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# The golden transformation of the Cretaceous plate subduction in the west Pacific

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## Abstract

Long-term couplings between the subducting and overlying plates are very important to understanding plate tectonics, in particular intraplate evolutions. Geological records of this coupling however, are usually not well preserved. Here we show a good example in eastern China where Cretaceous tectonic evolution matches remarkably well with the drifting history of the Pacific plate. The most pronounced phenomenon is that the eastern China large-scale orogenic lode gold (Au) mineralization occurred contemporaneously with an abrupt change of ~80° in the drifting direction of the subducting Pacific plate, concurrent with the formation of the Ontong Java Plateau. Given that lode Au deposits usually form at the onset of compressional or transpressional deformations, the Au deposits dated the major tectonic change from extension to transpression in eastern China, coherent with the subduction regime. The Cretaceous drifting history of the Pacific plate also tallies with other major geological events in eastern China, e.g., the evolution of the Tan-Lu fault and magmatic activities, suggesting that the major geological events in eastern China in the Cretaceous were mainly controlled by the subduction of the Pacific plate, and that plate interactions during subduction are important driving forces for geological evolution in eastern China and intraplate tectonics in general.

*Keywords:* Pacific plate; subduction; eastern China; Tan-Lu fault; plate interaction; Cretaceous; gold deposits

## 1. Introduction

Plate interaction along subduction zones usually cause deformations of overlying crusts as shown in the Andes (Sobolev and Babeyko, 2005), which is perhaps one of the most important driving forces for intraplate tectonic events. Therefore, it is crucial for understanding intraplate tectonic evolution. Studies on this interaction however, are limited by the lack of complementary geological records: one partner of this coupling-pair, the oceanic plate, generally vanishes during subduction, such that consequent geological records are usually not preserved. From this point of view, the long-term correspondence between the well-preserved drifting history of the Pacific plate since the Cretaceous and

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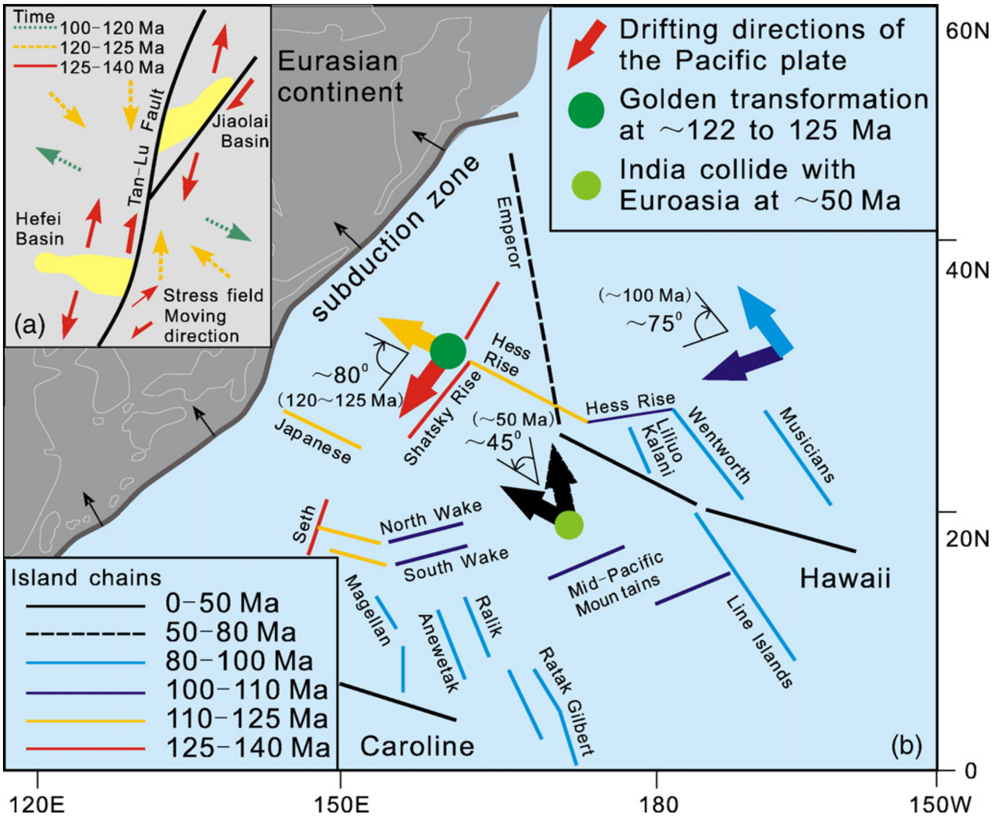

Fig. 1. Sketched maps for (a) eastern China showing the evolution of stress field along the Tan-Lu Fault (modified after refs Zhang et al., 2003c; Huang et al., 2005), (b) the drifting history of the Pacific plate since Cretaceous (modified after Koppers et al., 2001). Several basins were formed on both sides of the Tan-Lu Fault during the north–southward extension before the middle Early Cretaceous (~ 125 Ma), e.g., Hefei, Jiaolai and Luzong Basins (Wang et al., 2006). The extension was replaced by north–southward and then southeast–northwestward transpressions, which affected both Laiyang Group and Qinshan volcanic rocks, and lasted for several million years (Zhang et al., 2003c). The drifting direction of the Pacific plate has changed several times since 140 Ma (Koppers et al., 2001; Sharp and Clague, 2006). The first major event occurred at ~ 125–122 Ma, when the drifting direction changed by ~ 80° from roughly southward to northwestward.

the geological events in eastern China provides a valuable example to assess the effect of subducting plates on the evolution of the overlying continental crust. It also provides new insight into the tectonic evolution of the eastern Eurasian continent, e.g., the evolution of the Tan-Lu Fault, the mechanism behind lithosphere thinning and the Cretaceous giant igneous event (GIE) in eastern China.

## 2. Eastern China and Pacific subduction

Eastern China became an active continental margin before Jurassic (Zhou and Li, 2000; Li and Li, 2007). From Late Jurassic to Cretaceous, it was proposed that this margin was related to the subduction of the Pacific plate (Xu et al., 1987; Zhou and Li, 2000; Zhu et al., 2005; Zhou et al., 2006) in the south, concurrent with oblique subduction of the Izanagi plate in the north (Maruyama et al., 1997). Eastern China is well known for the removal of subcontinental lithosphere mantle and the Cretaceous GIE (Griffin et al., 1998; Xu, 2001; Gao et al., 2004; Wu et al., 2005a), which have been interpreted by different models, ranging from extension (Xu et al., 1987; Li, 2000) and subduction-related transpression (Xu et al., 1987; Zhou and Li, 2000; Zhou et al., 2006) to thermal erosion (Xu, 2001) and crustal delamination/foundering (Gao et al., 2004; Wu et al., 2005a), etc.

Detailed studies show that the stress field along the Tan-Lu Fault, the largest fault cutting across the northeastern Eurasian continent, experienced several major changes in the Cretaceous (Zhang et al., 2003c). In the Early Cretaceous (from ~140 to ~125–122 Ma), eastern China was dominated by roughly north–

southward extension and rifting, with a series of basins developed during this period in eastern China (Fig. 1). Some of these extensional basins are well known volcanic basins with abundant volcanic and intrusive rocks (Chen et al., 2001; Xie et al., 2003; Guo et al., 2005; Wang et al., 2006), and corresponding ore deposits (Pan and Dong, 1999; Mao et al., 2006) (Fig. 2). For example, magmatisms in Cretaceous basins (e.g., Lu-Zong, Ning-Zhen) in the lower Yangtze region started at ∼140 Ma (Chen et al., 1991; Wang et al., 2006), with abundant Cu, as well as Ag, Au, Pb, Zn, Mo mineralizations (Pan and Dong, 1999; Zhou et al., 2000; Sun et al., 2003; Wang et al., 2004; Mao et al., 2006). Volcanic rocks in these basins ceased at ∼125 Ma (Wang et al., 2006; Wang et al., 2007) (Fig. 3). In the north China Craton, Early Cretaceous magmatism associated with extension environment, the so called GIE, is systematically younger, with a peak at 125 Ma (Wu et al., 2005a) (Fig. 3). In the late Early Cretaceous (from ∼125–122 Ma to ∼110 Ma), the extension was replaced by southeast–northwestward transpression (Zhang et al., 2003c), and magmatism in east China generally ceased during this period (Li, 2000). Interestingly, the cessation of magmatism is more complete in the lower Yangtze region (Fig. 3). Several million years later, the stress field in eastern China switched to roughly east–westward pull-apart (Zhang et al., 2003c; Wang et al., 2005) (Fig. 1), and extension-related magmatism resumed (Li, 2000).

Remarkably, the major changes of the Pacific plate in the Early Cretaceous coupled surprisingly well with geological events, the adjustment of the stress field and magmatisms in eastern China (Fig. 1). The drifting direction of the subducting Pacific plate changed several times as shown by tracks of ocean island chains (Wessel and Kroenke, 1997; Koppers et al., 2001; Koppers et al., 2003). It first moved roughly towards south (from ∼140 to ∼125–122 Ma), as shown by the Shatsky Rise and Typhoon island chains, which matches the southward extension and rifting in eastern China (Koppers et al., 2001; Koppers et al., 2003). Suddenly, it turned by ∼80°, drifting northwestward at ∼125–122 Ma as indicated by Hess Rise and Japanese island chains (Koppers et al., 2001; Koppers et al., 2003). This is consistent with changes in the stress field in eastern China from extension to transpression (Fig. 1). Later on (from ∼110 to ∼100 Ma), the subduction direction changed to the southwest as indicated by the Hess Rise, which bends by ∼30° (Fig. 1). Another major change occurred at ∼100 Ma, the drifting direction of the Pacific plate changed by ∼75°, forming island chains of Wentworth, Musicians, etc (Fig. 1) (Koppers et al., 2001; Koppers et al., 2003). After the collision between Indian

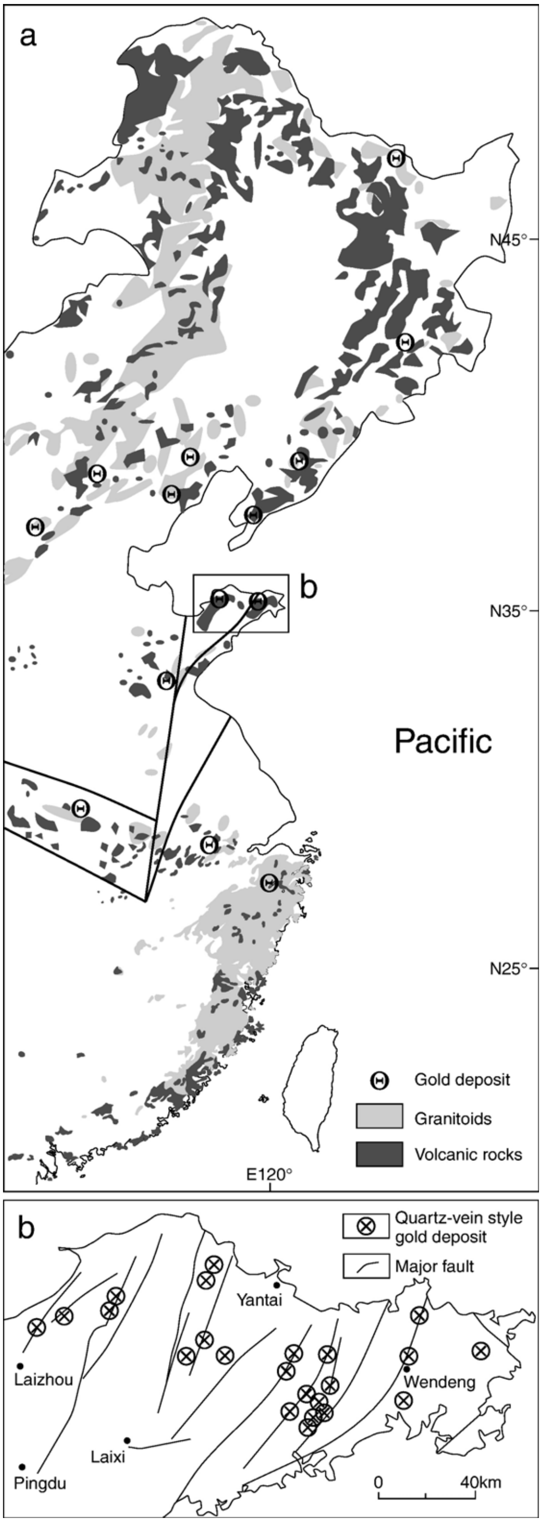

Fig. 2. (a) Distribution of Cretaceous magmatisms and gold mineralization in eastern China (Modified after Zhou and Li, 2000; Meng, 2003; Wu et al., 2005b). (b) Distribution of lode gold ore deposits in eastern Shandong (modified after Yang et al., 2003; Mao et al., 2005).

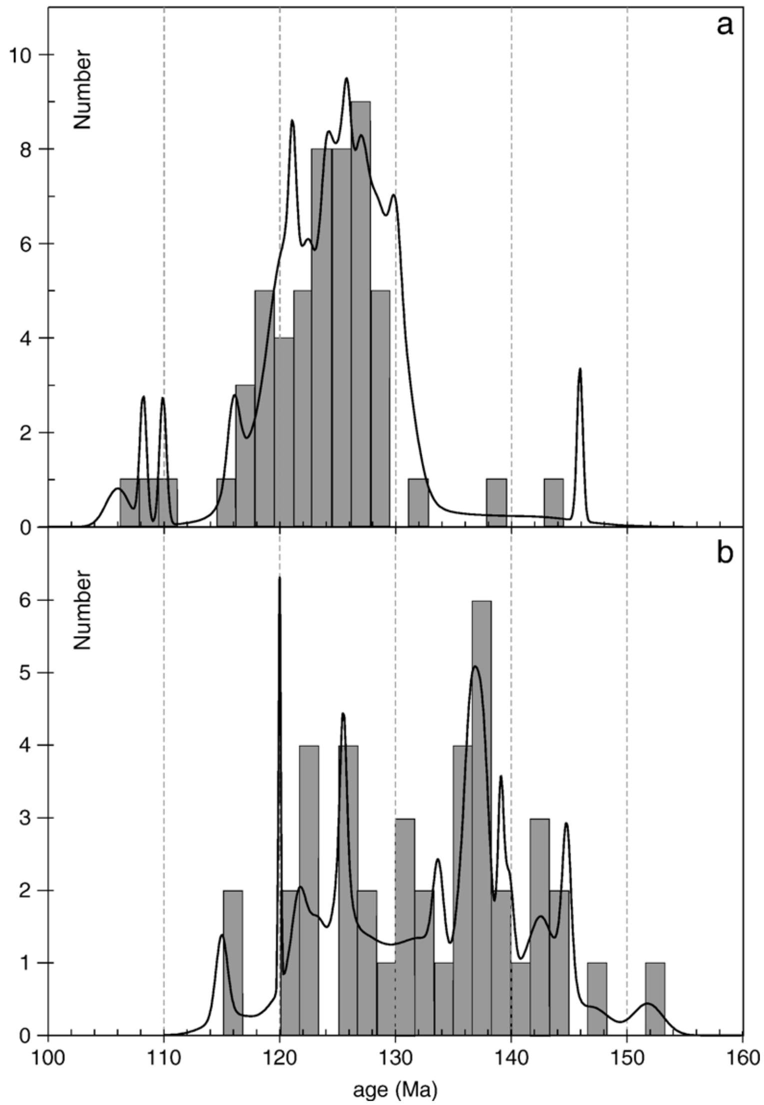

Fig. 3. Recent high precision dating results for the Cretaceous giant igneous event in eastern China. (a) east part of the North China Craton; (b), Lower Yangtze region. Only high precision SHRIMP and LA–ICP–MS zircon U–Pb ages, TIMS zircon U–Pb ages and $^{40}$Ar/$^{39}$Ar ages are included. Major data sources: (Li, 2000; Miao et al., 2002; Li et al., 2003; Guo et al., 2004; Liu et al., 2005; Mao et al., 2005; Wu et al., 2005a). The precisions are generally better than 1% (2$\sigma$) for most $^{40}$Ar–$^{39}$Ar ages, whereas those for SHRIMP dating are better than 2% (2$\sigma$).

and Eurasian continents (Beck et al., 1995), the drifting of the Pacific plate changed to the present day direction (~50 Ma) (Sharp and Clague, 2006) (Fig. 1).

## 3. The golden transformation

The first and most significant transformation in the drifting direction of the Pacific plate in the Cretaceous occurred between ~120 (Koppers et al., 2003) to ~125 Ma (Wessel and Kroenke, 1997; Koppers et al., 2001), when it changed by ~80° from roughly southward to northwestward (Fig. 1). The uncertainty of the transformation ages (5 Ma) is partly because the widths of ocean island volcano chains are usually more than 100 km, such that it takes more than 2 Ma for the drifting plate to move out of the old track and form an obvious new track at a moderate drifting rate of 5 cm/yr. Therefore, the real turning time of the Pacific plate is probably close to the upper end of the reported ages (i.e. 122–125 Ma). This is exactly the time when the stress field in eastern China changed from extension to transpression (Fig. 1) as well as corresponding geological events, e.g., extension-related magmatisms as well as the Cretaceous GIE in the North China Craton ceased

(~122 Ma) (Li, 2000), large scale lode gold mineralizations in eastern China occurred (125–120 Ma) (Li et al., 2005; Yang and Zhou, 2001).

Lode gold mineralization in eastern China is widely distributed in the Triassic Qinling–Dabie–Sulu and the Permian Inner Mongolia–Daxinganling (Ren et al., 1987) orogenic belts, surrounding the Precambrian basement of the North China Craton (Zhai et al., 2002; Zhang et al., 2003a,b; Yang et al., 2003; Chen et al., 2005). The lode Au ore bodies are structurally controlled by sets of regionally consistently oriented faults that cut through the Precambrian basement, as well as Late Jurassic to Early Cretaceous (165–125 Ma) granitoid intrusions (Wang et al., 1998; Yang et al., 2003). Although a number of models have been proposed for the eastern China Cretaceous gold mineralization (Yang et al., 2003), these ore deposits are generally regarded as typical orogenic lode Au deposits (Wang et al., 1998; Groves et al., 1998; Goldfarb et al., 2001). Given this and that all the deposits have similar hosting structures and deposit characteristics, they have been considered as "essentially a single event" (Wang et al., 1998). Based on the ages of the youngest granitoid intrusions, it has been proposed that these lode Au ore deposits formed between 120–125 Ma (Wang et al., 1998; Qiu et al., 2002), which is consistent with direct dating on the lode minerals (Yang and Zhou, 2001).

Mesothermal lode Au deposits are usually formed during compressional or transpressional deformations, and are typically associated with low displacement faults and shear zones that are controlled by, and clustered adjacent to, large strike-slip structures (Goldfarb et al., 2001; Cox and Ruming, 2004; Micklethwaite and Cox, 2004). Studies show that such ore mineralization usually occurs within a very short period of time after the faults are created, called "golden aftershocks" (Cox and Ruming, 2004), because fluid fluxes are usually localised in the hosting faults and shear zones that are actively deforming and thus more permeable. Therefore, the age of the ore hosting transpressional faults in eastern China should essentially be the same as that of the ore deposits, concurrent with the onset of the major transformation in the subduction direction of the Pacific plates.

A plausible interpretation is that when the subduction direction of the Pacific plate changed by ~80° at ~125–122 Ma, the regional tectonic stress fields changed from extensional to transpressional in eastern China, subsequently forming transpressional faults (Fig. 1) and releasing ore forming fluids.

The source of the ore forming fluids is still not clear. Given subduction related environments are usually more oxidizing (Brandon and Draper, 1996; Parkinson and Arculus, 1999; Parkinson et al., 2003; Sun et al., 2007), whereas high oxygen fugacity (Mungall, 2002; Wyborn and Sun, 1994; Sillitoe, 1997; Sun et al., 2004) and high degree evolution of magmas are favourable conditions for Au and Cu ore deposits (Sun et al., 2004), the ore forming fluids probably have been formed during plate subduction.

It has been proposed that the subduction of the Pacific Plate may have played an essential role (Goldfarb et al., 2001). The large scale lode Au deposits in eastern China however, distribute mainly along Triassic Qinling–Dabie–Sulu and the Permian Inner Mongolia–Daxinganling orogenic belts, but does not match the subduction boundary of the Pacific Plate. Therefore, the most likely candidate for ore forming fluids is collisions and precursive subductions along the Qinling–Dabie–Sulu orogenic belt (Li et al., 1993; Sun et al., 2002a,b; Zheng et al., 2003; Zhai and Liu, 2005; Xiao et al., 2006) and the Permian Inner Mongolia–Daxing'anling (Xiao et al., 2003; Zhang et al., 2007).

The first major transformation of Pacific drifting was also roughly coincident with the Cretaceous GIE in eastern China (Fig. 2) (Li, 2000; Miao et al., 2002; Guo et al., 2004; Liu et al., 2005; Mao et al., 2005; Wu et al., 2005a), which was taken to speculate a close relationship between subduction of the Paleo-Pacific plate and major geological events in eastern China (Wu et al., 2005a). GIE represents the Early Cretaceous magmatic event in the northeast part of the North China Craton and northeastern China, with an average age of ~125 Ma (Wu et al., 2005a). The formation of the GIE is not yet well constrained. Nevertheless, the occurrence of A-type granite, dolerite dyke swarms and metamorphic core complexes indicate that these rocks were all emplaced in an extensional setting (Wu et al., 2005a). Therefore, although the average age of GIE is close to the age of "golden transformation", it predates the latter.

Interestingly, the stress field in eastern China was first changed from extension to north–southward transpression at ~125 Ma, which then changed to southeast–northwestward transpression shortly after (Fig. 1) (Zhang et al., 2003c; Zhang et al., 2005; Zhang et al., 2006). These facts imply that the original force that changed the drifting direction of the Pacific was probably from the south. The interaction between the Pacific plate and the Eurasian continent finally resulted in northwestward drifting/subduction of the Pacific plate (Fig. 1). This is an important clue for understanding the driving force behind drifting transition of the Pacific plate.

Abrupt and significant change in the subduction direction of the Pacific plate required huge energy,

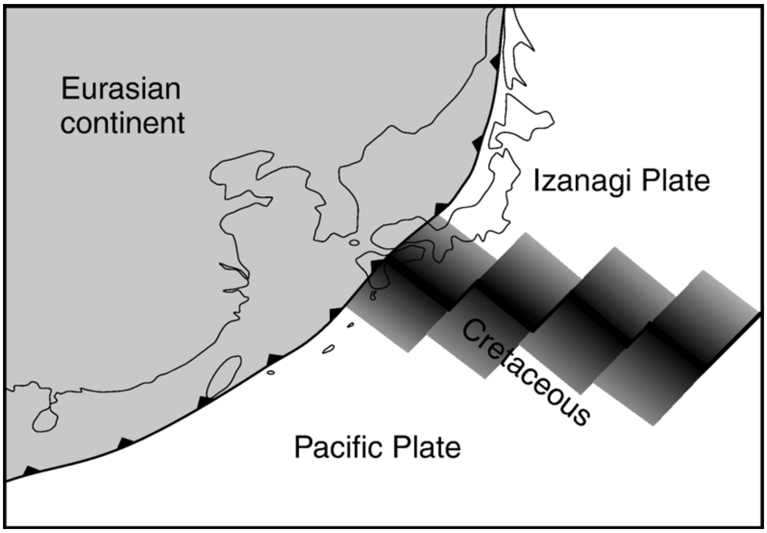

Fig. 4. The location of Pacific and Izanagi plates relative to eastern China at ~ 125 Ma, modified from (Maruyama et al., 1997). The mid-ocean ridge between these two plates at ~ 125 Ma is shifted northward by ~ 1000 km compared to previously proposed, based on the relationships between geological events in eastern China and the drifting histories of Pacific and Izanagi plates.

which presumably should have left other "marks" on the Earth. Among all Early Cretaceous events, the large igneous provinces, Ontong Java and Kerguelen Plateaus, are the most likely candidates that could have changed the subduction direction of the Pacific plate. The major eruption of Ontong Java occurred at about 122 to 125 Ma (Larson, 1997; Phinney et al., 1999), which matches very well with the major transformation of the subduction direction of the Pacific plate, whereas the eruption of Kerguelen large igneous province started at ~130 Ma, with enhanced eruption rates at ~120 Ma (Coffin et al., 2002).

The most straightforward model is that the plume heads of Ontong Java and Kerguelen have considerably elevated the south Pacific plate and changed its drifting direction and consequently changed the tectonic regime of eastern China.

## 4. Discussion

### 4.1. Correspondence between the drifting directions of the Pacific plate and geological events in eastern China

All major changes in the drifting direction of the Pacific plate in the Cretaceous mechanically match the tectonic evolution and magmatism in eastern China. The Pacific plate moved roughly towards south before ~125–122 Ma, with drifting direction nearly parallel to the east boundary of the Eurasian continent (with an angle of ~10°) (Fig. 1). Paleomagnetic results indicate that the cores of the South (Zhu et al., 2006) and North China blocks (Gilder and Courtillot, 1997) were fairly stable during the Cretaceous, such that the Pacific plate drifted southward relative to the South and North China blocks. In addition, there was no big continent to the south of eastern China, leaving it with a free boundary in the south, the subduction of the Pacific plate produced shearing force within the overlying continent, which can plausibly explain the roughly south–northward extension and rifting in the early to middle Early Cretaceous (Fig. 1), clockwise rotations in the east margin of the North China Block (Liu et al., 2005), extension-related magmas (> 122 Ma) (Chen et al., 1991; Li, 2000; Chen et al., 2001; Wu et al., 2005a; Wang et al., 2006), and corresponding ore genesis (Pan and Dong, 1999; Zhou et al., 2000; Sun et al., 2003; Wang et al., 2004; Mao et al., 2006).

The subduction direction changed by ~80° at ~125–122 Ma and persisted till ~110 Ma (Fig. 1). Because the drifting direction is roughly perpendicular to the east boundary of eastern China continent, and there was a big continental block to the north and west of eastern China (the Eurasian continent), this big conversion corresponds very well to the transformation from extension to transpression in eastern China as suggested by the formation of Au lode ore deposits (Wang et al., 1998; Yang and Zhou, 2001) and sinistral slip along the Tan-Lu fault zone (Zhang et al., 2003c) and the cessation of extension-related magmas during this period (Li, 2000).

The transpression only lasted for several million years before east–westward extension started, as represented by the opening of pull-apart basins, likely indicating the start of backarc extension (Fig. 1). From ~110 to ~100 Ma, the subduction direction changed by ~30° (Fig. 1), which somehow did not significantly change the stress field in eastern China, with backarc extension lasting till ~100 Ma. The reactivation of extension-related magmatism during ~109 to 101 Ma (Li, 2000) was probably due to the backarc extension.

At ~100 Ma, the subduction direction changed again by ~75° (Fig. 1). Correspondingly, magmatic activities dramatically declined (Li, 2000). The last big transformation occurred at ~50 Ma, likely due to the collision between Indian sub-continent and Eurasian continent. This transformation had considerably less effects on eastern China, probably due to the opening of Japan Sea and other back-arc basins in the western Pacific (Taira, 2001).

There were two oceanic plates to the east of the Eurasian continent, the Pacific and the Izanagi plates (Maruyama et al., 1997). It has been proposed that the Pacific plate started to subduct underneath Eurasia as early as Jurassic (Xu et al., 1987; Zhou and Li, 2000; Zhu et al., 2005; Zhou et al., 2006; Li and Li, 2007). Izanagi located to the north of the Pacific plate, which also was obliquely subducting (northwestward) underneath the Eurasia continent (Maruyama et al., 1997). In contrast to the close association between the Pacific plate and eastern China, the Izanagi plate drifted northwestward, without major changes in drifting direction that were mechanically correspondent to major geological events in eastern China. Therefore, the mid-ocean ridge between these two plates was probably located to the north of the North China Craton at ~125–122 Ma (Fig. 4), which is ~1000 km further north than previously proposed (Maruyama et al., 1997).

### *4.2. Lithospheric destruction, Cretaceous large igneous event and Pacific subduction*

Eastern China is well known for its removal of the lithospheric mantle (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Wu et al., 2003; Gao et al., 2004). Diamond inclusions, xenoliths and minerals in kimberlites indicate a thick (> 180 km), cold and refractory lithospheric keel beneath eastern China until the Palaeozoic. By contrast, xenoliths hosted in young basalts suggest the presence of thin (< 80 km), hot and fertile lithosphere in the Cenozoic (Menzies et al., 1993; Griffin et al., 1998; Xu, 2001; Gao et al., 2002; Wu et al., 2003; Gao et al., 2004). The mechanism for lithospheric destruction in eastern China is still controversial. It was first attributed to the collision of Indian and Eurasian continents, about 40 Ma ago (Menzies et al., 1993) and, then to the Mesozoic–Cenozoic subduction of the Kula-Pacific Plate or the Triassic collision between the North China and Yangtze Cratons (Griffin et al., 1998; Gao et al., 2002). The subduction of the Pacific plate during the Mesozoic was also proposed to be a main cause of lithospheric removal (Wu et al., 2003).

The Cretaceous GIE in eastern China (Fig. 2) is another major geological event. Considering that the lithospheric removal is usually accompanied by coeval magmatism (Kay and Kay, 1993), and there was major lithospheric destruction in eastern China sometime between Jurassic and Cretaceous (Xu, 2001), it has been proposed that the Cretaceous GIE was probably related to coeval lithospheric delamination/foundering in eastern China, which was possibly promoted by major superplume activity associated with global-scale mantle upwelling (Wu et al., 2005a; Zhao et al., 2007).

Given the Cretaceous GIE ceased when the tectonic regime in eastern China changed from extension to compression, corresponding to the major transformation in the subduction direction of the Pacific plate, extension and crust thinning in eastern China induced by the roughly southward oblique subduction of the Pacific plate is considered here to be the most likely driving force for the Cretaceous GIE. Large scale extension and crust thinning would certainly disturb the asthenosphere due to load adjustment, resulting in decompressional melting of the asthenosphere and interactions between the lithosphere and the hot asthenosphere as well as melts. This kind of magmatic activity ceased when the tectonic regime changed to compressional and, consequently crust thinning stopped, at ~125–122 Ma.

In addition to subduction induced extension and lithosphere thinning, the westward subduction of the Pacific plate lasted till 100 Ma, which might have led to subduction induced delamination/foundering, similar to that modelled for the Andes (Sobolev and Babeyko, 2005), followed by “backarc-type” extension. This might have also contributed to the final removal of old lithospheric keel in eastern China in the Late Cretaceous.

### *4.3. Driving forces for plate tectonics*

Theoretically, heat from the Earth’s interior is the major primary energy source of plate drifting, as well as within plate tectonic evolutions. Therefore, the well-organized heat loss through magmatism on the Earth’s surface provides the primary driving forces for most tectonic events. Among them, the mid-ocean ridge (MOR) magmatism is much more abundant and much better organized than any other magmatisms on the Earth, making up huge engines together with subduction zones: basalt forms along the MOR cools down, becomes denser, slides outward, and finally descends into the mantle along subduction zones. Descending slab becomes increasingly dense as subduction continues due to the transformation of basalt to eclogite. Sliding plates and subducting slabs together further pull the plates apart along MOR, forming more basalt, which becomes “fuel” for the engine later on. This kind of global scale “magmatic engine” is the dominating driving force for plate tectonic evolutions. For continental plates that are not directly connected to MOR, a major driving force comes from interaction with plates attached to MOR, e.g., interaction between subducting slabs and active plate margins.

The Cretaceous tectonic evolution of the eastern China is coupled remarkably well with the subduction of Pacific, which provides direct evidence supporting this model and is very important for further understanding of plate interaction and intraplate tectonic evolution in general. The interaction between the subducting Pacific plate and the Eurasian continent is also crucial to understanding tectonic evolution in eastern China, e.g., continental lithosphere thinning, the Cretaceous GIE and the evolution of the Tan-Lu Fault.

## 5. Conclusion

The Cretaceous geological evolution in eastern China matches surprisingly well with the drifting history of the Pacific plate. Remarkably, the eastern China large-scale orogenic lode gold (Au) mineralization and major tectonic change from extension to transpression in eastern China occurred contemporaneously with an abrupt change of ~80° in the drifting direction of the subducting Pacific plate. These facts suggest that the major geological events in eastern China in the Cretaceous were mainly controlled by the subduction of the Pacific plate.

These major events in eastern China and the Pacific plate were concurrent with the major eruption of the Ontong Java and Kerguelen Plateaus. The most straightforward model would be that the plume heads of Ontong Java and Kerguelen have considerably elevated the south part of the Pacific plate and changed its drifting direction and, consequently changed the tectonic regime of eastern China.

The lithospheric destruction in eastern China and the Cretaceous GIE were probably related to the subduction of the Pacific plate: extension induced thinning and magmatism before ~125–122 Ma. The final lithospheric removal was probably partly due to delamination/foundering triggered by further subduction.

Interactions between subducting and overriding plates provide a major driving force for geological evolutions in eastern China and intraplate tectonics in general.

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