6) is situated symmetrically over a major zone of very thin lithosphere (<60 km) that extends southwards to the Bohai Basin and the Eastern Block of the North China Craton (fig. 7B) (Yuan, 1996a; Zhang and others, 2000). The Songliao Basin has a very high heat flow (>105 mW/m^2)—fig. 8, is associated with Late Jurassic–Early Cretaceous basalt-andesite magmatism, and has over 590 Cenozoic volcanoes largely of alkali basalt; Liu, J. Q., and others (2001) pointed out that the volcanic development of the basin from 86 Ma to the Present has been intimately associated with the evolution of the Japan Sea, implying a genetic link between the water subduction and hydro-weakening associated with the formation of the West Pacific marginal basins and the processes responsible for the sub-continental lithospheric thinning beneath eastern China.

The Bohai Basin (Allen and others, 1997) occupies a critical position, being situated upon Precambrian rocks near the eastern margin of the North China Craton where the crustal thickness is only 28 km (fig. 7A), and the lithosphere thickness is only 50 km (fig. 7B), which is the thinnest in the whole of eastern China (Lysak and Dorofeeva, 2005; Li and others, 2006). Although regarded as an Early Tertiary basin, crustal extension commenced in the Late Jurassic, persisted into the Early Cretaceous, declined and resumed in the Palaeocene, when up to 6 km of continental and lacustrine clastic sediments accumulated in the Paleocene (Ren and others, 2002); the total Cenozoic fill is 10 to 12 km (Lysak and Dorofeeva, 2005). In the Paleocene to Oligocene, tholeiitic to transitional basalts were erupted throughout the basin. The average heat flow in the Bohai Basin is >1.6 HFU, and it reaches the highest values of 1.77 to 2.53 HFU in the Bohai Gulf and coastal areas (fig. 8), and the geothermal gradient is 1.41 to 1.21 W/m · K (Lysak and Dorofeeva, 2005). The association of active rifting, thin crust and lithosphere, high rates of volcanism, high heat flow and geothermal gradient points to extensive upwelling of the asthenosphere (Ren and others, 2002). Further support of these ideas comes from 3D P-wave tomographic models by Huang and Zhao (2009), which indicate that a high-velocity anomaly under the Bohai Basin extends from 150 km depth down to 200 to 300 km, suggestive of large-scale lithospheric thinning and detachment. These authors proposed that dehy-
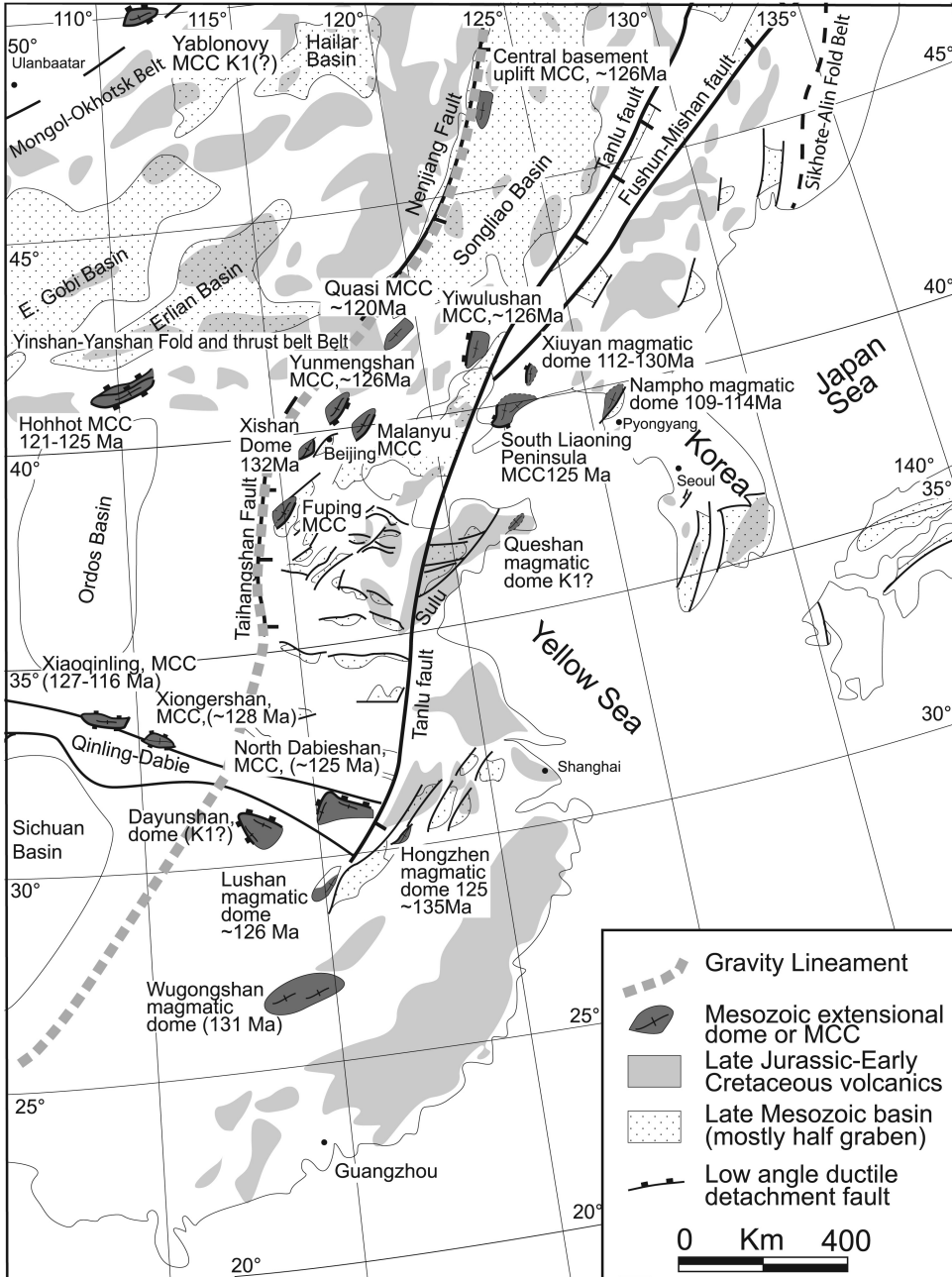
Fig. 6. Map showing the distribution of Mesozoic sedimentary basins, metamorphic core complexes (MCC) and magmatic domes within and surrounding the Eastern Block of the North China Craton. The times of formation of the metamorphic complexes and domes are indicated; modified from Lin, W., and others (2008) and Yan and others (2006). Late Jurassic–Early Cretaceous volcanic rocks occur within and surrounding the Eastern Block of the North China Craton.
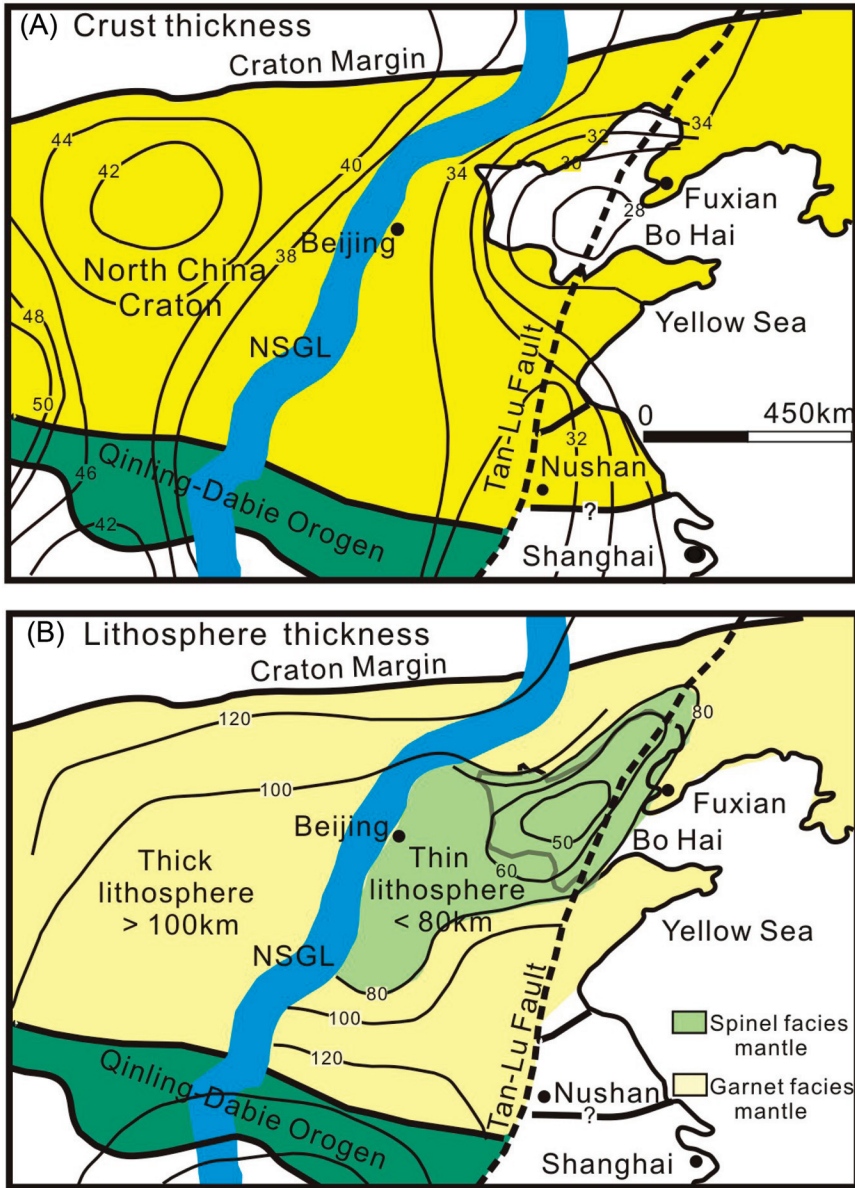
Fig. 7. Maps showing (A) crustal and (B) lithospheric thicknesses under the Eastern Block of the North China Craton and to the east. The crustal thicknesses are based on geophysical data of Ma (1987) and Liang and others (2004), and inferred mantle facies are from Menzies and others (2007). The area of thinnest crust is centred on the area of thinnest lithosphere, which in turn is coincident with the spinel mantle facies, which is consistent with the dominance of spinel peridotite xenoliths in erupted Cenozoic basalts. Note the change in lithosphere thickness across the gravity lineament. NSGL: N-S Gravity Lineament.

dration of the Pacific slab that is stagnating in the mantle transition zone has caused convective circulation and upwelling of hot asthenosphere above it, leading to thinning and detachment of the lithosphere below the eastern part of the North China Craton.
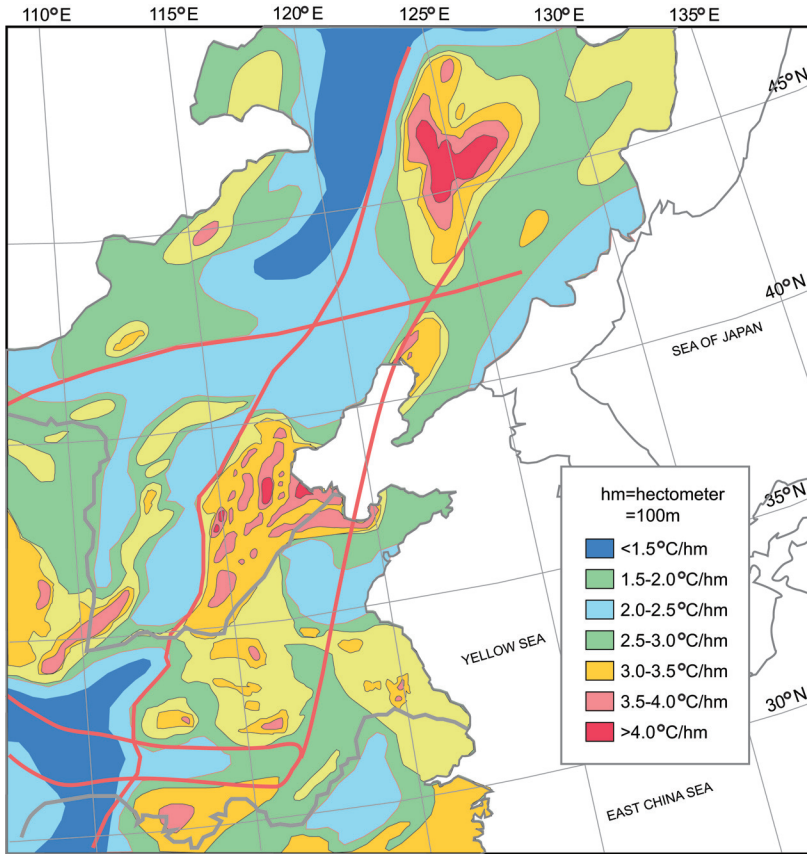
Fig. 8. Map showing the temperature at a depth of 2 km beneath eastern China from Yuan (1996). Note that the highest temperatures are east of the gravity lineament and focussed on the Eastern Block of the North China Craton and on the Songliao Basin to the north (see fig. 6), and the former is coincident with the area of thinnest lithosphere (fig. 4B).

Immediately south of the Bohai Basin is the Huabei Basin beneath which the lithosphere is only 60 to 100 km thick compared with at least 150 km farther east (Xu and Zhao, D. P., 2009).

Studies of the sedimentary basins, including the Yanshan and Hefei foreland basins, filled with clastics derived by erosion, and of early Mesozoic granitic and volcanic rocks, suggest that an intracontinental plateau (or we might say mountainous region) was created in eastern China during the Mesozoic (Yin and Nie, 1996; Zhang, Q., and others, 2001; Darby and Ritts, 2002; Meng, and others, 2003; Hu, and others, 2010). Extensional tectonics associated with collapse of the eastern China mountains or plateau began at the end of the mid-Jurassic—fig. 3 (Hu, and others, 2010) and continued in the Early Cretaceous, the high relief being removed by a combination of erosion and of crustal stretching and formation of metamorphic core complexes at 135–109 Ma.

Cope and Graham (2007) pointed out that most extensional basins throughout NE China and southern Mongolia lack post-rift thermal subsidence, and are generally bounded by low-angle ductile and brittle faults that root at mid-crustal levels. They, and Meng (2003), suggested that mid-lower crustal flow, indicated by the widespread coeval metamorphic core complexes, suppressed the post-rift thermal subsidence.

GOLD MINERALIZATION

A major result of the lithospheric thinning was the formation of many gold deposits, which provide us with useful information on fluids introduced into the upper crust.

Hundreds of lode-gold deposits, which are mostly Early Cretaceous (130-110 Ma) in age (fig. 3), occur around the margins of the Eastern Block of the craton (fig. 5B) where they are commonly hosted by or proximal to Late Jurassic–Early Cretaceous volcanic and granitic rocks (Zhai and others, 2002). Isotopic and geochemical constraints suggests that some ore fluids were generated by partial melting of the lower crust, and others from dehydrated mafic magmas derived from an enriched mantle source, and all during the main lithospheric thinning event (Yang and others, 2003).

METAMORPHIC CORE COMPLEXES

The post-collision period of compressional tectonics in the Jurassic was followed by a period of widespread extension throughout the delaminated zone in the Early Cretaceous, a major expression of which in the upper crust was the formation of at least 17 metamorphic core complexes (MCC) (fig. 6). It is important to note that these MCC should be distinguished from (a) the MCC that occur along/near the Chinese-Mongolian border to the west (Zheng and Wang, 2005) that formed as a result of extensional collapse of thrust-thickened crust on/near the Solonker suture (for example, the Hohhot complex, Davis and others, 2002), and (b) the MCC that formed as a result of collapse of over-thickened crust associated with the Mongol-Okhotsk suture (Tomurtogoo and others, 2005). In other words, there are at least three belts of MCC of different type in eastern Asia.

Prominent amongst the delamination-related core complexes are the Liaonan (Liu, J. L., and others, 2005) or South Liaodong Peninsula (Lin and others, 2008) complex, and the Yiwulushan (or Waziya) complex (fig. 6) (Darby and others, 2004), both of which formed at 125 ± 5 Ma. Note also that the eastern Dabie Shan orogen exhumed as a MCC at ~125 Ma (Yuan and others, 2003). The Wugongshan magmatic dome (131 Ma) or MCC is situated in the South China Craton (fig. 1), which on this evidence probably underwent thinning of the lithosphere in the Early Cretaceous. The age of formation of all the core complexes was in the period 135 to 109 Ma (figs. 3 and 6), which dates the maximum time of crustal extension (fig. 7A), which is within the overall time-range of the lithospheric thinning (fig. 7B) (140-110 Ma, see below), and which provides the best approximation for the time of the original subcontinental mantle root loss beneath the Eastern Block of the North China Craton—fig. 3 (Kusky and others 2007). In general, the MCC indicate mid- to lower crustal mobility during extension, supporting the idea that gravitational collapse above over thickened and thermally hydro-weakened crust was an important driver for the mid-Cretaceous extension (Cope and Graham, 2007).

TIMING OF THE LITHOSPHERIC THINNING

It is useful to summarize here the timing of some of the key events concerned with the thinning of sub-continental lithosphere in eastern China (fig. 3). The peak of lithospheric thinning (fig. 7B) is generally, and variably, considered to be at ~131 ± 2 to 117 ± 7 Ma (Wu and others, 2005), at ~140 to 120 Ma (Kusky and others, 2007) or at ~130 to 110 Ma (Zhai and others, 2003; Zhang, 2007); these peaks were based on the ages of intrusive and extrusive magmatism and of xenoliths in kimberlites and basaltic lavas (fig. 3) in the Eastern Block of the craton, and on the time of inversion in sedimentary basins. Gold mineralization that is pronounced around the eastern part of the craton (fig. 5B) has a peak age of 130 to 110 Ma—fig. 3 (Zhai and others, 2002; Yang and others, 2003), and the formation of metamorphic core complexes (fig. 6) ranged from 135 Ma to 109 Ma (fig. 3). The eruption of alkali basalts in plateau lavas

and volcanoes (fig. 1) reached a peak at 65 to 45 Ma, representing the time of generation from the asthenosphere. The main zones of crustal and lithospheric thinning are coincident with the zone of highest heat flow (fig. 8).

It is also important to consider the times of formation of sutures on the northern and southern sides of the eastern delaminated block of the NCC. First, a note of caution; it is impossible or difficult to define with any degree of precision the time of formation of Cenozoic sutures, as in the Himalayas (destructive collisional events that are invariably superimposed by post-collision deformation), and this applies to earlier sutures. The Mongol-Okhotsk suture formed in/by the mid-Jurassic in eastern Mongolia (Tomurtogoo and others, 2005). The time of formation of the Solonker suture on the northern side of the North China Craton was near the Permo-Triassic boundary (Xiao and others, 2003), or even as late as 234 Ma—mid-Triassic (fig. 3) (Chen and others, 2009; Xiao and others, 2009). The time of collision between the North and South China cratons must have been shortly after the main deep subduction metamorphic event at 244 to 236 Ma (Hacker and others, 2006), and before the 212 ± 4 Ma time of retrograde granulite facies metamorphism that took place during exhumation on the Dabie Shan subduction zone—fig. 3 (Liu, S., and others, 2005); however on paleogeographic evidence Metcalfe (2002) put the collision time near the end-Permian (fig. 3). The continental collision between the South China and Indochina cratons, giving rise to the Song Ma suture, was in the Early Triassic—fig. 3 (Lepvrier and others, 2004; Lin and others, 2007).

Perhaps surprisingly, evidence is accruing of possible delamination in the Late Triassic, as indicated, for example, in the NE Bohai area (figs. 1 and 5A) where 213 Ma dolerite dikes are succeeded by high-Mg andesite dikes and shoshonitic dikes (Yang, J. H., and others, 2007b). This is explained by subduction of UHP rocks of Dabie-Sulu at 245 Ma, breakoff of eclogitized oceanic lithosphere, exhumation at 244 to 226 Ma, and finally instability of the thickened lithosphere and dike intrusion at 213 Ma.

TOMOGRAPHIC CONSTRAINTS

Why was the lithosphere under the Eastern Block of the North China Craton both thinned and multi-hydrated in contrast to the Western Block? The seismic tomographic images of Zhao (2004) and Huang and Zhao (2006) clearly show that the slow subduction velocity Pacific oceanic plate descends from the Izu-Bonin trench below Japan to the 410 to 600 km-deep transition zone, within which it slides westwards as a stagnant slab (fig. 9) until it reaches the boundary between the Eastern and Western Blocks of the North China Craton below the Datong volcano (fig. 1), situated just west of the gravity lineament where the slab thins and continues westwards as a very thin slab (fig. 9). This P-wave tomography supports the idea that the formation of the active Wudalianchi (see earlier under Cenozoic Magmatism) and Changbai volcanoes in eastern China (fig. 1) was closely related to the Pacific plate subduction process (Zhao and others, 2009). Comparable images of the Pacific plate ponding within the transition zone were shown by Fukao and others (2001) and Kárason and van der Hilst (2000). However, the tomographic results of Xu and Zhao (2009) suggest that the lithospheric delamination occurred in localized areas rather than through the entire eastern North China Craton.

Shear wave splitting data by Zhao and Zheng (2005) indicate that mantle flow, identified by fast polarization directions and oriented olivine crystals, is northwestward below the Eastern Block of the North China Craton until it reaches the boundary of the Western Block near the gravity lineament focussed on the central Trans-North China Orogen. Their data and conclusions suggest that the NW-directed mantle flow below the 60 to 100-km thick lithosphere of the Eastern Block was deflected downwards when it reached the 150 to 200 km-thick lithosphere of the Western Block and that the present mantle flow reflects the northwestward flow created during the Late Mesozoic–
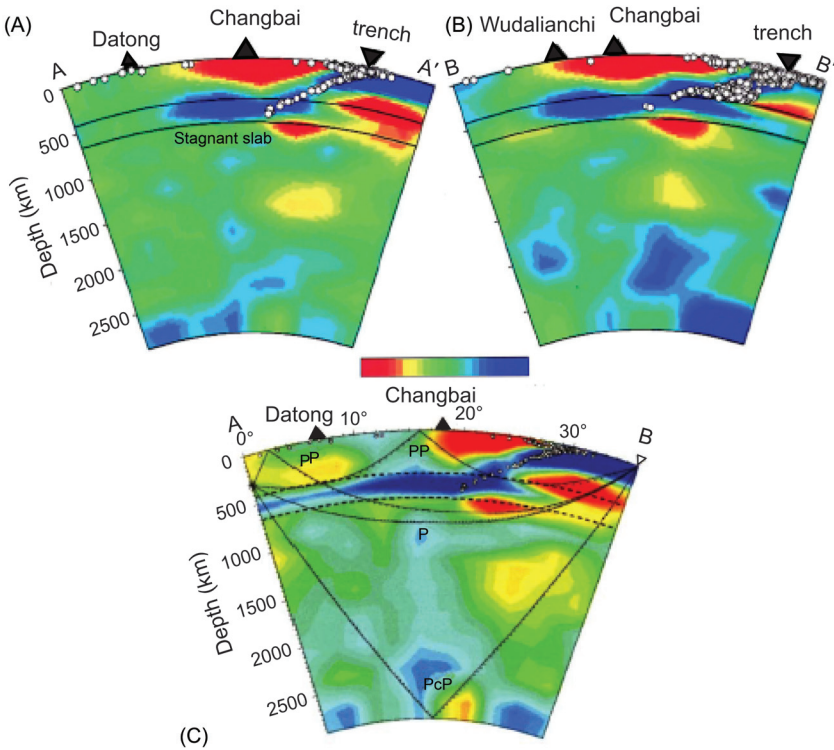
Fig. 9. Vertical cross-sections of whole-mantle P-wave tomography from the Japanese trench to the Changbai volcano (fig. 1), and farther west through the eastern part of the North China Craton to Datong and Wudlianchi located just to the east and west of the gravity lineament, respectively (fig. 1). Red and blue colors denote slow and fast velocities, respectively. (A) and (B) from Zhao and others (2009) show that the Pacific plate has ponded as a stagnant slab along the mantle transition zone. (C) from Zhao (2004) shows that the stagnant slab does not stop at the gravity lineament below Datong, but continues farther west as a thinned slab.

Early Cenozoic extension of the Eastern Block. The flow of the asthenosphere above the Pacific subduction zone from 86 Ma to the Present was outlined by Liu, J. Q., and others (2001). We conclude that the tomographic and shear wave data, combined with other geophysical and geochemical evidence summarized above, suggest that the subducted Pacific plate played an important, but not the only, role in creating the tectonic framework of the Eastern Block, focussing water into the mantle below it, providing the trigger for partial melting of "hydrated" lithospheric mantle and assisting the rise of new, replacing, fertile asthenosphere into this thinned zone (Zhang, 2007). But other plates were also subducted around the North China Craton, and the Pacific plate did not provide the tectonic trigger for their associated lithospheric thinning (see later). Note that Van der Voo and others (1999) proposed that a slab of high seismic velocity was subducted northwards from what is now the Mongol-Okhotsk suture to a depth of at least 2500 km, this being a relict of the Mongol-Okhotsk oceanic plate.

Salah and Zhao (2003) proposed that fluids released by dehydration of the water-rich Philippine Sea plate (see earlier) under SW Japan caused weakening of the seismogenic layer in the upper and middle crust. From P-wave tomographic data Huang and Zhao (2004) demonstrated that under the earthquake-prone Yanshan mountains in the northern part of the delaminated Eastern Block of the North China

Craton (fig. 1) the lower crust to uppermost mantle shows low-velocity and high-conductivity anomalies, which they speculated to be associated with fluids released from the Pacific slab stagnating in the underlying mantle transition zone, and it was these fluids that caused weakening of the seismogenic layer.

HYDRATION OF THE SUB-OCEANIC LITHOSPHERIC MANTLE AND FORMATION OF MARGINAL
BASINS OF THE WESTERN PACIFIC

Before we interpret data on the sub-continental lithosphere under eastern China, it is useful to consider some current ideas on the tectonic development of the sub-oceanic lithosphere under the adjacent western and southwestern Pacific, where 90 percent of the world's small ocean basins, and 75 percent of the marginal basins, are concentrated. Komiya and Maruyama (2007) pointed out that the source mantle for oceanic basalts in the Philippine Sea plate (fig. 10) is enriched in water (0.2 wt. %) and in consequence is 50 to 60 °C cooler than that of the Pacific MORB. Furthermore, they suggested that the extensive melting necessary to generate the oceanic crust of the marginal basins is due to the high water content of their source mantle, and that the well-known greater depth of some marginal basins at a given age (Tamaki and Honza, 1991) like the Philippine Sea (3222 km) compared with that of MORB of the Pacific (2500 km) is due to the fact that they are underlain by cooler, more hydrous mantle, and that the bulk density of the mantle increases with decreasing temperature (Fei, 1995). Moreover, the western Pacific is underlain by relatively low temperature mantle, *ca.* 100 to 150K, compared with the mantle under mid-oceanic ridges, and this correlates with the fact that it is about 10 times more water-rich than MORB-source mantle (Yamamoto and others, 2009b).

It is well known that oceanic crust is extensively hydrated by hydrothermal alteration at a mid-oceanic ridge; the top ~5 km of oceanic lithosphere is hydrated by hydrothermal circulation (Karato, 2003). Although subduction of a young, hot slab, as in the Nankai subduction zone, supplies considerable quantities of water to the overlying mantle wedge (Peacock, 2003), the subduction of old, cold oceanic lithosphere, as in most of the western Pacific, transports much water to the mantle, which reaches the mantle transition zone at 410 to 660 km depth (Komiya and Maruyama, 2007; Omori and Komabayashi, 2007). Maruyama and Okamoto (2007) calculated that the water is transported into the transition zone if the age of the plate is older than ~50 Ma, and therefore that water is transported into the deep mantle in three-quarters of the total length of 37,000 km of subduction zones on Earth. The western Pacific has been a western-directed convergent margin since 450 Ma (Isozaki, 1996), and in the last 150 Ma ~18,000 km of oceanic plates have been subducted; today it has the highest amount of subducting plate boundaries with an estimated total length of 30,000 km (Engebretson and others, 1992). Therefore, the mantle transition zone under the western Pacific Ocean, and adjacent eastern mainland of China, should be highly enriched in water.

Double Subduction

Maruyama and others (2004, 2009) and Komiya and Maruyama (2007) pointed out that, at the same time as the old Pacific plate was being subducted westwards under the western and southwestern Pacific margin, there was also subduction northeastwards from the Indo-Australian plate (fig. 10). The history of the Indo-Australian plate shows that northwards to northeastwards (present coordinates) subduction has been taking place since the break-up of Gondwanaland. The Lhasa block broke off at 250 Ma and India at ~200 Ma (Le Fort, 1996), and they drifted northwards to accrete to the margin of Eurasia. Although India collided with the amalgamated Tibetan block at ~50 Ma, farther to the southeast the Indo-Australian plate is still subducting under Indonesia. Northeastwards subduction on this Sumatra section of the plate boundary
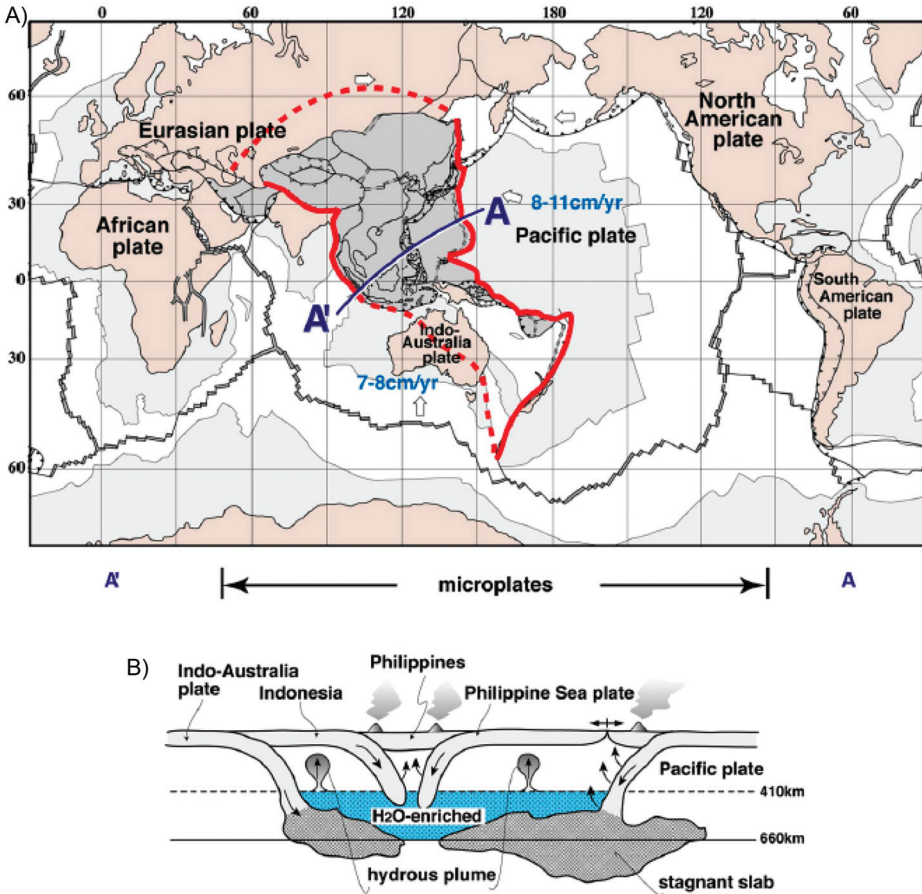
Fig. 10. Sketch map (A) showing the western Pacific triangular zone (outlined in red) defined by double-sided subduction zones between which the western Pacific and eastern Asia are characterised by many micro-plates, active magmatism and seismicity. This triangular zone is most enriched with water in the underlying mantle derived from the subducted Pacific and Indo-Australian plates. (B) shows a schematic cross-section, marked in (a), across the Philippine Sea and associated microplates beneath which the mantle transition zone has been enriched in water derived from the underlying stagnant slabs of the Indo-Australian and Pacific plates. After Maruyama and others (2009).

probably started in the Late Permian when the Sibamasu terrane of Sumatra rifted off the NW margin of Australia (Metcalfe, 2002); accordingly, there has been at least 250 Ma of northeastward subduction under Indonesia. Seismic data indicate that the Seram Trough slab in the Banda Sea region extends to 400 to 500 km depth (Milsom, 2001), thus capable of transporting water into the mantle transition zone. North and northeast of Australia tomographic images of mantle structure show several flat-lying fast anomalies within the transition zone that are not related to present subduction, but are interpreted as former subduction zones overridden by Australia since 25 Ma (Hall and Spakman, 2002). The implication of this interpretation is that a flat-lying slab can survive for many tens of millions of years in the transition zone, until it becomes unstable due to conductive heating from the underlying lower mantle, a process that would release water and create hydrous plumes. These old subducted oceanic plates are capable of transporting considerable quantities of water from

hydrated MORB crust and from hydrated upper mantle. The dual subduction of the Pacific and Indo-Australian plates has created a double-sided, triangular, or Y-shaped zone (fig. 10), implying that double the amount of water has been transported into the mantle for a total of at least 700 million years, the combined length of time of subduction from the Pacific and Indo-Australian plates (Komiya and Maruyama, 2007), and, as figure 10 shows, this double subduction affected not only the western Pacific oceanic regions, but also the continental regions of eastern Asia, especially eastern China.

<div align="center">WATER IN THE TRANSITION ZONE</div>

The water in oceanic basalts is transported by subduction into the mantle transition zone between 410 km and 660 km, that is, between the upper and lower mantle (Ohtani and others, 2004), and it is stored in nominally anhydrous minerals in hydrogen-related point defects, if the geotherm is cold enough (Bolfan-Casanova and others, 2000; Hirschmann and others, 2005; Maruyama and Okamoto, 2007). The solubility of water in nominally anhydrous mantle minerals is so high that separate hydrous phases such as amphibole and phlogopite are not stable in an upper mantle of pyrolite composition (Mierdel and others, 2007). Olivine, generally considered to be the most abundant mineral in the upper 400 km of the mantle, can store up to 2000 ppm by weight of H_2O at 13 GPa and 1100°C (Smyth and others, 2003), and pure enstatite has a similar storage capacity for water as olivine (Rauch and Keppler, 2002). Clinopyroxene can accommodate up to 3000 ppm hydroxyl (Katayama and Na-kashima, 2003), and majorite can contain up to ~700 ppm H_2O (Katayama and others, 2003). In eclogites from Kokchetav, omphacites contain up to 870 ppm H_2O (by weight) and garnets up to 130 ppm H_2O, and the water content in these phases increases systematically with increasing pressure; eclogitic rutile contains up to 740 ppm H_2O (Katayama and others, 2006). Wadsleyite (β-Mg_2SiO_4; stable below 350 km) and ringwoodite (γ-dimorph of forsterite), principal components of the mantle transition zone, can contain up to 2.7 to 3.3 weight percent and 2.2 to 2.4 weight percent H_2O respectively (Smyth and others, 2003; Richard and others, 2006). If saturated, a transition zone containing 70 modal percent wadsleyite could contain 4 times the amount of water in the Earth's hydrosphere, and would form the largest reservoir of hydrogen in the planet (Smyth and Frost, 2002). Moreover, nominally anhydrous minerals in lower crustal granulite xenoliths in Cenozoic basalts in eastern China contain high water contents up to 2360 ppm weight percent in clinopyroxene and 1170 ppm in orthopyroxene (Xia and others, 2006), and appreciable quantities of water may even reach the lower mantle: stishovite can contain about 800 ppm H_2O (Chung and Kagi, 2002; Panero and others, 2003).

Besides oceanic crust, subducted continental crust may also transport consider-able quantities of water into the deep mantle (Wu and others, 2009). This is important for us, because we know that continental crust at Dabie Shan and Sulu has been subducted and exhumed from UHP depths (Wang and others, 2008). The experimen-tal studies of Wu and others (2009) demonstrate that phengite and lawsonite can carry c. 0.5 weight percent water at pressures up to 9 GPa (*ca.* 200 km depth), and beyond 9 GPa pressures clinopyroxene, stishovite and K-hollandite are the major water carriers. Clinopyroxene with a $Di_{60}Jd_{40}$ composition could contain *ca.* 1200 ppm water up to 10 to 14 GPa (410 km), and a jadeite-stishovite-K-hollandite lithology could carry 0.5 weight percent H_2O into the transition zone.

The 410-km seismic discontinuity at the top of the transition zone represents the phase transformation of olivine to β spinel, which can store up to 3.1 weight percent H_2O at 15.5 GPa (Inoue and others, 1995). Thus, it is generally considered that water in a subducting slab would react with olivine to form hydrous modified β spinel that would transport considerable amounts of water into the transition zone. Meier and

others (2009) calculated that the 410-km discontinuity has an average width of 17 to 31 km, implying a significant water content, because the stability field of the phase transition associated with this discontinuity broadens with increasing water content (Hirschmann and others, 2006).

Hae and others (2006) were able to estimate the water content in the mantle transition zone by combining data on the hydrogen diffusion coefficient in wadsleyite, the major constituent mineral in the transition zone, and the observed electrical conductivity in the transition zone. Electro-magnetic tomography shows that the mantle in the transition zone at 400 to 550 km depth below the Philippine Sea has a high conductivity anomaly that is most likely associated with, or can be best explained by, water released from a stagnant slab, because hydrogen can enhance electrical conductivity and wadsleyite can accommodate up to 33,000 weight ppm. Accordingly, the concentration of hydrogen in the transition zone beneath the Philippine Sea (fig. 10) is around 300 to 4000 weight ppm H_2O, which makes the transition zone under the western Pacific a major water reservoir, and the presence of significant amounts of water in the deep part of the mantle wedge beneath the Philippine Sea was confirmed by anomalies in seismic attenuation and velocity (Shito and Shibutani, 2003).

Ichiki and others (2006) estimated the water content and geotherm of the upper mantle under NE China from electrical conductivity and seismic P-wave velocity (V_p) data. The results suggest that the mantle above the transition zone under eastern Asia is water-bearing, which is consistent with the tomographic data of Zhao and others (2009) that show a prominent low-velocity anomaly down to 410 km depth beneath the Changbai volcano (figs. 1 and 9). As pointed out by Shieh and others (1998), Ohtani and others (2004) and Komabayashi and others (2004), the dehydration reactions of the hydrated, ponded or stagnant Pacific slab probably contributed the water to the overlying wet upper mantle (Leahy and Bercovici, 2010). Zhao and others (2009) concluded that the upper mantle under eastern Asia has formed a wide, wet and hot mantle wedge (above the stagnant slab) that exhibits a low seismic velocity and high electrical conductivity.

Stored water in "hydrous" phases at 410 to 660 km depth would become unstable with time due to conductive heating from the underlying mantle, and would eventually decompose into anhydrous phases to release free water at the 410 km boundary, which would create hydrous plumes that would instigate plate fragmentation (Karato, 2003). Alternatively/in addition, according to Maruyama and others (2009) the extensive subduction of TTG arc crust, as is ongoing today under Japan (Yamamoto and others, 2009a), would lead to emplacement of a thick TTG layer in the mantle transition zone at 660 km depth, where it would stagnate due to gravitational instability. With time such a TTG layer would generate heat by the decay of radiogenic elements such as U, K and Th, which in turn would generate hydrous plumes from the 410 km boundary. Maruyama and Okomoto (2007) proposed that this was the principal dynamic process in formation of the marginal basins of the Western Pacific (fig. 10).

Although a large proportion of subducted water is expelled by dehydration at depths of 70 to 100 km and is transported back to the hydrosphere through arc volcanism, about 40 percent of the initial water content from sediments, crust and serpentinized mantle continues to be subducted to be stored in the mantle transition zone (Tonegawa and others, 2008), which may be further hydrated by water released from flat-lying slabs stalled and stagnating in the transition zone (Richard and others, 2006). Variations in seismic velocity confirm that hydrous minerals are stable along the top surface of the subducting Pacific slab below Japan and that these minerals could carry water down to the 410 km discontinuity in a relatively cold subduction zone (Tonegawa and others, 2008). Experimental data by Komabaysahi and others (2005) suggest that the seismologically observed low-velocity zone on top of the 410-km

boundary immediately above the transition zone may represent a partially melted hydrous plume crossing the dehydration reaction of hydrous wadsleyite (Song and others, 2004). Such hydrous plumes rose up and contributed the formation of the marginal basins in the western and southwestern Pacific (fig. 10).

The Effects of Deep Mantle Water

The main effects of water on the mantle are changes in viscosity, degree of partial melting, magma genesis and hydro-weakening, because the solidus temperature and viscosity of the mantle are lowered with addition of water. Melting experiments of hydrous peridotite show that the addition to the mantle of 0.2 weight percent or 0.5 weight percent of water decreases the solidus temperature by 150 °C or 200 °C, respectively, compared with dry mantle (Hirose, 1997); this promotes partial melting and magma generation. Under such hydrous conditions in the clinopyroxene-plagioclase-olivine system, the crystallization of clinopyroxene precedes that of plagioclase (Gaetani and others, 1993), commonly observed as augite phenocrysts in basalts of marginal basins of the Western Pacific (Komiya and Maruyama, 2007).

The addition of only 100 to 1000 ppm of water decreases mantle viscosity about two orders of magnitude (Karato and Jung, 1998). Under water-saturated conditions, viscosity of the mantle decreases with increasing pressure, because water fugacities increase strongly with pressure, water solubility in olivine increases with increasing water fugacity, and viscosities decrease with increasing water concentration (Dixon and others, 2004). Accordingly, a more hydrated, low viscosity mantle becomes hydro-weakened, more mobile and capable of flow, facilitating partial melting, mantle convection, plume ascent, fragmentation of continental crust/lithosphere, and formation of marginal basins, as in the western Pacific (Komiya and Maruyama, 2007). If the water concentration in the transition zone exceeds the storage capacity of upper mantle olivine, the water filter model of Bercovici and Karato (2003) predicts that a 2 to 20 km-thick layer of melt should lie on top of the 400-km discontinuity, and this would facilitate upward fluid/melt transport and plume migration (Meier and others, 2009). Song and others (2004) suggested that seismic data confirm the presence of such a low-velocity layer on top of the 410-km discontinuity that may be attributed to such a melt layer. According to the model of Bercovici and Karato (2003), ascending ambient mantle rises up from the above melt layer as well as from the high-water-solubility transition zone into the overlying lower solubility upper mantle, where it undergoes dehydration-induced partial melting, the depleted phases of which continue to rise in plumes to become the source material for hydrated ridge basalts in such marginal basins.

ECLOGITES AND THE TECTOSPHERE

Eclogites may be related to the thinning/delamination process under eastern China in two ways:

1. Dewey and others (1993) proposed that eclogites may form in the deeper parts of thrust-thickened and/or magmatically thickened orogens where the Moho-depth may reach 120 km. This idea has been commonly applied to the delamination problem under eastern China by calculating or assuming that a deep crustal root became eclogitized, thus assisting break-off and sinking into the mantle (Gao and others, 2004). Adakitic intrusions near the center of the delamination zone have brought up xenoliths of eclogite (Xu and others, 2006a). Gao and others (2004) and Xu, W. L., and others (2008) suggested that the adakites were derived by partial melting of eclogitized thickened Archean lower crust that sank into the mantle.

2. Eclogitization of northward-subducted basaltic crust in front of the South

China Craton led to exhumation in Dabie Shan of coesite-bearing eclogites from depths of at least 100 km (Wang and others, 2000; Xu and others, 2006b). However, the inter-relationships between the two types of eclogite and eclogitization are still unknown with respect to the delamination/thinning problem.

Importantly, in spite of nearly two decades of research on lithosphere delamination under eastern China, there is still little understanding of the nature/structure of the mantle transition zone and the overlying mantle, and of the structure of the tectosphere-subcontinental lithospheric mantle (Jordan, 1975), which preceded the delamination/thinning process. Such knowledge would be useful, because it would help to constrain the processes involved in the lithosphere removal process.

Crustal roots or tectosphere (Jordan, 1975) are the depleted residues from partial melting and thus are normally expected to be buoyant and dehydrated, and they are mostly Archean in age. Fast seismic velocities indicate that the average depth of cratonic roots is 200 to 300 km, and some may extend to 400 km (O'Reilly and others, 2009). It is widely accepted that an Archean lithospheric root is refractory and buoyant (for example, Jordan, 1975; Poudjom Djomani and others, 2001; O'Reilly and others, 2001).

Kay and Kay (1993) pointed out that in orogens where the crust has been thickened to more than 50 km, basaltic rocks in the lower crust would be metamorphosed to eclogite. Deng and others (2007) proposed that the emplacement (by a plume or plumes—Deng and others, 2004) of volumetrically significant basalts in the lower crust (underplating) is required to explain the large-scale crustal melting in the Mesozoic (mid-Late Jurassic and Early Cretaceous) in eastern China, and Chen and others (2007) that the Mesozoic crustal-melt magmas were generated by upwelling of the asthenosphere in a back-arc regime related to the subduction of the Paleo-Pacific slab. However, we consider that there is little evidence of such plumes, basaltic underplating, or back-arc upwelling, and suggest that early crustal thickening caused by post-collisional thrusting and contraction in Late Triassic and Early Jurassic time (Wang, Y. H., and others, 2005), as outlined below, would be sufficient to account for deep crustal melting in the mid-Late Jurassic and Early Cretaceous.

Eclogitization is a fluid-induced process (Austrheim, 1991). We can expect that the multiple subduction of hydrous slabs in the Paleozoic beneath the Eastern part of the North China Craton (before it was thinned or delaminated) would have hydrated and eclogitized the Archean crustal root, creating garnet-bearing assemblages (eclogite and garnet pyroxenite) with densities of up to 3.8 g cm^{-3} (Huang and others, 2007). In addition, although water enhances the formation of eclogite, at the same time it has a disproportionately large weakening influence on its mechanical and physicochemical properties.

Subducted water enters into the structure of eclogitic pyroxenes and garnets (see earlier). In ultrahigh-pressure eclogites, omphacite is the most important hydrous phase −100 to 200 μg/g (Zhang, J. F., and others, 2001a, 2005), and H_2O in pyrope occurs as clusters of water molecules and as hydroxyl, the former promoting elongation of the garnet through hydrolytic weakening (Su and others, 2002). Majoritic garnet can contain 1130 to 1250 ppm OH by weight at 20 GPa and 1400 to 1500 °C (Katayama and others, 2003). Clinopyroxene can contain up to 3000 ppm hydroxyl; because clinopyroxene represents 40 to 50 volume percent of eclogites, bulk eclogites can contain ca. 1300 ppm hydroxyl at depths greater than 150 km; this water will enhance the mechanical weakening of stagnant slabs in the transition zone (Katayama and Nakashima, 2003; Katayama and others, 2003). Under high water fugacity conditions grain boundary processes dominate deformation and lower the flow strength of garnets, creating a strong elongation and preferred orientation (Zhang and others, 2005). Rheological experiments demonstrate that "wet" garnets from Dabie-Sulu have

only one-quarter the strength of "dry" garnets, and that "wet" eclogites (~50/50 garnet/omphacite) have 2/3 the strength of "dry" eclogites (Zhang and others, 2001b). So, a thick, low viscosity, rheologically weak, eclogitized, thickened lower crustal keel would overlie a hydro-weakened transition zone. If delamination, in contrast to chemical replacement, is envisaged, such tectonic juxtaposition would enable the dense but weak root to sink or collapse into the underlying hydro-weakened mantle (see also Deng and others, 2007). As the hydrated crustal root warms up with time, it would attain anomalously low viscosity, becoming highly mobile and capable of extensive flow. This heating is documented by fission track analyses from the North China Craton, which demonstrate that the temperature of the lithosphere increased gradually during the early to mid-Jurassic (also the time of main thrusting—fig. 3), underwent a major thermal event from 140 to 130 Ma (also the time of peak lithospheric thinning and root loss—fig. 3), and then cooled from about 85 Ma to the Quaternary (Wang and others, 2005).

The Dabie Shan suture and orogen between the North and South China cratons formed in the Permo-Triassic (Wang and others, 2008). Zircon and monazite dating indicates that the main deep subduction metamorphic event was at 244 to 236 Ma (Hacker and others, 2006) when the crust and underlying mantle of the South China craton were subducted to depths of >180 to 200 km (Re-Os data of UHP peridotites, Yuan and others, 2007). A Sm-Nd model age of 212 ± 4 Ma represents the retrograde granulite facies metamorphism during exhumation (Liu, S. F., and others, 2005). At Sulu, considered to be the along-strike equivalent of the Dabie Shan orogen, the high-pressure eclogite facies metamorphism records a zircon age of 225 to 215 Ma (Zhao and others, 2006). Interestingly, the Triassic peridotitic zircons at Dabie have trace element affinities with zircons in granitic rocks; this led Zheng and others (2006a) to conclude that the zircons record metasomatism by fluids released from the subducted continental crust of the South China Craton.

Dabie Shan must have been a very thick orogen, because the presence of coesite- and diamond-bearing rocks suggests that a thickness of >100 km of crust (4×10^6 km^3 in volume) has been denuded (Nie and others, 1994). Today the abundant eclogites on the surface do not extend downwards for more than 5 km, the crust of the orogen has a maximum thickness today of 35 km and the present-day crustal root is only 6.5 km thick (Wang and others, 2000). The remarkably thin, present-day crust of the Dabie Shan orogen suggests that much of the lower crust has been delaminated, and mass balance modeling suggests that eclogite of the type exposed today is the most likely candidate as the delaminated material and that a cumulative 37 to 82 km-thick eclogitic lower crust is required to have been delaminated in order to explain the relative Eu, Sr, and transition metal deficits in the crust of eastern China (Gao and others, 1998b). Quantitative modeling of the thickness of the lithosphere under Dabie Shan suggests a lithospheric thermal thickness of <100 km (Wang and others, 2000; Yuan, 1996a).

Eclogites and garnet clinopyroxenites occur as xenoliths in Early Cretaceous high-Mg adakitic porphyry intrusions in the southern margin of the Eastern Block of the NCC (Xu and others, 2006a). The eclogite facies metamorphism has a U-Pb zircon age of ~220 Ma (close to that in Dabie Shan). This suggests some degree of contemporaneity of crustal thickening and foundering between the eclogitization of the (basaltic?) crustal root of the overriding North China Craton and the eclogitization of subducted basaltic crust of the South China Craton in the Dabie orogen (Xu and others, 2006b).

TECTONIC FORCING OF HYDRO-WEAKENED MANTLE

Subcontinental lithosphere, especially in thrust-thickened crustal roots, may founder into the deeper mantle (for example, Yang and others, 2003; Wang and

others, 2006; Huang and Zhao, 2009), but in eastern China were there tectonic forces that may have facilitated the process? Such forces would need to have been in operation after the formation of the Solonker and Dabie sutures in the Permo-Triassic, and before the delamination, which was mostly in the Cretaceous (Kusky and others, 2007; Zhang, 2007, and references therein). Significantly, the Inner Mongolian (Solonker) and Dabie Shan orogens both underwent extensive post-collisional thrusting in the Jurassic.

In the Solonker orogen, the Hegenshan ophiolite was thrust over unmetamorphosed early Jurassic red bed sediments (Hsü and others, 1991) and some thrusts have a minimum displacement of 40 km (Ruzhentsev, 2001). The post-collisional thrusting was so intensive and widespread that Xiao and others (2003) concluded that it was of Himalayan proportions. It led to the formation of the Yanshan-Yinshan fold-and-thrust belt and foreland basin (Davis and others, 1998; Li and others, 2007; Dong and others, 2008; Hu and others, 2010). Davis and others (1998) reported thrust displacements of >40 to 45 km, but they ascribed this deformation to closure of the distant Mongol-Okhotsk ocean, and did not consider the more likely post-collisional deformation of the Solonker suture. The Yanshan fold-and-thrust belt underwent thrusting in the Late Triassic and Early Jurassic (Hu and others, 2010) and (?) in the mid-Jurassic to Early Cretaceous (Davis and others, 1998, 2000; Davis, 2003).

In the south of the craton, post-collisional deformation after the Dabie Shan collision led to formation of a major fold-and-thrust belt and the Hefei foreland basin, where crustal thinning peaked at 132 Ma (He and others, 1998; Li and others, 2007).

The lithosphere of the North China Craton was thickened by as much as 50 percent by collision and post-collision with the South China Craton in the Triassic and Jurassic (Wang and others, 2005). Post-collisional compression related to the Dabie Shan orogen in the Late Jurassic to Cretaceous was responsible for 88 km of shortening within the Yangtze fold-and-thrust belt (fig. 3) along the northern margin of the South China craton (Yan and others, 2003).

Zhang, H.–F., and others (2003) proposed that subduction of oceanic crust beneath the southern margin of the North China Craton at Dabie Shan and below the northern margin from the Mongol-Okhotsk ocean was responsible for destabilization of the eastern North China Craton and for the resulting thinning and replacement of the lithospheric mantle, and therefore, significantly, that the lithospheric mantle beneath the center of the eastern North China Craton was less extensively modified. However, they did not take into account either subduction of the Solonker ocean, or the post-collisional Yanshan-Yinghan and Hefei thrust belts on the northern and southern sides of the North China Craton, respectively. Meng (2003) and Meng and others (2003) ignored the Solonker suture and considered that subduction of the Mongol-Okhotsk oceanic slab, strangely only towards the north, was the main trigger for late Mesozoic lithospheric extension in the northern part of the Eastern Block; we consider this most unlikely.

The Mongol-Okhotsk orogen formed in/by the mid-Jurassic in Mongolia (Tomurtogoo and others, 2005) (fig. 3) and in the Cretaceous farther east. Some workers envisaged that subduction on the Mongol-Okhotsk suture was only to the north (for example, Zorin, 1999; Meng, 2003), and others only to the south (for example, Zhang, H. F., and others, 2003), but Tomurtogoo and others (2005) pointed out that there must have been subduction both ways, because of the presence of Andean-type magmatic arcs on both sides of the suture zone. The post-collisional thrusting led to crustal thickening and, in the Early Cretaceous, to extension, uplift, formation of rift basins and exhumation of metamorphic core complexes in and around the Mongol-Okhotsk orogen.

The Song Ma suture and orogen on the southern side of the South China Craton formed by collision with the Indo-China craton in the Early Triassic (fig. 3) (Lepvrier and others, 2004; Lin and others, 2007). Post-collision deformation continued until the Cretaceous (Ren and others, 2002). Figure 11 illustrates formation of the Song Ma suture as a result of northward subduction of the Paleo-Tethyan ocean. The subduction may have had some influence on transport of water under the North China Craton and post-collisional deformation may have had a long-distant effect on the delamination.

We propose that post-collision thrusting in the Jurassic associated with the Dabie and Solonker orogens triggered or assisted collapse and thinning/delamination by the Early Cretaceous of the hydro-weakened and eclogitic crustal root of the intervening Archean craton. Replacement of the sub-continental lithosphere, either physically or chemically, by fertile asthenosphere in the Cenozoic led to extrusion of extensive alkali flood basalts throughout the Eastern Block of the North China Craton and farther north in and around the Songliao Basin (Xu and others, 2004a).

MODELS FOR LITHOSPHERIC THINNING

The issue of how the massive lithospheric thinning took place under eastern China has generated many diverse models that can be grouped into two categories (Kusky and others, 2007): *(1) Mechanical Removal, that is, delamination and (2) Chemical replacement/erosion, that is, thinning.*

(1) Mechanical removal
Mechanical detachment or foundering of ancient mantle or lithospheric root and replacement by upwelling of hot new asthenosphere (O'Reilly and others, 2001; Chu and others, 2009) could have renewed the upper mantle.
The tectosphere could have been reduced in size during the rifting of Gondwana by the flow of underlying mantle, plume or superplume activity, and mantle overturn and delamination that could have caused the replacement of mantle (Wilde and others, 2003; Wu and others, 2005).
Collision of India against Asia (Menzies and others, 1993; Zhang, Y. Q., and others, 2003; Deng and others, 2004; Liu and others, 2004), or collision of the North and South China cratons (Griffin and others, 1998; Gao and others, 2002).
Subduction of the Pacific Plate beneath eastern China (Li, 2000; Niu, 2005; Wu and others, 2005; Huang and Zhao, 2009).
Removal of thickened lithosphere beneath northern (Mongol-Okhotsk) and southern (Dabie Shan) subducted margins of the delaminated zone (Zhang, H. F., and others, 2003).
Delamination or mechanical removal of whole slabs of lithosphere due to density foundering of tectonically thickened lithosphere that had been transformed to eclogite (Gao and others, 2004; Wu and others, 2005; Deng and others, 2007; Huang, F., and others, 2007). Magmatism may have been initiated by post-collisional break-off of slabs from the Solonker and Dabie subduction zones (Cope and Graham, 2007).
(2) Chemical replacement/erosion
Replacement and modification by upwelling fertile asthenosphere by thermo-chemical processes (Griffin and others, 1998; Xu and others, 2004b; Zheng and others, 2005).
Thermal perturbation (Lin and others, 2005).
Magmatic underplating, melting and replacement of lower crust (Zhai and others, 2007)
Coupled thermo-mechanical and chemical erosion induced by subduction of the Pacific plate (Xu, 2001).
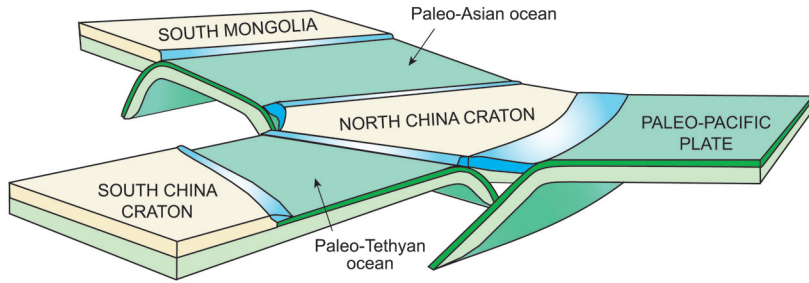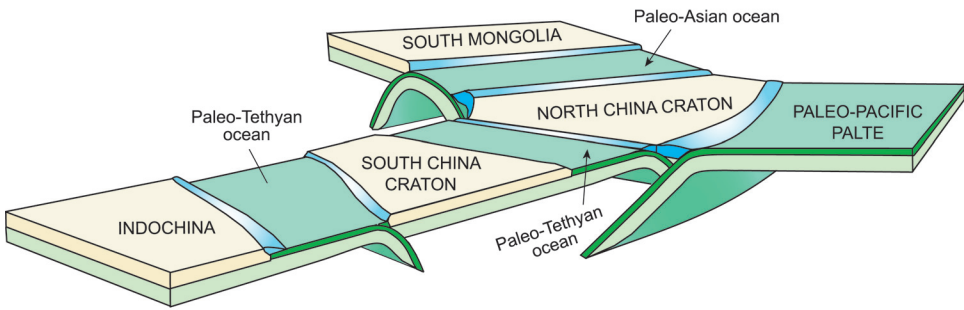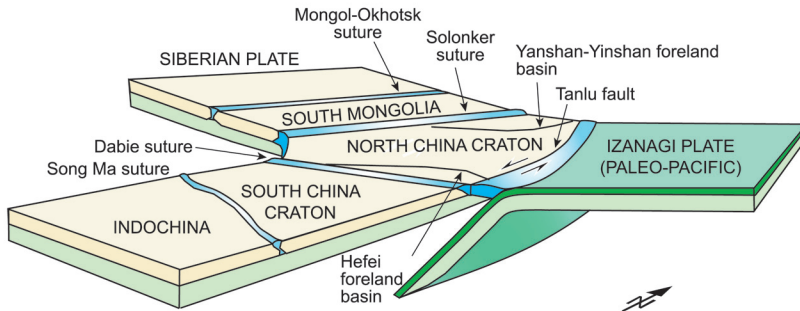
A. Early Paleozoic

B. Late Paleozoic to Early Triassic

C. Early Cretaceous to Tertiary

Fig. 11. A three-dimensional model illustrating the way that oceanic plates of the Mongol-Okhotsk ocean (not shown), the Paleo-Asian ocean, and the Paleo-Tethyan ocean have all subducted, and predictably carried water beneath the delaminated zone of the Eastern Block of the North China Craton. Closure of these oceanic plates gave rise to the Mongol-Okhotsk suture, the Solonker suture, the Dabie suture, and the Song Ma suture.

Long-term replacement of ancient lithosphere by metamorphism, and chemical and
    thermal erosion of hot asthenosphere (Tian and others, 2009).
Water derived from subduction of just the Pacific plate (Niu, 2005), or from multiple
    subduction of the Pacific plate and of Palaeozoic-Mesozoic oceans surrounding
    the North China Craton was responsible for hydro-weakening and thinning of the
    sub-continental lithosphere (Windley and others, 2005; Huang and others, 2007;
    Kusky and others, 2007; this paper). This is due to the order of magnitude
    decrease of viscosity by addition of water into the mantle wedge.

The idea that subduction of water into the mantle caused hydro-weakening of the sub-continental lithosphere and was responsible for the thinning/delamination under the eastern part of the North China Craton came independently from Maruyama and others (2004), Windley and others (2005) and Niu (2005). However, whereas Niu (2005) considered that only the subducted Pacific plate carried water to the upper mantle, Windley and others (2005), building on the ideas of Maruyama and others (2004) of double subduction, as summarized above, extended the water-subduction process to include the subduction zones sited on the Solonker, Dabie Shan, Mongol-Okhotsk and Song Ma sutures. Huang and others (2007) quoted Windley and others (2005).

Multiple Subduction around the Eastern North China Craton

Besides being affected by subduction of the Pacific plate from the east and the Indo-Australian plate from the south since Tertiary time, the Eastern Block of the North China Craton was also affected by other subduction zones. The craton is surrounded by sutures that are the sites of former oceans that were subducted in all cases towards and under it; the Solonker suture on the immediate northern side, the Mongol-Okhotsk suture farther north in eastern Mongolia and Transbaikalia, the Qinling-Dabie Shan suture on the immediate southern side, and the Song Ma suture farther south.

On the northern side, the Paleo-Asian Ocean began to subduct southwards in the Ordovician and continued thus until the Permo-Triassic when the ocean closed and the Solonker suture formed; a total of at least 200 million years of subduction occurred beneath the North China Craton (Xiao and others, 2003).

The Mongol-Okhotsk ocean began its southwards subduction in the mid-Carboniferous until the suture formed in the mid-Jurassic in what is now eastern Mongolia; southwards subduction lasted for at least 150 Ma (Tomurtogoo and others, 2005).

The Qinling-Dabie suture forms the boundary between the North China (or Sino-Korean) Craton and the South China (or Yangtze) Craton. Following break-off from eastern Gondwanaland, northwards subduction of the Paleo-Tethys below the southern margin of the North China Craton began in the Carboniferous, and the Permo-Triassic is the most commonly cited time for the collision; accordingly, subduction under the southern margin of the North China Craton lasted for ~50 Ma.

The NW/SE-oriented Song Ma suture is located in north Vietnam and separates the South China and Indochina cratons. Subduction was to the north (Lepvrier and others, 2004) and collision was in the Early Triassic at 245 Ma (Lin and others, 2007).

The cumulative time-equivalent sum of the lengths of time that subduction was taking place under eastern China on the plate boundaries referred to so far (that is, Pacific, Indo-Australian, Solonker, Mongol-Okhotsk, Qinling-Dabie and Song Ma) amounts to ~1150 Ma, assuming that old oceanic plates, as opposed to young hot plates, were most likely subducted in all these cases, and if the oceanic crust of these plates was as hydrated as that of today. Far more subduction took place, and much more water was transported to the mantle, under the eastern North China Craton than under any other Precambrian craton in the world. We suggest that this unique multi-hydration was the fundamental cause of the unique thinning of the sub-continental lithosphere under eastern China. The correlation of these two situations seems compelling.

In their thoughtful evaluation of explanatory models for the delamination/ thinning of lithosphere under the eastern North China Craton, Menzies and others (2007) pointed out that, besides rapid delamination and slow transformation, a third viable model is hydration of a crustal root driven by dewatering of recycled slabs. We have provided abundant data above that support the water-based model. However, instead of the single subduction zone (Pacific plate) model of Niu (2005), we propose that multiple subduction zones emplaced hydrated oceanic slabs under the Eastern Block of the NCC during the Paleozoic. This occurred from the north, from oceans sited on what is now the Solonker suture and the Mongol-Okhotsk suture, and from the south, from the Dabie Shan suture and the Song Ma suture (figs. 11 and 12), and possibly from the Indo-Australian plate. Tomography shows that the Pacific plate has subducted and ponded along the mantle transition zone under eastern Asia, and considerable evidence suggests that the main nominally anhydrous minerals become hydrated in the transition zone, providing a vast hydrous reservoir. Many plumes rise from the mantle transition zone to create mid-oceanic ridges and plate accretion and that includes the marginal basins of Indonesia and the western Pacific, such as the Philippine Sea, the basalts of which are known to contain twice as much water as those of the Pacific plate (Komiya and Maruyama, 2007). The multiple subduction of many hydrous oceanic slabs under eastern China would have had major consequences for the composition and rheology of the underlying lithosphere, and especially of the mantle transition zone. If hydrous plumes were ultimately responsible for the formation of the marginal basins of the western Pacific as a result of double subduction of the Pacific and Indo-Australian plates, as was argued by Komiya and Maruyama (2007), then it is highly likely that the rise of asthenosphere material hydrated by at least five oceanic plates subducted during the Phanerozoic would have caused formation of the Bohai Basin/Sea, which is situated on the oceanic margin of the delaminated Eastern Block of the North China Craton (figs. 1, 11 and 12), and which began to form in the early stages of thinning in the Late Jurassic.

Melting experiments of hydrous peridotite indicate that an addition of 0.2 weight percent H_2O lowers the solidus temperature by 150 °C (Hirose, 1997). This would lead to extensive melting of low-melting point components in the hydrous mantle transition zone; this provides a viable model to generate plumes and to account for the voluminous plutonic and volcanic rocks, emplaced largely in the period 135 to 127 Ma, in and around the Eastern Block (Chen, B., and others, 2007) during the "giant igneous event" of Wu and others (2005). This process, with all its variants, would adequately account for the production of adakites, monzonites, shoshonites, and crustal melt granites, as summarized earlier.

Early papers on this subject used the term delamination, which was taken to mean physical detachment of a mantle slab. However, O'Reilly and others (2001) pointed out that the Archean lithosphere was too refractory and buoyant to be physically delaminated, and thus more likely to be chemically replaced. Detailed seismic tomography of eastern China led Yuan (1996b) and Griffin and others (1998) to suggest that lithosphere replacement involved some extension and rifting, with structurally-controlled coeval upwelling of fertile asthenospheric material, rather than physical removal and delamination. The idea of thinning and thermo-chemical modification of the old mantle by upwelling fertile asthenosphere (Zheng and others, 2006b) was supported by the discovery that some relics of older mantle are preserved within the new mantle under the Eastern Block (Griffin and others, 1998; Xu and others, 2004b; Zheng and others, 2005; O'Reilly and others, 2009), and by the discovery that delamination has occurred in only localised areas (Xu and Zhao, 2009).

Fig. 12. Sequential diagrams showing the geodynamic processes and the mantle-crustal interactions during the development of the North China Craton and adjacent regions (modified after Griffin and others, 1998; Zhang, Y. Q., and others, 2003; Huang and others, 2007; Zhang, 2007). A: Paleozoic; B: Permo-Triassic; C: Jurassic-Cretaceous; D: Early Tertiary-Present.

It has been suggested that fluid-induced eclogitization led to hydration of the thickened crustal root of the eastern part of the NCC. We have proposed that post-collisional thrusting largely in the Jurassic on the Solonker and Dabie sutures evidently led to extension and thinning of the lithosphere on the northern and southern margins of the delaminated zone largely in the Cretaceous, because of the presence of the Yanshan and Hefei foreland basins, respectively; such marginal extension and thinning could have triggered major extension of the hydro-weakened crustal root under the center of the eastern part of the craton. Evidence for such major extension is indicated not only by the voluminous intrusions and extrusions, but also by abundant metamorphic core complexes formed in the period 135 to 109 Ma, which coincides with the main period of overall crustal extension and magmatism at 140 to 110 Ma (fig. 3).

The delaminated/thinned zone of sub-continental lithosphere has traditionally been confined to the limits of the Eastern Block of the North China Craton (Menzies and others, 1993; Griffin and others, 1998). However, the zone may have been more extensive than previously thought. The Dabie Shan orogen has lost most of its crustal root that may have been as much as 82 km thick, and its eclogites have a peak metamorphic age close to that of eclogites entrained in intrusive adakites within the Eastern Block of the craton. Moreover, the Yangtze foreland basin, situated in a fold-and-thrust belt on thinned crust-lithosphere on the southern side of the Dabie orogen, formed from the Late Triassic to Early Tertiary. To the north of the North China Craton, the NS-aligned Songliao Basin is situated on very thin lithosphere (<60 km) that extends southwards via the Bohai Basin to the Eastern Block of the craton (Yuan, 1996a; Zhang and others, 2000). The Songliao Basin has a high heat flow (>105 mW/m^2), contains Early Jurassic–Early Cretaceous basalt-andesite lavas, and over 590 Cenozoic alkali basalt volcanoes. The fact that it has a N-S alignment suggested to Liu, J. Q., and others (2001) that its development in the Cenozoic was closely associated with the evolution of the Japan Sea (one of the hydrous marginal basins of Komiya and Maruyama, 2007), and this implies another link between water subduction associated with the formation of the West Pacific marginal basins and the processes responsible for the hydro-weakening and thinning of the sub-continental lithosphere beneath eastern China.

The Late Jurassic–Early Tertiary Bohai Basin, situated on 28 km-thick crust and the thinnest lithosphere (60 km) in eastern China, is located on the eastern margin of the Eastern Block of the craton (Lysak and Dorofeeva, 2005; Li and others, 2006). Because of its extensive Cenozoic basaltic volcanism it has a heat flow that reaches 1.77 to 2.53 HFU in the Bohai Gulf and coastal areas, and a geothermal gradient of 1.41 to 1.21 W/m · K (Lysak and Dorofeeva, 2005). As Ren and others (2002) pointed out, the association of thin crust and lithosphere, extensive volcanism, high heat flow and geothermal gradient indicates extensive upwelling of the asthenosphere, which is supported by 3D P-wave tomographic data that suggest large-scale lithospheric thinning and detachment (Huang and Zhao, 2009). The Bohai Basin provides critical information on the processes that gave rise to and followed lithospheric removal below the Eastern magin of the NCC.

Amongst the Early Precambrian cratons in the world, the eastern North China Craton is almost unique in containing Cenozoic volcanoes and alkali basalt flood basalts, although the basalts were also extruded to the east and northwest of the craton in regions of thinned lithosphere (Yan, J., and Zhao, 2008). Volcanism in the period 65 to 45 Ma likely reflected the replacement by hot fertile asthenosphere of the old lithosphere, as predicted in models of sub-continental lithosphere detachment (Griffin and others, 1998). As a result, the present lithospheric mantle is completely different from that which was present in the Paleozoic (Chu and others, 2009). This

process terminated the lithospheric removal under eastern China and especially below the Eastern Block of the North China Craton (figs. 11 and 12).

<div align="center">CONCLUSIONS</div>

We envisage the following sequence of events (figs. 3 and 12):

1. During the Paleozoic, four hydrated oceanic plates were subducted and ponded at the mantle transition zone under the eastern North China Craton. Their transported water entered into nominally anhydrous minerals and established a major hydrous reservoir in the transition zone.

2. Conductive heating from the underlying mantle caused the "hydrous" phases to destabilize, releasing water at the 410 km boundary to form a partially melted, hydrous, low velocity layer above that boundary, which triggered the rise of hydrous plumes into the overlying mantle. Also, the possible subduction of TTG arc crust may have led to formation of a TTG layer along the base of the transition zone at 660 km depth; this layer generated heat by radioactive decay facilitating the formation of hydrous plumes at 410 km.

3. We do not know the maximum thickness of the original Archean cratonic root of the eastern part of the NCC, but the interaction with rising hydrous melts would have started the process of eclogitization, creating a dense, but also hydro–weakened, lower root.

4. By the end of the Paleozoic, subduction of three oceanic plates was terminated by formation of the Solonker, Dabie Shan and Song Ma sutures; although an underlying, broken-off plate may have lasted, and been influential for up to some 50 Ma after collision.

5. Post-collision thrusting on the southern side of the Solonker suture created the Yanshan-Yinshan thrusted foreland basin and the Hefei and Yangtze thrusted foreland basins on the northern and southern sides of the Dabie Shan suture/orogen, respectively. This thrusting began in the Triassic and continued into the Jurassic. Closure of the Mongol-Okhotsk ocean took place in the Jurassic (north of the North China Craton). The intense post-collisional thrusting thickened considerably the lower crust and the upper mantle root of the eastern North China Craton, and accordingly facilitated or triggered the delamination/thinning of the underlying hydro-weakened cratonic root after the mid-Jurassic.

6. The delamination/thinning of the sub-continental lithospheric mantle enabled or assisted the creation of a post-thrusting extensional regime, which began after the mid-Jurassic in, for example, the Yanshan-Yinshan foreland basin, facilitating collapse of the intracontinental mountains or plateau in eastern China in the Late Jurassic and into the Early Cretaceous. Also, upwelling hot asthenosphere triggered thermal-chemical replacement and partial melting of enriched sub-continental mantle and provided heat to melt the lower crust to generate voluminous granitic magmas, which gave rise to a variety of magmatic rocks such as granites and adakite, as well as gold mineralization, largely in the Cretaceous. The peak time of lithospheric thinning and crustal extension was in the Early Cretaceous, expressed by the formation of metamorphic core complexes, and this is the best estimate of the peak time of subcontinental mantle root loss.

7. Replacement of the old lithosphere by new fertile asthenosphere led in the early Tertiary to the rise of extensive alkali flood basalts and formation of volcanoes on the thinned Eastern Block of the North China Craton and farther east to the present Pacific margin and northwards to the Songliao region.

REFERENCES

Allen, M. B., Macdonald, D. I. M., Xun, Z., Vincent, S. J., and Brouet-Menzies, C., 1997, Early Cenozoic two-phase extension and late Cenozoic thermal subsidence and inversion of the Bohai Basin, northern China: Marine Petroleum Geology, v. 14, n. 7–8, p. 951–972, doi:10.1016/S0264-8172(97)00027-5.

Austrheim, H., 1991, Eclogite formation and dynamics of crustal roots under continental collision zones: Terra Nova, v. 3, n. 5, p. 492–499, doi:10.1111/j.1365-3121.1991.tb00184.x.

Avigad, D., and Gvirtzman, Z., 2009, Late Neoproterozoic rise and fall of the northern Arabian-Nubian shield: The role of lithospheric mantle delamination and subsequent thermal subsidence: Tectonophysics, v. 477, n. 3–4, p. 217–228, doi:10.1016/j.tecto.2009.04.018.

Barry, T. L., Ivanov, A. V., Rasskazov, S. V., Demonterova, E. I., Dunai, T. J., Davies, G. R., and Harrison, D., 2007, Helium isotopes provide no evidence for deep mantle involvement in widespread Cenozoic volcanism across Central Asia: Lithos, v. 95, n. 3–4, p. 415–424, doi:10.1016/j.lithos.2006.09.003.

Basu, A. R., Wang, J., Huang, W., Xie, G., and Tatsumoto, M., 1991, Major element, REE, and Pb, Nd and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: implications for their origin from suboceanic-type mantle reservoirs: Earth and Planetary Science Letters, v. 105, p. 149–169, doi:10.1016/0012-821X(91)90127-4.

Bercovici, D., and Karato, S., 2003, Whole-mantle convection and the transition-zone water filter: Nature, v. 425, p. 39–44, doi:10.1038/nature01918.

Bolfan-Casanova, N., Keppler, H., and Rubie, D. C., 2000, Water partitioning between nominally anhydrous minerals in the $MgO-SiO_2-H_2O$ system up to 24 GPa: implications for the distribution of water in the Earth's mantle: Earth and Planetary Science Letters, v. 182, p. 209–221, doi:10.1016/S0012-821X(00)00244-2.

Boyd, O. S., Jones, C. H., and Sheehan, A. F., 2004, Foundering lithosphere imaged beneath the Southern Sierra Nevada, California, USA: Science, v. 305, n. 5684, p. 660–662, doi:10.1126/science.1099181.

Bunge, H.-P., Richards, M. A., and Baumgardner, J. R., 1996, Effect of depth-dependent viscosity on the planform of mantle convection: Nature, v. 379, p. 436–438, doi:10.1038/379436a0.

Chen, B., and Zhai, M., 2003, Geochemistry of late Mesozoic lamprophyric dykes from the Taihang Mountains, North China, and implications for the sub-continental lithospheric mantle: Geological Magazine, v. 140, p. 87–93, doi:10.1017/S0016756802007124.

Chen, B., Zhai, M.-G., and Tian, W., 2007, Origin of the Mesozoic magmatism in the North China Craton: constraints from petrological and geochemical data, *in* Zhai, M., Windley, B. F., Kusky, T. M., and Meng, Q., editors, Mesozoic Sub-continental Lithospheric Thinning under Eastern Asia: Geological Society of London, Special Publications, v. 280, p. 131–151, doi:10.1144/SP280.6.

Chen, B., Tian, W., Jahn, B. M., and Chen, Z. C., 2008, Zircon SHRIMP U-Pb ages and in-situ Hf isotopic analysis for the Mesozoic intrusions in South Taihang, North China Craton: Evidence for hybridization between mantle-derived magmas and crustal components: Lithos, v. 102, n. 1–2, p. 118–137, doi:10.1016/j.lithos.2007.06.012.

Chen, B., Jahn, B. M., and Tian, W., 2009, Evolution of the Solonker suture zone: Constraints from zircon U-Pb ages, Hf isotopic ratios and whole-rock Nd-Sr isotope compositions of subduction- and collision-related magmas and forearc sediments: Journal of Asian Earth Sciences, v. 34, n. 3, p. 245–257, doi:10.1016/j.jseaes.2008.05.007.

Chen, L., Cheng, C., and Wei, Z., 2009, Seismic evidence for significant lateral variations in lithospheric thickness beneath the central and western North China Craton: Earth and Planetary Science Letters, v. 286, n. 1–2, p. 171–183, doi:10.1016/j.epsl.2009.06.022.

Chen, S. H., O'Reilly, S. Y., Zhou, X., Griffin, W. L., Zhang, G., Sun, M., Feng, J., and Zhang, M., 2001, Thermal and petrological structure of the lithosphere beneath Hannuoba, Sino-Korean Craton, China: evidence from xenoliths: Lithos, v. 56, p. 267–301, doi:10.1016/S0024-4937(00)00065-7.

Chu, Z.-Y., Wu, F.-Y., Walker, R. J., Rudnick, R. L., Pitcher, L., Puchtel, I. S., Yang, Y.-H., and Wilde, S. A., 2009, Temporal evolution of the lithospheric mantle beneath the Eastern North China Craton: Journal of Petrology, v. 50, p. 1857–1898, doi:10.1093/petrology/egp055.

Chung, J., and Kagi, H., 2002, High concentration of water in stishovite in the MORB system: Geophysical Research Letters, v. 29, doi; 10.1029/2002GL015579.

Chung, S.-L., Liu, D., Ji, J., Chu, M.-F., Lee, T.-Y., Wen, D.-J., Lo, H.-L., Lee, T.-Y., Qian, Q., and Zhang, Q., 2003, Adakites from continental collision zones: melting of thickened lower crust beneath southern Tibet: Geology, v. 31, n. 11, p. 1021–1024, doi:10.1130/G19796.1.

Cope, T., and Graham, S. A., 2007, Upper crustal response to Mesozoic tectonism in western Liaoning, North China, and implications for lithospheric delamination, *in* Zhai, M., Windley, B. F., Kusky, T. M., and Meng, Q., editors, Mesozoic Sub-continental Lithospheric Thinning under Eastern Asia: Geological Society, London, Special Publications, v. 280, p. 201–222, doi:10.1144/SP280.1.

Darby, B. J., and Ritts, B. D., 2002, Mesozoic contractional deformation in the middle of the Asian tectonic collage: the intraplate western Ordos fold-thrust belt, China: Earth and Planetary Science Letters, v. 205, p. 13–24, doi:10.1016/S0012-821X(02)01026-9.

Darby, B. J., Davis, G. A., Zhang, X., Wu, F., Wilde, S., and Yang, J., 2004, The newly discovered Waziyu metamorphic core complex, Yiwulü Shan, western Liaoning Province, North China: Earth Science Frontiers, v. 11, p. 145–155.

Davis, G. A., 2003, The Yanshan belt of North China: tectonics, adakitic magmatism, and crustal evolution: Earth Science Frontiers, v. 10, p. 374–384.

Davis, G. A., Wang, C., Zheng, Y., Zhang, J., Zhang, C., and Gehrels, G. E., 1998, The enigmatic Yinshan fold-and-thrust belt of northern China: New views on its intraplate contractional styles: Geology, v. 26, p. 43–46, doi:10.1130/0091-7613(1998)026⟨0043:TEYFAT⟩2.3.CO;2.

Davis, G. A., Zheng, Y., Wang, C., Darby, B. J., Zhang, C., and Gehrels, G., 2001, Mesozoic tectonic evolution of the Yanshan fold and thrust belt, with emphasis on Hebei and Liaoning provinces, northern China, *in* Hendrix, H. S., and Davis, G. A., editors, Paleozoic and Mesozoic Tectonic Evolution of Central Asia: From Continental Assembly to Intracontinental Deformation: Geological Society of America Memoirs, v. 194, p. 171–197, doi:10.1130/0-8137-1194-0.171.

Davis, G. A., Darby, B. J., Yadong, Z., and Spell, T. L., 2002, Geometric and temporal evolution of an extensional detachment fault, Hohhot metamorphic core complex, Inner Mongolia, China: Geology, v. 30, p. 1003–1006, doi:10.1130/0091-7613(2002)030⟨1003:GATEOA⟩2.0.CO;2.

Deng, J. F., Mo, X. X., Zhao, H. L., Wu, Z. X., Luo, Z. H., and Su, S. G., 2004, A new model for the dynamic evolution of Chinese lithosphere: "continental roots—plume tectonics": Earth Science Reviews, v. 65, p. 223–275, doi:10.1016/j.earscirev.2003.08.001.

Deng, J., Su, S., Niu, Y., Liu, C., Zhao, G., Zhao, X., Zhou, S., and Wu, Z., 2007, A possible model for the lithospheric thinning of North China Craton: evidence from the Yanshanian (Jura-Cretaceous) magmatism and tectonism: Lithos, v. 96, p. 22–35, doi:10.1016/j.lithos.2006.09.009.

Dewey, J. F., Ryan, P. D., and Andersen, T. B., 1993, Orogenic uplift and collapse, crustal thickness, fabrics and metamorphic phase changes: the role of eclogites: Geological Society, London, Special Publications, v. 76, p. 325–343, doi:10.1144/GSL.SP.1993.076.01.1.

Dixon, J. E., Dixon, T. H., Bell, D. R., and Malservisi, R., 2004, Lateral variation in upper mantle viscosity: role of water: Earth and Planetary Science Letters, v. 222, p. 451–467, doi:10.1016/j.epsl.2004.03.022.

Dong, S. W., Gao, R., Cong, B., Zhao, Z., Liu, X., Li, S., Li, Q., and Huang, D., 2004, Crustal structure of the southern Dabie ultrahigh-pressure orogen and Yangtze foreland from deep seismic reflection profiling: Terra Nova, v. 16, p. 319–324, doi:10.1111/j.1365-3121.2004.00568.x.

Dong, S., Zhang, Y., Long, C., Yang, Z., Ji, Q., Wang, T., Hu, J., and Chen, X., 2008, Jurassic tectonic revolution in China and new interpretation of the "Yanshan movement": Acta Geologica Sinica, v. 82, n. 2, p. 334–347, doi:10.1111/j.1755-6724.2008.tb00583.x.

Ducea, M., and Saleeby, J., 1997, A case for delamination of batholithic crust beneath the Sierra Nevada, California: International Geology Review, v. 40, p. 78–93, doi:10.1080/00206819809465199.

Engebretson, D. C., Kelley, K. P., Cashman, H. J., and Richards, M. A., 1992, 180 million years of subduction: GSA Today, v. 2, p. 93–100.

Fan, W. M., and Menzies, M. A., 1992, Destruction of aged lower lithosphere and accretion of asthenosphere mantle beneath eastern China: Geotectonica et Metallogenia, v. 16, p. 171–180.

Fan, W. M., Zhang, H. F., Baker, J., Jarvis, K. E., Mason, P. R. D., and Menzies, M. A., 2000, On and off the North China Craton: Where is the Archean keel?: Journal of Petrology, v. 41, p. 933–950, doi:10.1093/petrology/41.7.933.

Fei, Y., 1995, Thermal expansion, *in* Ahrens, T. J., editor, Mineral Physics and Crystallography: A Handbook of Physical Constants: Washington, D. C., American Geophysical Union, p. 29–44.

Fukao, Y., Widiyantoro, S., and Obayashi, M., 2001, Stagnant slabs in the upper and low mantle transition zone: Reviews of Geophysics, v. 39, p. 291–323, doi:10.1029/1999RG000068.

Gaetani, G. A., Grove, T. L., and Bryan, W. B., 1993, The influence of water on the petrogenesis of subduction-related igneous rocks: Nature, v. 365, p. 332–33, doi:10.1038/365332a0.

Gao, S., Zhang, B.-R., Jin, Z.-M., Kern, H., Luo, T.-C., and Zhao, Z.-D., 1998a, How mafic is the lower continental crust?: Earth and Planetary Science Letters, v. 161, n. 1–4, p. 101–117, doi:10.1016/S0012-821X(98)00140-X.

Gao, S., Luo, T.-C., Zhang, B.-R., Zhang, H.-F., Han, Y.-W., Zhao, Z.-D., and Hu, Y.-K., 1998b, Chemical composition of the continental crust as revealed by studies in East China: Geochimica et Cosmochimica Acta, v. 62, n. 11, p. 1959–1975, doi:10.1016/S0016-7037(98)00121-5.

Gao, S., Rudnick, R., Yuan, H.-L., Liu, X.-M., Liu, Y.-S., Xu, W.-L., Ling, W.-L., Ayers, J., Wang, X.-C., and Wang, Q.-H., 2004, Recycling lower continental crust in the North China Craton: Nature, v. 432, p. 892–897, doi:10.1038/nature03162.

Gao, S., Rudnick, R. L., Carlson, R. W., McDonough, W. F., and Liu, Y.-S., 2002, Re-Os evidence for replacement of ancient mantle lithosphere beneath the North China Craton: Earth and Planetary Science Letters, v. 198, n. 3–4, p. 307–322, doi:10.1016/S0012-821X(02)00489-2.

Garzione, C. N., Molnar, P., Libarkin, J. C., and MacFadden, B. J., 2006, Rapid late Miocene rise of the Bolivian Altiplano: Evidence for removal of mantle lithosphere: Earth and Planetary Science Letters, v. 241, n. 3–4, p. 543–556, doi:10.1016/j.epsl.2005.11.026.

Griffin, W. L., O'Reilly, S. Y., and Ryan, C. G., 1992, Composition and thermal structure of the lithosphere beneath South Africa, Siberia and China: proton microprobe studies: Beijing, Institute of Geology, Chinese Academy of Sciences, International Symposium, Cenozoic Volcanic Rocks and Deep-seated Xenoliths of China and its Environs, p. 20.

Griffin, W. L., Zhang, A. D., O'Reilly, S. Y., and Ryan, C. G., 1998, Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton, *in* Flower, M. F., Chung, S. L., and Li, T. Y., editors, Mantle Dynamics and Plate Interaction in East Asia: American Geophysical Union Monograph, v. 27, p. 107–126.

Griffin, W. L., Kobussen, A. F., Babu, E. V. S. S. K., O'Reilly, S. Y., Norris, R., and Sengupta, P., 2009, A translithospheric suture in the vanished 1-Ga lithospheric root of South India: Evidence from contrasting lithosphere sections in the Dharwar Craton: Lithos, v. 112, supplement 2, p. 1109–1119, doi:10.1016/j.lithos.2009.05.015.

Hacker, B. R., Wallis, S. R., Ratschbacher, L., Grove, M., and Gehrels, G., 2006, High-temperature geochronology constraints on the tectonic history and architecture of the ultrahigh-pressure Dali-Sulu orogen: Tectonics, v. 25, TC50006, 17 p., doi:10.1029/2005TC001937.

Hae, R., Ohtani, E., Kubo, T., Koyama, T., and Utada, H., 2006, Hydrogen diffusivity in wadsleyite and water distribution in the mantle transition zone: Earth and Planetary Science Letters, v. 243, n. 1–2, p. 141–148, doi:10.1016/j.epsl.2005.12.035.

Hales, T. C., Abt, D. L., Humphreys, E. D., and Roering, J. J., 2005, A lithospheric instability origin for Columbia River flood basalts and Wallowa Mountain uplift in northeast Oregon: Nature, v. 438, p. 842–845, doi:10.1038/nature04313.

Hall, R., and Spakman, W., 2002, Subducted slabs beneath the eastern Indonesia-Tonga region: insights from tomography: Earth and Planetary Science Letters, v. 201, n. 2, p. 321–336, doi:10.1016/S0012-821X(02)00705-7.

He, Z. J., Li, J. Y., Niu, B. G., and Ren, J. S., 1998, A Late Jurassic intense thrusting-uplifting event in the Yanshan-Yinshan area, northern China, and its sedimentary response: Geological Review, v. 44, p. 407–418 (in Chinese with English abstract).

Hirose, K., 1997, Melting experiments on lherzolite KLB-1 under hydrous conditions and generation of high-magnesian andesitic melts: Geology, v. 25, n. 1, p. 42–44, doi:10.1130/0091-7613(1997)025⟨0042:MEOLKU⟩2.3.CO;2.

Hirschmann, M. M., Aubaud, C., and Withers, A. C., 2005, Storage capacity of H_2O in nominally anhydrous minerals in the upper mantle: Earth and Planetary Science Letters, v. 236, n. 1–2, p. 167–181, doi:10.1016/j.epsl.2005.04.022.

Hirschmann, M. M., Withers, A. C., and Aubaud, C., 2006, Petrologic structure of a hydrous 410 km discontinuity *in* Jacobsen, S. D., and van der Lee, S., editors, Earth's deep water cycle: American Geophysical Union Geophysical Monograph, v. 168, p. 277–287, doi:10.1029/168GM21.

Hsü, K. J., Wang, Q., Li, J., and Hao, J., 1991, Geologic evolution of the Neimonides: a working hypothesis: Eclogae Geologae Helvetiae, v. 84, n. 1, p. 1–31.

Hu, J., Zhao, Y., Liu, X., and Xu, G., 2010, Early Mesozoic deformations of the eastern Yanshan thrust belt, northern China: International Journal of Earth Sciences, v. 99, n. 4, p. 785–800, doi:10.1007/s00531-009-0417-5.

Huang, F., Li, S.-G., and Yang, W., 2007, Contributions of the lower crust to Mesozoic mantle-derived mafic rocks from the North China Craton: implications for lithospheric thinning, *in* Zhai, M., Windley, B. F., Kusky, T. M., and Meng, Q., editors, Mesozoic Sub-continental Lithospheric Thinning under Eastern Asia: Geological Society, London, Special Publications, v. 280, p. 55–75, doi:10.1144/SP280.3.

Huang, F., Li, S., Dong, F., He, Y., and Chen, F., 2008, High-Mg adakitic rocks in the Dabie orogen, central China: implications for foundering mechanism of lower continental crust: Chemical Geology, v. 255, n. 1–2, p. 1–13, doi:10.1016/j.chemgeo.2008.02.014.

Huang, J., and Zhao, D., 2004, Crustal heterogeneity and seismotectonics of the region under Beijing, China: Tectonophysics, v. 385, n. 1–4, p. 159–180, doi:10.1016/j.tecto.2004.04.024.

—— 2006, High-resolution mantle tomography of China and surrounding regions: Journal of Geophysical Research, v. 111, B09305, 21 p., doi:10.1029/2005JB004066.

—— 2009, Seismic imaging of the crust and upper mantle under Beijing and surrounding regions: Physics of the Earth and Planetary Interiors, v. 173, n. 3–4, p. 330–348, doi:10.1016/j.pepi.2009.01.015.

Ichiki, M., Baba, K., Obayashi, M., and Utada, H., 2006, Water content and geotherm in the upper mantle above the stagnant slab: interpretation of electrical conductivity and seismic P-wave velocity models: Physics of the Earth and Planetary Interiors, v. 155, n. 1–2, p. 1–15, doi:10.1016/j.pepi.2005.09.010.

Inoue, T., Yurimoto, H., and Kudoh, Y., 1995, Hydrous modified spinel, $Mg_{1.75}SiH_{0.5}O_4$: a new water reservoir in the mantle transition region: Geophysical Research Letters, v. 22, n. 2, p. 117–120, doi:10.1029/94GL02965.

Isozaki, Y., 1996, Anatomy and genesis of a subduction-related orogen: a new view of geotectonic subdivision and evolution of the Japanese Islands: The Island Arc, v. 5, n. 3, p. 289–320, doi:10.1111/j.1440-1738.1996.tb00033.x.

Iwamori, H., 1998, Transportation of H_2O and melting in subduction zones: Earth and Planetary Science Letters, v. 160, n. 1–2, p. 65–80, doi:10.1016/S0012-821X(98)00080-6.

Jian, P., Liu, D., Kröner, A., Windley, B. F., Shi, Y., Zhang, W., Zhang, F., Miao, L., Zhang, L., and Tomurhuu, D., 2010, Evolution of a Permian intraoceanic arc-trench system in the Solonker suture zone, Central Asian Orogenic Belt, China and Mongolia: Lithos, v. 118, p. 169–190, doi:10.1016/j.lithos.2010.04.014.

Jones, C. H., Farmer, G. L., and Unruh, J., 2004, Tectonics of Pliocene removal of lithosphere of the Sierra Nevada, California: Geological Society of America Bulletin, v. 116, p. 1408–1422, doi:10.1130/B25397.1.

Jordan, T. H., 1975, The continental tectosphere: Reviews of Geophysics and Space Physics, v. 13, n. 3, p. 1–12, doi:10.1029/RG013i003p00001.

Kárason, H., and van der Hilst, R., 2000, Constraints on mantle convection from seismic tomography, *in* Richards, M. A., Gordon, R. G., and van der Hilst, R. D., editors, The History and Dynamics of Global Plate Motions: American Geophysical Union Monograph, v. 121, p. 277–288.

Karato, S., 2003, Mapping water content in the upper mantle, *in* Eiler, J., editor, Inside the Subduction Factory: American Geophysical Union Monograph, v. 138, p. 135–152.

Karato, S., and Jung, H., 1998, Water, partial melting and the origin of the seismic low velocity and high attenuation zones in the upper mantle: Earth and Planetary Science Letters, v. 157, n. 3–4, p. 193–207, doi:10.1016/S0012-821X(98)00034-X.

Katayama, I., and Nakashima, S., 2003, Hydroxyl in clinopyroxene from the deep subducted crust: evidence for H_2O transport into the mantle: American Mineralogist, v. 88, p. 229–234.

Katayama, I., Hirose, K., Yuromoto, H., and Nakashima, S., 2003, Water solubility in majoritic garnet in subducting oceanic crust: Geophysical Research Letters, v. 30, 2155, 4 p., doi:10.1029/2003GL018127.

Katayama, I., Nakashima, S., and Yurimoto, H., 2006, Water content in natural eclogite and implication for water transport into the deep upper mantle: Lithos, v. 86, n. 3–4, p. 245–259, doi:10.1016/j.lithos.2005.06.006.

Kay, R. W., and Kay, S. M., 1993, Delamination and delamination magmatism: Tectonophysics, v. 219, n. 1–3, p. 177–189, doi:10.1016/0040-1951(93)90295-U.

—— 2002, Andean adakites: three ways to make them: Acta Petrologica Sinica, v. 18, n. 3, p. 303–311 (in Chinese with English abstract).

Komabayashi, T., Omori, S., and Maruyama, S., 2004, Petrogenetic grid in the system $MgO\text{-}SiO_2\text{-}H_2O$ up to 30GPa, 1600 degree C: applications to hydrous peridotite subducting into the Earth's deep interior: Journal of Geophysical Research, v. 109, B03206, 12 p., doi:10.1029/2003JB002651.

—— 2005, Experimental and theoretical study of stability of dense hydrous magnesium silicates in the deep upper mantle: Physics of the Earth and Planetary Interiors, v. 153, n. 4, p. 191–209, doi:10.1016/j.pepi.2005.07.001.

Komiya, T., and Maruyama, S., 2007, A very hydrous mantle under the western Pacific region: Implications for formation of marginal basins and style of Archean plate tectonics: Gondwana Research, v. 11, n. 1–2, p. 132–147, doi:10.1016/j.gr.2006.02.006.

Kusky, T. M., Windley, B. F., and Zhai, M., 2007, Lithospheric thinning in eastern Asia: constraints, evolution, and tests of models, *in* Zhai, M., Windley, B. F., Kusky, T. M., and Meng, Q., editors, Mesozoic Sub-continental Lithospheric Thinning under Eastern Asia: Geological Society, London, Special Publications, v. 280, p. 331–343, doi:10.1144/SP280.18.

Leahy, G. M., and Bercovici, D., 2010, Reactive infiltration of hydrous melt above the mantle transition zone: Journal of Geophysical Research, v. 115, B08406, 17 p., doi:10.1029/2009JB006757.

Le Fort, P., 1996, Evolution of the Himalaya, *in* Yin, A., and Harrison, M., editors, The Tectonic Evolution of Asia: Cambridge, Cambridge University Press, p. 95–109.

Lepvrier, C., Maluski, H., van Tich, V., Leyreloup, A., Thi, P. T., and van Vuong, N., 2004 The Early Triassic Indosinian orogeny in Vietnam (Truong Son belt and Kontum massif): implications for the geodynamic evolution of Indonesia: Tectonophysics, v. 393, n. 1–4, p. 87–118, doi:10.1016/j.tecto.2004.07.030.

Li, J.-W., Zhao, X.-F., Zhou, M.-F., Ma, C.-Q., de Souza, Z. S., and Vasconcelos, P., 2009, Late Mesozoic magmatism from the Daye region, eastern China: U-Pb ages, petrogenesis, and geodynamic implications: Contributions to Mineralogy and Petrology, v. 157, n. 3, p. 383–409, doi:10.1007/s00410-008-0341-x.

Li, S., Zhao, G., Sun, M., Wu, F., Liu, J., Hao, D., Han, Z., and Luo, Y., 2004, Mesozoic, not Paleoproterozoic SHRIMP U-Pb zircon ages of two Liaoji granites, Eastern block, North China Craton: International Geology Review, v. 46, n. 2, p. 162–176, doi:10.2747/0020-6814.46.2.162.

Li, S., Mooney, W. D., and Fan, J., 2006, Crustal structure of mainland China from deep seismic sounding data: Tectonophysics, v. 420, n. 1–2, p. 239–252, doi:10.1016/j.tecto.2006.01.026.

Li, W.-P., Li, X.-H., and Lu, F.-X., 2001, Genesis and geological significance for the middle Jurassic high Sr and low Y type volcanic rocks in Fuxin area of West Liaoning, northeastern China: Acta Petrologica Sinica, v. 17, n. 4, p. 523–532 (in Chinese with English abstract).

Li, X.-H., 2000, Cretaceous magmatism and lithospheric extension in southeast China: Journal of Asian Earth Sciences, v. 18, p. 293–305, doi:10.1016/S1367-9120(99)00060-7.

Li, Z., Li, Y., Zheng, J.-P., and Han, D., 2007, Late Mesozoic tectonic inversion of the eastern North China Craton: evidence from basin-fill records, *in* Zhai, M., Windley, B. F., Kusky, T. M., and Meng, Q., editors, Mesozoic Sub-continental Lithospheric Thinning under Eastern Asia: Geological Society, London, Special Publications, v. 280, p. 239–265, doi:10.1144/SP280.12.

Liang, C., Song, X., and Huang, J., 2004, Tomographic inversion of *Pn* travel times in China: Journal of Geophysical Research, v. 109, B11304, 19 p., doi:10.1029/2003JB002789.

Lin, G., Zhang, Y., Guo, F., Wang, Y., and Fan, W., 2005, Numerical modelling of lithospheric evolution in the North China block: thermal versus tectonic thinning: Journal of Geodynamics, v. 40, p. 92–103, doi:10.1016/j.jog.2005.07.011.

Lin, T., Chung, S., Lo, C., Lan, C., Wang, P., Lee, T., Tran, T., and Hoang, H., 2007, Implications for the Indosinian orogeny and closure of eastern Paleo-Tethys: a perspective from the Song Ma suture: American Geophysical Union, Fall Meeting 2007, Abstract #V41D-0822.

Lin, W., Faure, M., Monié, P., Schärer, U., and Panis, D., 2008, Mesozoic extensional tectonics in eastern Asia: the South Liaodong Peninsula metamorphic core complex (NE China): Journal of Geology, v. 116, p. 134–154, doi:10.1086/527456.

Liu, G., 1987, The Cenozoic rift system of the North China plain and the deep internal process: Tectonophysics, v. 133, n. 3–4, p. 277–285, doi:10.1016/0040-1951(87)90270-8.

Liu, J. L., Ye, K., Maruyama, S., Cong, B., and Fan, H. R., 2001, Mineral inclusions in zircon from gneisses in the ultrahigh-pressure zone of the Dabie mountains, China: Journal of Geology, v. 109, p. 523–535, doi:10.1086/320796.

Liu, J. L., Davis, G. A., Lin, Z., and Wu, F., 2005, The Liaonan metamorphic core complex, southeastern Liaoning province, North China: A likely contributor to Cretaceous rotation of eastern Liaoning, Korea and contiguous areas: Tectonophysics, v. 407, n. 1–2, p. 65–80, doi:10.1016/j.tecto.2005.07.001.

Liu, J. Q., Han, J., and Fyfe, W. S., 2001, Cenozoic episodic volcanism and continental rifting in northeast China and possible link to Japan Sea development as revealed from K-Ar geochronology: Tectonophysics, v. 339, n. 3–4, p. 385–401, doi:10.1016/S0040-1951(01)00132-9.

Liu, M., Cui, X., and Liu, F., 2004, Cenozoic rifting and volcanism in eastern China: a mantle dynamic link to the Indo-Asian collision?: Tectonophysics, v. 393, n. 1–4, p. 29–42, doi:10.1016/j.tecto.2004.07.029.

Liu, S., Heller, P. L., and Zhang, G., 2003, Mesozoic basin development and tectonic evolution of the Dabieshan orogenic belt, central China: Tectonics, v. 22, 1038, 21 p., doi:10.1029/2002TC001390.

Liu, S., Steel, R., and Zhang, G., 2005, Mesozoic sedimentary basin development and tectonic implication, northern Yangtze block, eastern China: record of continent-collision: Journal of Asian Earth Sciences, v. 25, n. 1, p. 9–27, doi:10.1016/j.jseaes.2004.01.010.

Lysak, S. V., and Dorofeeva, R. P., 2005, Heat flow in Cenozoic rift in East China: Russian Geology and Geophysics, v. 46, n. 6, p. 667–680.

Ma, L., 2002, Geological Atlas of China [cartographic material], Compilation Committee of Geological Atlas of China; chief compiler, Ma, Lifang; chief translator, Liu, Nailong: Beijing, China, Geological Publishing House, 348 p.

Ma, X. Y., 1987, Lithospheric Dynamics Map of China and Adjacent Seas and Explanatory Notes: Beijing, China, Geological Publishing House, scale 1:4.000,000.

Maruyama, S., and Okamoto, K., 2007, Water transportation from the subducting slab into the mantle transition zone: Gondwana Research, v. 11, n. 1–2, p. 148–165, doi:10.1016/j.gr.2006.06.001.

Maruyama, S., Liou, J. G., and Windley, B. F., 2004, The Western Pacific Triangular Zone: frontier to form a future supercontinent and a window of seawater into the mantle: Singapore, Joint AOGS (Asia Oceanic Geoscience Society), 1st Annual Meeting, Abstract volume, p. 54.

Maruyama, S., Hasegawa, A., Santosh, M., Kogiso, T., Omori, S., Nakamura, H., Kawai, K., and Zhao, D., 2009, The dynamics of big mantle wedge, magma factory, and metamorphic-metasomatic factory in subduction zones: Gondwana Research, v. 16, n. 3–4, p. 414–430, doi:10.1016/j.gr.2009.07.002.

Meier, U., Trampert, J., and Curtis, A., 2009, Global variations of temperature and water content in the mantle transition zone from higher mode surface waves: Earth and Planetary Science Letters, v. 282, n. 1–4, p. 91–101, doi:10.1016/j.epsl.2009.03.004.

Meng, Q.-R., 2003, What drove late Mesozoic extension of the northern China-Mongolia tract?: Tectonophysics, v. 369, n. 3–4, p. 155–174, doi:10.1016/S0040-1951(03)00195-1.

Meng, Q.-R., and Zhang, G.-W., 2000, Geologic framework and tectonic evolution of the Qinling orogen, central China: Tectonophysics, v. 323, p. 183–196, doi:10.1016/S0040-1951(00)00106-2.

Meng, Q.-R., Hu, J.-M., Jin, J.-Q., Zhang, Y., and Xu, D.-F., 2003, Tectonics of the late Mesozoic wide extensional basin system in the China-Mongolia border region: Basin Research, v. 15, n. 3, p. 397–415, doi:10.1046/j.1365-2117.2003.00209.x.

Menzies, M., Fan, W., and Zhang, M., 1993, Paleozoic and Cenozoic lithoprobes and loss of >120 km of Archean lithosphere, Sino-Korean craton, China, *in* Prichard, H. M., Alabaster, T., Harris, N. B. W., and Neary, C. R., editors, Magmatic Processes and Plate Tectonics: Geological Society, London, Special Publications, v. 76, p. 71–81, doi:10.1144/GSL.SP.1993.076.01.0.

Menzies, M., Xu, Y., Zhang, H., and Fan, W., 2007, Integration of geology, geophysics, and geochemistry: a key to understanding the North China Craton: Lithos, v. 96, n. 1–2, p. 1–21, doi:10.1016/j.lithos.2006.09.008.

Metcalfe, I., 2002, Permian tectonic framework and palaeogeography of SE Asia: Journal of Asian Earth Sciences, v. 20, n. 6, p. 551–566, doi:10.1016/S1367-9120(02)00022-6.

Mierdel, K., Keppler, H., Smyth, J. R., and Langenhorst, F., 2007, Water solubility in aluminous orthopyroxene and the origin of Earth's asthenosphere: Science, v. 315, n. 5810, p. 364–368, doi:10.1126/science.1135422.

Milsom, J., 2001, Subduction in eastern Indonesia: how many slabs?: Tectonophysics, v. 338, n. 2, p. 167–178, doi:10.1016/S0040-1951(01)00137-8.

Nie, S., Yin, A., Rowley, D. B., and Jin, Y., 1994, Exhumation of the Dabie Shan ultrahigh-pressure rocks, and accumulation of the Songpan-Ganzi flysch sequence, central China: Geology, v. 22, n. 11, p. 999–1002, doi:10.1130/0091-7613(1994)022⟨0999:EOTDSU⟩2.3.CO;2.

Niu, Y., 2005, Generation and evolution of basaltic magmas: some basic concepts and a new view on the origin of Mesozoic-Cenozoic basaltic volcanism in eastern China: Geological Journal of China Universities, v. 11, p. 9–46.

Ohtani, E., Litasov, K., Hosoya, T., Kubo, T., and Kondo, T., 2004, Water transport into the deep mantle and formation of a hydrous transition zone: Physics of the Earth and Planetary Interiors, v. 143–144, p. 255–269, doi:10.1016/j.pepi.2003.09.015.

Okamura, S., Arculus, R. J., and Martynov, Y. A., 2005, Cenozoic magmatism of the northeastern Eurasian margin: the role of lithosphere versus asthenosphere: Journal of Petrology, v. 46, n. 2, p. 221–253, doi:10.1093/petrology/egh065.

Okay, A. I., and Şengör, A. M. C., 1992, Evidence for intracontinental thrust-related exhumation of the ultra-high-pressure rocks in China: Geology, v. 20, n. 5, p. 411–414, doi:10.1130/0091-7613(1992)020⟨0411:EFITRE⟩2.3.CO;2.

Omori, S., and Komabayashi, T., 2007, Subduction zone: the water channel to the mantle, *in* Yuen, D. A., Maruyama, S., Karato, S., and Windley, B. F. editors, Superplumes: Dordrecht, Springer, Beyond Plate Tectonics, p. 113–138.

O'Reilly, S. Y., Griffin, W. L., Poudjom Djomani, Y. H., and Morgan, P., 2001, Are lithospheres forever? Tracking changes in subcontinental lithospheric mantle through time: GSA Today, v. 11, p. 4–10.

O'Reilly, S. Y., Zhang, M., Griffin, W. L., Begg, G., and Hronsky, J., 2009, Ultradeep continental roots and their oceanic remnants: A solution to the geochemical "mantle reservoir" problem?: Lithos, v. 112, supplement 2, p. 1043–1054, doi:10.1016/j.lithos.2009.04.028.

Panero, W. R., Bemedetti, L. R., and Jeanloz, R., 2003, Transport of water into the lower mantle: role of stishovite: Journal of Geophysical Research, v. 108, 2039, 9 p., doi:10.1029/2002JB002053.

Peacock, S. M., 1993, Large-scale hydration of the lithosphere above subducting slabs: Chemical Geology, v. 108, n. 1–4, p. 49–59, doi:10.1016/0009-2541(93)90317-C.

—— 2003, Thermal structure and metamorphic evolution of subducting slabs, *in* Eiler, J., editor, Inside the Subduction Factory: American Geophysical Union Monograph, v. 138, p. 7–22.

Peng, Z. C., Zartman, R. E., Futa, K., and Chen, D. G., 1986, Pb-, Sr- and Nd-isotopic systematics and chemical characteristics of Cenozoic basalts, Eastern China: Chemical Geology, v. 59, n. 1, p. 3–33, doi:10.1016/0009-2541(86)90041-0.

Poudjom Djomani, Y. H., O'Reilly, S. Y., Griffin, W. L., and Morgan, P., 2001, The density structure of subcontinental lithosphere through time: Earth and Planetary Science Letters, v. 184, n. 3–4, p. 605–621, doi:10.1016/S0012-821X(00)00362-9.

Rauch, M., and Keppler, H., 2002, Water solubility in orthopyroxene: Contributions to Mineralogy and Petrology, v. 143, n. 5, p. 525–536, doi:10.1007/s00410-002-0365-6.

Regenauer-Lieb, K., and Kohl, T., 2003, Water solubility and diffusivity in olivine: its role in planetary tectonics: Mineralogical Magazine, v. 67, p. 697–715, doi:10.1180/0026461036740128.

Regenauer-Lieb, K, Yuen, D., and Branlund, J., 2001, The initiation of subduction: criticality by addition of water: Science, v. 294, n. 5542, p. 578–580, doi:10.1126/science.1063891.

Ren, J., Tamaki, K., Li, S., and Junxia, Z., 2002, Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas: Tectonophysics, v. 344, n. 3–4, p. 175–205, doi:10.1016/S0040-1951(01)00271-2.

Richard, G., Bercovici, D., and Karato, S., 2006, Slab dehydration in the Earth's mantle transition zone: Earth and Planetary Science Letters, v. 251, n. 1–2, p. 156–167, doi:10.1016/j.epsl.2006.09.006.

Ruzhentsev, S. V., 2001, The Indo-Sinides of Inner Mongolia, *in* Dergunov, A. B., editor, Tectonics, Magmatism, and Metallogeny of Mongolia: London, Routledge, p. 129–141.

Salah, M. K., and Zhao, D., 2003, Three-dimensional seismic structure of Kii Peninsula, Southwest Japan: evidence for slab dehydration in the forearc: Tectonophysics, v. 364, n. 3–4, p. 191–213, doi:10.1016/S0040-1951(03)00059-3.

Shieh, S. R., Mao, H., Hemley, R. J., and Ming, L. C., 1998, Decomposition of phase D in the lower mantle and the fate of dense hydrous silicates in subducting slabs: Earth and Planetary Science Letters, v. 159, n. 1–2, p. 13–23, doi:10.1016/S0012-821X(98)00062-4.

Shito, A., and Shibutani, T., 2003, Nature of heterogeneity of the upper mantle beneath the northern Philippine Sea as inferred from attenuation and velocity tomography: Physics of the Earth and Planetary Interiors, v. 140, n. 4, p. 331–341, doi:10.1016/j.pepi.2003.09.010.

Smyth, J. R., and Frost, D. J., 2002, The effect of water on the 410-km discontinuity: an experimental study: Geophysical Research Letters, v. 29, n. 10. 1485, 4 p., doi:10.1029/2001GL014418.

Smyth, J. R., Holl, C. M., Frost, D. J., Jacobsen, S. D., Langenhorst, F., and McCammon, C. A., 2003, Structural systematics of hydrous ringwoodite in Earth's interior: American Mineralogist, v. 88, n. 10, p. 1402–1407.

Song, T.-R. A., Helmberger, D. V., and Grand, S. P., 2004, Low-velocity zone atop the 410-km seismic discontinuity in the northwestern United States: Nature, v. 427, p. 530–533, doi:10.1038/nature02231.

Song, Y., Frey, F. A., and Zhi, X., 1990, Isotopic characteristics of Hannuoba basalts, eastern China: implications for their petrogenesis and the composition of subcontinental mantle: Chemical Geology, v. 88, n. 1–2, p. 35–52, doi:10.1016/0009-2541(90)90102-D.

Su, W., You, Z., Cong, B., Ye, K., and Zhong, Z., 2002, Cluster of water molecules in garnet from ultrahigh-pressure eclogite: Geology, v. 30, n. 7, p. 611–614, doi:10.1130/0091-7613(2002)030⟨0611:COWMIG⟩2.0.CO;2.

Tamaki, K., and Honza, E., 1991, Global tectonics and formation of marginal basins: role of the western Pacific: Episodes, v. 14, p. 224–230.

Tian, Y., Zhao, D., Sun, R., and Teng, J., 2009, Seismic imaging of the crust and upper mantle beneath the North China Craton: Physics of the Earth and Planetary Interiors, v. 172, n. 2–4, p. 169–182, doi:10.1016/j.pepi.2008.09.002.

Tomurtogoo, O., Windley, B. F., Kröner, A., Badarch, G., and Liu, D. Y., 2005, Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: constraints on the evolution of the Mongol-Okhotsk ocean, suture and orogen: Journal of the Geological Society, London, v. 162, n. 1, p. 125–134, doi:10.1144/0016-764903-146.

Tonegawa, T., Hirahara, K., Shibutani, T., Iwamori, H., Kanamori, H., and Shiomi, K., 2008, Water flow to the mantle transition zone inferred from a receiver function image of the Pacific slab: Earth and Planetary Science Letters, v. 274, n. 3–4, p. 346–354, doi:10.1016/j.epsl.2008.07.046.

Tubía, J. M., Cuevas, J., and Esteban, J. J., 2004, Tectonic evidence in the Ronda peridotites, Spain, for mantle diapirism related to delamination: Geology, v. 32, n. 11, p. 941–944, doi:10.1130/G20869.1.

Van der Voo, R., Spakman, W., and Bijwaard, H., 1999, Mesozoic subducted slabs under Siberia: Nature, v. 397, p. 246–249, doi:10.1038/16686.

Wang, C.-Y., Zeng, R.-S., Mooney, W. D., and Hacker, B. R., 2000, A crustal model of the ultrahigh-pressure Dabie Shan orogenic belt, China, derived from deep seismic refraction profiling: Journal of Geophysical Research, v. 105, B5, p. 10857–10869, doi:10.1029/1999JB900415.

Wang, Q., Wyman, D. A., Xu, J.-F., Zhao, Z.-H., Jian, P., Xiong, X.-L., Bao, Z.-W., Li, C.-F., and Bai, Z.-H., 2006, Petrogenesis of Cretaceous adakitic and shoshonitic igneous rocks in the Luzong area, Anhui province (eastern China): Implications for geodynamics and Cu-Au mineralization: Lithos, v. 89, n. 3–4, p. 424–446, doi:10.1016/j.lithos.2005.12.010.

Wang, Q., Li, R., Yonghong, S., Wei, L., and Jinghui, G., 2008, Exhumation of the Dabie Shan UHP terrane, China: International Geology Review, v. 50, n. 1, p. 15–31, doi:10.2747/0020-6814.50.1.15.

Wang, W., and Gasparik, T., 2001, Metasomatic clinopyroxene inclusions in diamonds from the Liaoning Province, China: Geochimica et Cosmochimica Acta, v. 65, n. 4, p. 611–620, doi:10.1016/S0016-7037(00)00553-6.

Wang, X., Liou, J. G., and Mao, H. K., 1989, Coesite-bearing eclogite from the Dabie Mountains in central China: Geology, v. 17, p. 1085–1088, doi:10.1130/0091-7613(1991)019⟨0933:RUPCBE⟩2.3.CO;2.

Wang, Y., Houseman, G. A., Lin, G., Guo, F., Wang, Y.-J., Fan, W.-M., and Chang, X., 2005, Mesozoic lithospheric deformation in the North China block: numerical simulation of evolution from orogenic belt to extensional basin: Tectonophysics, v. 405, n. 1–4, p. 47–63, doi:10.1016/j.tecto.2005.05.012.

Wiechert, U., Ionov, D. A., and Wedepohl, K. H., 1997, Spinel peridotite xenoliths from the Atsagin-Dush volcano, Dariganga lava plateau, Mongolia: a record of partial melting and cryptic metasomatism in the upper mantle: Contributions to Mineralogy and Petrology, v. 126, n. 4, p. 345–364, doi:10.1007/s004100050255.

Wilde, S. A., Zhou, X., Nemchin, A. A., and Sun, M., 2003, Mesozoic crust-mantle interaction beneath the North China Craton: A consequence of the dispersal of Gondwanaland and accretion of Asia: Geology, v. 31, n. 9, p. 817–820, doi:10.1130/G19489.1.

Windley, B. F., Maruyama, S., and Xiao, W., 2005, Multiple subduction of hydrated oceanic lithosphere as the cause of the removal of hydro-weakened subcontinental lithosphere under Eastern China, *in* The Origin, Evolution and Present State of Subcontinental Lithosphere: Beijing, China, IUGS-SECE (Commission on Solid Earth Composition and Evolution), Abstract volume, p. 31–33.

Wu, F.-Y., Lin, J.-Q., Wilde, S. A., Zhang, X., and Yang, J.-H., 2005, Nature and significance of the Early Cretaceous giant igneous event in eastern China: Earth and Planetary Science Letters, v. 233, n. 1–2, p. 103–119, doi:10.1016/j.epsl.2005.02.019.

Wu, Y., Fei, Y., Jin, Z., and Liu, X., 2009, The fate of subducted upper continental crust: an experimental study: Earth and Planetary Science Letters, v. 282, n. 1–4, p. 275–284, doi:10.1016/j.epsl.2009.03.028.

Xia, Q.-K., Yang, X.-Z., Deloule, E., Sheng, Y.-M., and Hao, Y.-T., 2006, Water in the lower crustal granulite xenoliths from Nushan, eastern China: Journal of Geophysical Research, v. 111, B11202, 9 p., doi:10.1029/2006JB004296.

Xiao, W., Windley, B. F., Hao, J., and Zhai, M., 2003, Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: termination of the Central Asian Orogenic belt: Tectonics, v. 22, 1069, 20 p., doi:10.1029/2002TC001484.

Xiao, W. J., Windley, B. F., Huang, B. C., Han, C. M., Yuan, C., Chen, H. L., Sun, M., Sun, S., and Li, J. L., 2009, End-Permian to mid-Triassic termination of the accretionary processes of the southern Altaids: implications for the geodynamic evolution, Phanerozoic continental growth, and metallogeny of Central Asia: International Journal of Earth Sciences, v. 98, n. 6, p. 1189–1217, doi:10.1007/s00531-008-0407-z.

Xu, J.-F., Shinjo, H., Defant, M. J., Wang, Q., and Rapp, R. P., 2002, Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: Partial melting of delaminated lower continental crust?: Geology, v. 30, n. 12, p. 1111–1114, doi:10.1130/0091-7613(2002)030⟨1111:OOMAIR⟩2.0.CO;2.

Xu, J., editor, 1993, The Tancheng-Lujiang Wrench Fault System: Chichester, Wiley, 279 p.

Xu, P., and Zhao, D., 2009, Upper-mantle velocity structure beneath the North China Craton: implications for lithospheric thinning: Geophysical Journal International, v. 177, p. 1279–1283, doi:10.1111/j.1365-246X.2009.04120.x.

Xu, S. H., Zhong, J. H., and Liu, Z. Q., 2007, Activity characteristics and controlling factors of the faults in the Hefei basin: Geotectonica et Metallogenia, v. 31, n. 1, p. 31–36 (in Chinese with English abstract).

Xu, W.-L., Wang, Q.-H., Wang, D.-Y., Guo, J.-H., and Pei, F.-P., 2006a, Mesozoic adakitic rocks form the Xuzhou-Suzhou area, eastern China: Evidence for partial melting of delaminated lower continental crust: Journal of Asian Earth Sciences, v. 27, n. 2, p. 230–240, doi:10.1016/j.jseaes.2005.03.005.

Xu, W., Gao, S., Wang, Q., Wang, D., and Liu, Y., 2006b, Mesozoic crustal thickening of the eastern North China Craton: Evidence from eclogitic xenoliths and petrologic implications: Geology, v. 34, n. 9, p. 721–724, doi:10.1130/G22551.1.

Xu, W., Hergt, J. M., Gao, S., Pei, F., Wang, W., and Yang, D., 2008, Interaction of adakitic melt-peridotite: Implications for the high-Mg# signature of Mesozoic adakitic rocks in the eastern North China Craton: Earth and Planetary Science Letters, v. 265, n, 1–2, p. 123–137, doi:10.1016/j.epsl.2007.09.041.

Xu, X. S., O'Reilly, S. Y., Griffin, W. L., Zhou, X. M., and Huang, X. L., 1998, The nature of the Cenozoic lithosphere at Nushan, eastern China, *in* Flower, M. F., Chung, S. L., and Li, T. Y., editors, Mantle Dynamics and Plate Interaction in East Asia: American Geophysical Union Monograph, v. 27, p. 167–195.

Xu, X., Griffin, W. L., O'Reilly, S. Y., Pearson, N. J., Geng, H., and Zheng, J., 2008, Re-Os isotopes of sulfides in mantle xenoliths from eastern China: Progressive modification of lithospheric mantle: Lithos, v. 102, n. 1–2, p. 43–64, doi:10.1016/j.lithos.2007.06.010.

Xu, Y.-G., 2001, Thermo-tectonic destruction of the Archean lithospheric keel beneath the Sino-Korean craton in China: evidence, timing and mechanism: Physics and Chemistry of the Earth, v. 26, n. 9–10, p. 747–757, doi:10.1016/S1464-1895(01)00124-7.

—— 2007, Diachronous lithospheric thinning of the North China Craton and formation of the Daxin'anling-Taihangshan gravity lineament: Lithos, v. 96, n. 1–2, p. 281–298, doi:10.1016/j.lithos.2006.09.013.

Xu, Y.-G., Chung, S.-L., Ma, J., and Shi, L., 2004a, Contrasting Cenozoic lithosphere evolution and architecture in the western and eastern Sino-Korean craton: Constraints from geochemistry of basalts and mantle xenoliths: Journal of Geology, v. 112, p. 593–605, doi:10.1086/422668.

Xu, Y. G., Huang, X.-L., Ma, J.-L., Wang, Y.-B., Iizuka, Y., Xu, J.-F., Wang, Q., and Wu, X.-Y., 2004b, Crust-mantle interaction during the tectono-thermal reactivation of the North China Craton: constraints from SHRIMP zircon U-Pb chronology and geochemistry of Mesozoic plutons from western Shandong: Contributions to Mineralogy and Petrology, v. 147, n. 6, p. 750–767, doi:10.1007/s00410-004-0594-y.

Xu, Y.-G., Ma, J.-L., Frey, F. A., Feigenson, M. D., and Liu, J.-F., 2005, Role of lithosphere-asthenosphere interaction in the genesis of Quaternary alkali and tholeiitic basalts from Datong, western North China Craton: Chemical Geology, v. 224, n. 4, p. 247–271, doi:10.1016/j.chemgeo.2005.08.004.

Xu, Y.-G., Blusztajn, J., Ma, J.-L., Suzuki, K., Liu, J.-F., and Hart, S. R., 2008, Late Archean to Early Proterozoic lithospheric mantle beneath the western North China Craton: Sr-Nd-Os isotopes of peridotite xenoliths from Yangyuan and Fansi: Lithos, v. 102, n. 1–2, p. 25–42, doi:10.1016/j.lithos.2007.04.005.

Xue, F., Rowley, D. B., and Baker, J., 1996, Refolded syn-ultrahigh-pressure thrust sheets in the South Dabie complex, China: Field evidence and tectonic implications: Geology, v. 24, n. 5, p. 455–458, doi:10.1130/0091-7613(1996)024<0455:RSUPTS>2.3.CO;2.

Yamamoto, S., Nakajima, J., Hasegawa, A., and Maruyama, S., 2009a, Izu-Bonin arc subduction under the Honshu island, Japan: evidence from geological and seismological aspects: Gondwana Research, v. 16, n. 3–4, p. 572–580, doi:10.1016/j.gr.2009.05.014.

Yamamoto, S., Senshu, H., Rino, S., Omori, S., and Maruyama, S., 2009b, Granite subduction: Arc subduction, tectonic erosion and sediment subduction: Gondwana Research, v. 15, p. 443–453, doi:10.1016/j.gr.2008.12.009.

Yan, D.-P., Zhou, M.-F., Song, H.-L., Wang, X.-W., and Malpas, J., 2003, Origin and tectonic significance of a Mesozoic multi-layer over-thrust system within the Yangtze block (South China): Tectonophysics, v. 361, n. 3–4, p. 239–254, doi:10.1016/S0040-1951(02)00646-7.

Yan, D.-P., Zhou, M.-F., Song, H.-L., Wang, G.-H., and Sun, M., 2006, Mesozoic extensional structures of the Fangshan tectonic dome and their subsequent reworking during collisional accretion of the North China block: Journal of the Geological Society, London, v. 163, n. 1, p. 127–142, doi:10.1144/0016-764904-154.

Yan, J., and Zhao, J.-X., 2008, Cenozoic alkali basalts from Jingpohu, NE China: The role of lithosphere-asthenosphere interaction: Journal of Asian Earth Sciences, v. 33, n. 1–2, p. 106–121, doi:10.1016/j.jseaes.2007.11.001.

Yang, F.-Q., Wu, H., Pirajno, F., Ma, B.-Y., Xia, H.-D., Deng, H.-J., Liu, X.-W., Xu, G., and Zhao, Y., 2007, The Jiashan syenite in northern Hebei: A record of lithospheric thinning in the Yanshan intracontinental orogenic belt: Journal of Asian Earth Sciences, v. 29, n. 5–6, p. 619–636, doi:10.1016/j.jseaes.2006.04.005.

Yang, J.-H., Wu, F.-Y., and Wilde, S. A., 2003, A review of the geodynamic setting of large-scale Late Mesozoic gold mineralization in the North China Craton: an association with lithospheric thinning: Ore Geology Reviews, v. 23, p. 125–152, doi:10.1016/S0169-1368(03)00033-7.

Yang, J.-H., Wu, F.-Y., Wilde, S. A., and Liu, X.-M., 2007a, Petrogenesis of Late Triassic granitoids and their enclaves with implications for post-collisional lithospheric thinning of the Liaodong Peninsula, North China Craton: Chemical Geology, v. 242, n. 1–2, p. 155–175, doi:10.1016/j.chemgeo.2007.03.007.

Yang, J.-H., Sun, J.-F., Chen, F.-K., Wilde, S. A., and Wu, F.-Y., 2007b, Sources and petrogenesis of Late Triassic dolerite dikes in the Liaodong peninsula: Implications for post-collisional lithosphere thinning of the Eastern North China Craton: Journal of Petrology, v. 48, n. 10, p. 1973–1997, doi:10.1093/petrology/egm046.

Yang, W., and Li, S., 2008, Geochronology and geochemistry of the Mesozoic volcanic rocks in western Liaoning: implications for lithospheric thinning of the North China Craton: Lithos, v. 102, n. 1–2, p. 88–117, doi:10.1016/j.lithos.2007.09.018.

Yang, X.-Z., Xia, Q.-K., Deloule, E., Dallai, L., Fan, Q.-C., and Feng, M., 2008, Water in minerals of the continental lithosphere mantle and overlying lower crust: A comparative study of peridotite and granulite xenoliths from the North China Craton: Chemical Geology, v. 256, n. 1–2, p. 33–45, doi:10.1016/j.chemgeo.2008.07.020.

Ye, K., Cong, B., and Ye, D., 2000, The possible subduction of continental material to depths greater than 200 km: Nature, v. 407, p. 734–736, doi:10.1038/35037566.

Yin, A., and Nie, S., 1996, A Phanerozoic palinspastic reconstruction of China and its neighboring regions, *in* Yin, A., and Harrison, T. M., editors, Tectonic Evolution of Asia: Cambridge, Cambridge University Press, p. 442–485.

Ying, J.-F., Zhang, H.-F., and Tang, Y.-J., 2010, Zoned olivine xenocrysts in a late Mesozoic gabbro from the southern Taihang Mountains: implications for old lithospheric mantle beneath the central North China Craton: Geological Magazine, v. 147, p. 161–170, doi:10.1017/S0016756809990379.

Yuan, H., Gao, S., Rudnick, R. L., Jin, Z., Liu, Y., Puchtel, I. S., Walker, R. J., and Yu, R., 2007, Re-Os evidence for the age and origin of peridotites from the Dabie-Sulu ultramafic pressure metamorphic belt, China: Chemical Geology, v. 236, n. 3–4, p. 323–338, doi:10.1016/j.chemgeo.2006.10.009.

Yuan, X.-C., 1996a, Atlas of Geophysics in China: Beijing, China, Geological Publishing House, B217 p.

—— 1996b, Velocity structure of the Qinling lithosphere and mushroom cloud model: Science in China, Series D: Earth Sciences, v. 39, p. 235–244.

Yuan, X.-C., Klemperer, S. L., Teng, W.-B., Liu, L.-X., and Chetwin, E., 2003, Crustal structure and exhumation of the Dabie Shan ultrahigh-pressure orogen, eastern China, from seismic reflection profiling: Geology, v. 31, n. 5, p. 435–438, doi:10.1130/0091-7613(2003)031<0435:CSAEOT>2.0.CO;2.

Zhai, M., Yang, J., Fan, H., Miao, L., and Li, Y., 2002, A large-scale cluster of gold deposits and metallogenesis in the eastern North China Craton: International Geology Review, v. 44, p. 458–476, doi:10.2747/0020-6814.44.5.458.

Zhai, M., Zhu, R., Liu, J., Meng, Q., Hou, Q., Hu, S., Liu, W., Li, Z., Zhang, H., and Zhang, H., 2003, Time range of Mesozoic tectonic regime inversion in eastern North China block: Science in China Series D: Earth Sciences, v. 47, n. 2, p. 151–159, doi:10.1360/02yd0416.

Zhai, M., Fan, Q., Zhang, H., Sui, J., and Shao, J., 2007, Lower crustal processes leading to Mesozoic lithospheric thinning beneath eastern North China: underplating, replacement and delamination: Lithos, v. 96, n. 1–2, p. 36–54, doi:10.1016/j.lithos.2006.09.016.

Zhang, H.-F., 2007, Temporal and spatial distribution of Mesozoic mafic magmatism on the North China Craton and implications for secular lithospheric evolution, *in* Zhai, M., Windley, B. F., Kusky, T. M., and Meng, Q., editors, Mesozoic Sub-continental Lithospheric Thinning under Eastern Asia: Geological Society, London, Special Publications, v. 280, p. 35–54, doi:10.1144/SP280.2.

Zhang, H.-F., and Sun, M., 2002, Geochemistry of Mesozoic basalts and mafic dikes, southeastern North China Craton, and tectonic implications: International Geology Review, v. 44, n. 4, p. 1–13, doi:10.2747/0020-6814.44.4.370.

Zhang, H.-F., Sun, M., Zhou, X.-H., Fan, W.-M., Zhai, M.-G., and Ying, J.-F., 2002, Mesozoic lithosphere destruction beneath the North China Craton: evidence from major-, trace-elements and Sr-Nd-Pb isotope studies of Fangcheng basalts: Contributions to Mineralogy and Petrology, v. 144, n. 2, p. 241–253, doi:10.1007/s00410-002-0395-0.

Zhang, H.-F., Sun, M., Zhou, X.-H., Zhou, M.-F., Fan, W.-M., and Zheng, J.-P., 2003, Secular evolution of the lithosphere beneath the eastern North China Craton: evidence from Mesozoic basalts and high-Mg andesites: Geochimica et Cosmochimica Acta, v. 67, n. 22, p. 4373–4387, doi:10.1016/S0016-7037(03)00377-6.

Zhang, J., Jin, Z., Green, H. W., and Jin, S., 2001a, Hydroxyl in continental deep subduction zone: evidence from UHP eclogites of the Dabie mountains: Chinese Science Bulletin, v. 46, n. 7, p. 592–596, doi:10.1007/BF02900418.

Zhang, J. F., Green, H. W., Jin, Z. S, and Bozhilov, K., 2001b, Rheological implications of dissolution of hydroxyl in eclogite: American Geophysical Union, Fall meeting, Abstract T21C-10.

Zhang, J., Jin, Z., and Green, H. W., 2005, Hydroxyl-induced eclogite fabric and deformation mechanism: Chinese Science Bulletin, v. 50, n. 7, p. 685–690, doi:10.1360/982004-274.

Zhang, J.-H., Ge, W.-C., Wu, F.-Y., Wilde, S. A., Yang, J.-H., and Liu, X.-M., 2008, Large-scale Early Cretaceous volcanic events in the northern Great Xing'an Range, northeastern China: Lithos, v. 102, n. 1–2, p. 138–157, doi:10.1016/j.lithos.2007.08.011.

Zhang, M., Suddaby, P., O'Reilly, S. Y., Norman, M., and Qiu, J. X., 2000, Nature of the lithospheric mantle beneath the eastern part of the Central Asian fold belt: mantle xenolith evidence: Tectonophysics, v. 328, n. 1–2, p. 131–156, doi:10.1016/S0040-1951(00)00181-5.

Zhang, Q., Qian, Q., Wang, E., Wang, Y., Zhao, T., Hao, J., and Guo, G., 2001, An East China plateau in mid-late Yanshan period: implications from adakites: Chinese Journal of Geology, v. 36, p. 248–255.

Zhang, Y., Ma, Y., Yang, N., Shi, W., and Dong, S., 2003, Cenozoic extensional stress evolution in North China: Journal of Geodynamics, v. 36, n. 5, p. 591–613, doi:10.1016/j.jog.2003.08.001.

Zhao, D. P., 2004, Global tomographic images of mantle plumes and subducting slabs: insights into deep Earth dynamics: Physics of the Earth and Planetary Interiors, v. 146, n. 1–2, p. 3–34, doi:10.1016/j.pepi.2003.07.032.

Zhao, D., Tian, Y., Lei, J., Liu, L., and Zheng, S., 2009, Seismic image and origin of the Changbai intraplate volcano in East Asia: role of big mantle wedge above the stagnant Pacific slab: Physics of the Earth and Planetary Interiors, v. 173, n. 3–4, p. 197–206, doi:10.1016/j.pepi.2008.11.009.

Zhao, G., 2001, Palaeoproterozoic assembly of the North China Craton: Geological Magazine, v. 138, p. 87–91, doi:10.1017/S0016756801005040.

Zhao, G., Cawood, P. A., Wilde, S. A., Sun, M., and Lu, L., 2000, Metamorphism of basement rocks in the central zone of the North China Craton: implications for Paleoproterozoic tectonic evolution: Precambrian Research, v. 103, n. 1–2, p. 55–88, doi:10.1016/S0301-9268(00)00076-0.

Zhao, L., and Zheng, T., 2005, Using shear wave splitting measurements to investigate the upper mantle anisotropy beneath the North China Craton: distinct variation from east to west: Geophysical Research Letters, v. 32, L10309, 4 p.,doi:10.1029/2005GL022585.

Zhao, Z.-F., Zheng, Y.-F., Gao, T.-S., Wu, Y.-B., Chen, F.-K., and Wu, F.-Y., 2006, Isotopic constraints on age and duration of fluid-assisted high-pressure eclogite-facies recrystallization during exhumation of deeply subducted continental crust in the Sulu orogen: Journal of Metamorphic Geology, v. 24, n. 8, p. 687–702, doi:10.1111/j.1525-1314.2006.00662.x.

Zheng, J., O'Reilly, S. Y., Griffin, W. L., Lu, F., and Zhang, M., 1998, Nature and evolution of Cenozoic lithospheric mantle beneath Shandong peninsula, Sino-Korean craton: International Geology Review, v. 40, n. 6, p. 471–499, doi:10.1080/00206819809465220.

Zheng, J., O'Reilly, S. Y., Griffin, W. L., Lu, F., Zhang, M., and Pearson, N. J., 2001, Relic refractory mantle beneath the eastern North China blocks: significance for lithosphere evolution: Lithos, v. 57, n. 1, p. 43–66, doi:10.1016/S0024-4937(00)00073-6.

Zheng, J., Griffin, W. L., O'Reilly, S. Y., Lu, F., Yu, C., Zhang, M., and Li, H., 2004, U-Pb and Hf-isotope analysis of zircons in mafic xenoliths from Fuxian kimberlites: evolution of the lower crust beneath the North China Craton: Contributions to Mineralogy and Petrology, v. 148, n. 1, p. 79–103, doi:10.1007/s00410-004-0587-x.

Zheng, J., Griffin, W. L., O'Reilly, S. Y., Liou, J. G., Zhang, R. Y., and Lu, F., 2005, Late Mesozoic-Eocene mantle replacement beneath the eastern North China Craton: evidence from the Paleozoic and Cenozoic peridotite xenoliths: International Geology Review, v. 47, n. 5, p. 457–472, doi:10.2747/0020-6814.47.5.457.

Zheng, J., Griffin, W. L., O'Reilly, S. Y., Zhang, M., and Pearson, N., 2006a, Zircons in mantle xenoliths record the Triassic Yangtze–North China continental collision: Earth and Planetary Science Letters, v. 247, n. 1–2, p. 130–142, doi:10.1016/j.epsl.2006.05.011.

Zheng, J., Griffin, W., O'Reilly, S., Zhang, M., Pearson, N., and Luo, Z., 2006b, The lithospheric mantle beneath the southwestern Tianshan area, northwest China: Contributions to Mineralogy and Petrology, v. 151, n. 4, p. 457–479, doi:10.1007/s00410-006-0071-x.

Zheng, Y. D., and Wang, T., 2005, Kinematics and dynamics of the Mesozoic orogeny and late-orogenic extensional collapse in the Sino-Mongolian border areas: Science in China, Series D: Earth Sciences, v. 48, n. 7, p. 849–862.

Zorin, Yu. A., 1999, Geodynamics of the western part of the Mongolia-Okhotsk collisional belt, Trans-Baikal (Russia) and Mongolia: Tectonophysics, v. 306, n. 1, p. 33–56, doi:10.1016/S0040-1951(99)00042-6.