Ore Geology Reviews 65 (2015) 574–588

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

The Jiaodong gold district, northeastern China, in the context of the Late Paleozoic and Late Mesozoic large igneous provinces, orogeny and metallogeny in Eurasia

Hugo de Boorder

Institute of Earth Sciences, Utrecht University, POB 80.021, 3508 TA Utrecht, The Netherlands

A R T I C L E I N F O

Article history:
Received 24 January 2014
Received in revised form 31 March 2014
Accepted 4 April 2014
Available online 15 April 2014

Keywords:
Jiaodong
Eurasia
Gold
Large igneous provinces
Scattered igneous provinces
Lithosphere destruction

A B S T R A C T

The Permo-Triassic continental large igneous provinces (LIPs) of Eurasia linked in to orogenic systems in decay. Their bulk appearance varies from the massive flood-basalts and (ultra)mafic intrusives to the groups of coeval, widely spread, diverse intrusions and extrusions of the Scattered Igneous Provinces (SIPs). In the interval from the demise of the orogens to the inception of the LIPs and SIPs, diverse ore deposits were formed which, depending on the predominant expression of the hosting system, have been interpreted as orogen-related and LIP- or SIP-related. In the case of the voluminous (ultra)mafic complexes, a mantle origin is indicated. This leads to the concept of active mantle plumes issuing from the core–mantle boundary in view of the exceptional volumes and the high temperature inferred to melt the source complexes. However, the substantial volumes of fluids that entered the sub-continental mantle on prior subduction of oceanic lithosphere lowered the solidus temperature and modified the composition of the sub-continental mantle. As a consequence, the conditional high temperature is superfluous. In this context, the setting of the Jiaodong Province and the evolution of the hosting North China Craton suggest that:

1 the introduction of fluids during prolonged subduction of oceanic lithosphere can also modify the rheology of the deep lithosphere; this reinforces the role of plate tectonic processes in the generation and the in-and extrusion of voluminous, mantle-derived melts;
2 the prolific gold deposits could form because of the stalled, subducted Pacific lithosphere slab with its oxidizing potential and its position within the mantle transition zone; as elsewhere, continent-scale, translithospheric strike-slip deformation played an indispensable role in decompression and in the migration of melts, fluids, volatiles and metals;
3 orogenic gold deposits can form independent of orogenesis; should, after all, a relevant orogen be delineated in the coastal belt of eastern Asia, the question arises concerning the dependence of orogenic gold deposits on the nature of an orogen.

1. Introduction

Ever after the seminal paper by Dobretsov (1997), Asia has been the principal scene of inferred mantle plumes as the sources of the continental, Late Paleozoic Siberian, Tarim and Emeishan Large Igneous Provinces (LIPs; Fig. 1). At about the same time, Doblas et al. (1998) drew attention to the Late Carboniferous–Early Permian volcanism in Western Europe and Northwest Africa as a large igneous province in a complex framework of collapse of the Variscan Orogen, its final disruption by wrench faulting, the release of heat that had accumulated below Pangea, and a superplume. In view of the widely spread distribution of the volcanic complexes Doblas et al. (1998) coined the term ‘scattered igneous province’. Dobretsov et al. (2010) formally recognized the Early Permian volcanics in Western Europe as the ‘Central European Large Igneous Province’ and summarized the diverse ore deposits generally associated with large igneous provinces: ‘magmatic Cu–Ni–Pt and Fe–Pt; hydrothermal Ni–Co–As (±Ag, U, Au), Au–As, Ag–Sb, Au–Hg, Sb–Hg and stratiform Cu (copper-bearing sandstones and shales enriched in Co, Ni, Ag, Pt)’. However, in Western Europe, the hydrothermal types, of Late Paleozoic age, are generally viewed as exponents of the Variscan Orogen (e.g., Marignac and Cuney, 1999; Spiering et al., 2000; Bouchot et al., 1997, 2005; see also De Boorder, 2012, 2014). A striking example of this ambivalence is represented by the ‘orogenic’ gold deposits in the French Massif Central (Bouchot et al., 1997, 2005)

E-mail address: H.deBoorder@uu.nl.

http://dx.doi.org/10.1016/j.oregeorev.2014.04.007
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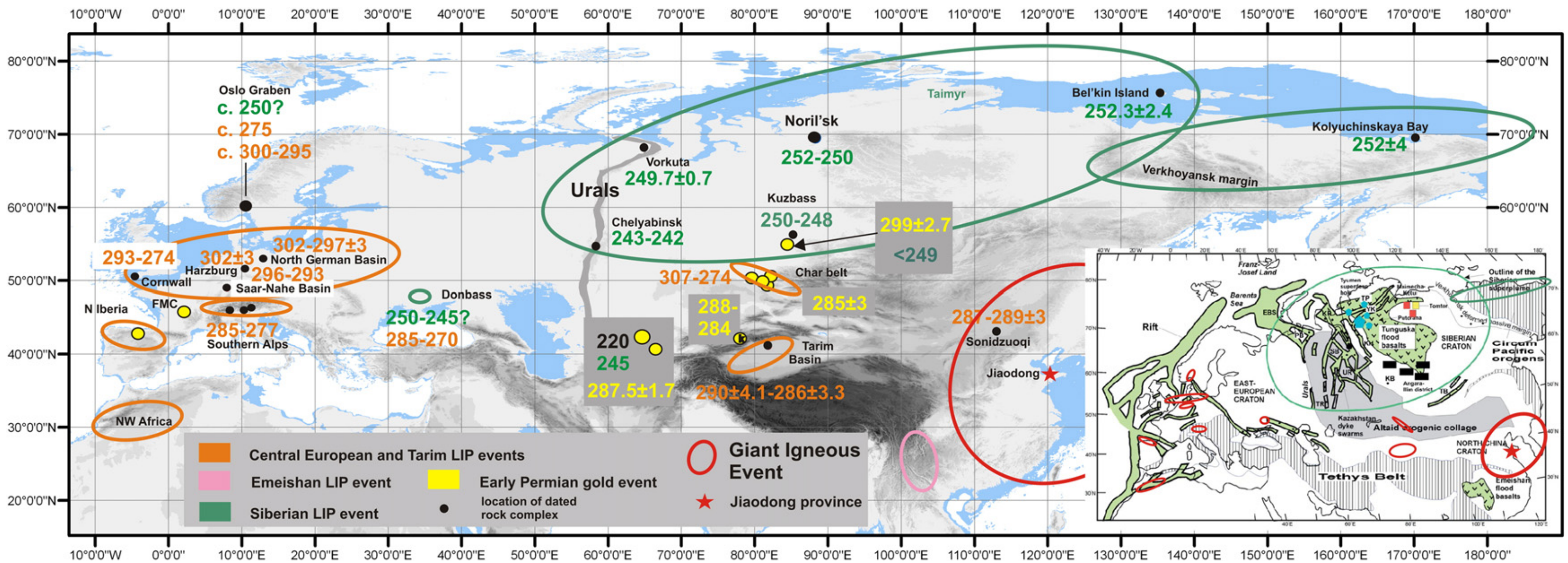

Fig. 1. Schematic overview of the distribution of Early Permian–Triassic large igneous provinces of Eurasia and the Jiaodong gold district. Sources: *Western Europe* — Benek et al. (1996), Breitkreuz and Kennedy (1999), Vinx (1982), Baumann et al. (1991), Von Seckendorff et al. (2004), Schmidberger and Hegner (1999), Vavra et al. (1999), Schaltegger and Brack (2007), Henk et al. (1997), Mulch et al. (2002), Rottura et al. (1998), Hansmann et al. (2001), Tribuzio et al. (1999), Monjoie et al. (2001), Bussy et al. (1998), Montanini and Tribuzio (2001), Cocherie et al. (2005), Fernández-Suárez et al. (2000), Dias et al. (1998). *Southern Tianshan* — Seltmann et al. (2011, 2012), Konopelko et al. (2007, 2009), Wang et al. (2009), Laurent-Charvet et al. (2003), De Jong et al. (2009), Qin et al. (2011), Su et al. (2011), Tian et al. (2010), X. Zhang et al. (2011). *Northern Eurasia* — Timmerman et al. (2009), Reichow et al. (2009), Kuzmichev and Pease (2007), Ledneva et al. (2011), Ivanov et al. (2009), Alexandre et al. (2004). *Early Permian gold event* — Spiering et al. (2000), Bouchot et al. (2005), Morelli et al. (2007), Seltmann et al. (2012), Mao et al. (2004), Naumov et al. (2010).
Modified after De Boorder (2014); inset modified from Nikishin et al. (2002).

which were formed at the same time as the (ultra)mafic and felsic complexes of the Central European Large Igneous Province (De Boorder, 2012). Other examples are the nominal gold and nickel–copper associations of the Southern Tianshan orogen and the Tarim LIP (Mao et al., 2008a; Pirajno et al., 2008) and of the Western Altaid orogen with the Siberian LIP (Barnes et al., 2006; Borisenko et al., 2006; Li et al., 2009; Spiridonov, 2010). Recently, Seltmann et al. (2012) inferred the extent of the Tarim LIP with the intervention of a Tarim mantle plume as far as the Kyzyl Kum region and the Muruntau gold district of Uzbekistan. The relations are further complicated by the interpretation of the above gold-dominated deposits as 'intrusion-related' (De Boorder, 2012) instead of 'orogenic' (e.g., Bierlein and Crowe, 2000; Bouchot et al., 2005) in the sense of Groves et al. (1998, 2009).

In Central Europe, Central Asia and Western Siberia an orogen in decay gave way to the in- and extrusive complexes of a continental, scattered or large igneous province, at the time of formation of comparable, diverse ore deposit types. In all cases a mantle plume has been inferred. The apparently coherent orogen-lip sequences then raise the question in which of the two settings these ore deposits were really formed. The temporal overlap of the orogen's tail and the inception of the large igneous province touches upon the sources and mechanisms of concentration of the metals and, fundamentally, the processes underlying the formation of continental large igneous provinces (De Boorder, 2014). The related controversies concerning mantle plumes and lithosphere plates have been presented extensively in Foulger (2010) and its reviews (MantlePlumes, 2013) and need not be summarized here. However, the widely recognized process of lithosphere delamination is generally the preferred cause of large igneous provinces as an alternative for the plume mechanisms. At the same time, it is also the most queried hypothesis because of the allegedly too small magma volumes to form a large igneous province (e.g., Arndt and Christensen, 1992; Begg et al., 2010; White and McKenzie, 1995). On the other hand, the same kind of (ultra)mafic melts as those of the seemingly autonomous large igneous provinces may form and reach the surface as flood basalts in the course of orogenic collapse (Dewey, 1988). The igneous rocks then expose a relation of the mantle with a decaying orogen or, in a more general sense, with a disintegrating segment of the continental lithosphere, at the time of formation of several types of ore deposits within the by then defunct orogen. So far, the recognized mechanisms or processes involved are the inferred loss of an orogenic root and/or detachment of a subducted slab, slab rollback, and dissection of an orogen by translithospheric strike-slip deformation. The tectonic framework is characterized by spreading extension of the lithosphere. The uncertainties affect the controversy concerning plates and plumes and the understanding of several types of ore deposits in orogenic domains. These are generally thought to have evolved in close association with orogenic processes but are also seen in relation with the LIP complexes. In order to refine these concepts towards a further focus on the metallogenic aspects of mantle and crust dynamics, the Mesozoic evolution of the North China Craton could possibly help because of the evidence of the partial destruction of its cratonic root, the inherent ascent of asthenospheric melts and fluxes to lithosphere levels, the association with a Giant Igneous Event, and the abundance of associated ore deposits. Therefore, in this paper, I discuss principal aspects of the Late Paleozoic orogen-lip sequences in Eurasia and their ore deposits and turn to the current hypotheses concerning the Jiaodong gold district and its setting in the North China Craton, in a further contribution to the resolution of the 'plume or plate' controversy and its bearing on metallogeny.

2. The Variscides and the Central European LIP

The Mid- to Late-Paleozoic Variscides extended from the Baltic Shield (East European Craton) and the southern Urals in the east to the southern Appalachians in the west, following rifting in northern Gondwana, northward migration of Gondwana fragments and collision between Laurussia and Gondwana. During the Late Carboniferous and the Early Permian, the orogen may have been affected by gravitational collapse (Echtler and Chauvet, 1991–1992; Echtler and Malavieille, 1990; Henk, 1997, 1999; Malavieille et al., 1990; Ménard and Molnar, 1988) and by dextral, intracratonic, translithospheric, strike-slip deformation (Fig. 2) between the Southern Appalachians in the west and the Urals in the east (Arthaud and Matte, 1977; Bard, 1997; Franke et al., 2011; Henk, 1997, 1999; Ziegler, 1986, 1989; Ziegler et al., 2006). The dynamic framework was dominated by the translation of Gondwana relative to Laurussia and the closure of the Paleotethys Ocean. Most dated hydrothermal ore deposits in the by then defunct Variscan domain were formed at that stage. These include meso- and epizonal gold deposits (Bouchot et al., 1997, 2005; Marignac and Cuney, 1999), tin–tungsten–copper deposits (Chen et al., 1993; Snee et al., 1988) skarn deposits with copper and gold concentrations (Romer and Soler, 1995; Spiering et al., 2000), Ni–Co–As (Paniagua et al., 1988) and complex mercury-dominated deposits (Krupp, 1989), all currently exposed in and around the crystalline massifs of western and central Europe, together with a hidden molybdenum–tungsten porphyry in western Poland (Bula et al., 2001). The association of the diverse mineralization in the gold districts of northern Spain with strongly altered, locally banded, hornblende gabbro stocks was pointed out by Suárez and Corretgé (1987). This association is a prominent indication of the involvement of hydrous mafic magmas. A comparable association, of gold-bearing quartz veins and lamprophyres was reported by Chalier et al. (1994) from the French Massif Central. It was considered enigmatic because of the mutual intersections of quartz veins and lamprophyres (Bouchot et al., 2005). Further north, a relation was found by Seifert (2008) between volatile-rich lamprophyric and rhyolitic intrusions with diverse ore deposits in the Erzgebirge of the Bohemian Massif in Central Europe. The lamprophyres were thought to be indicative of melting of a metasomatically enriched mantle. This detailed, relatively local study converges with the earlier observations by Turpin et al. (1988) concerning the sources of the Late Carboniferous to Early Permian lamprophyres throughout the Variscan orogen. In this regional project the lamprophyres in general were attributed to melting of a mantle enriched by subduction-related processes during recycling of crustal material. Comparable ore deposit types and settings are also encountered in northeastern China.

Between ca. 300 and 280 Ma, igneous complexes, intrusive and extrusive, of both felsic and (ultra)mafic composition formed within the Variscan domain and its adjacent platforms (see De Boorder, 2012). The large volcanic complexes in the subsurface of the North German Basin and in the Oslo Rift were interpreted as plateau basalts by Ziegler (1990) and Sundvoll et al. (1990), respectively. The ultramafic and mafic rocks of the Ivrea–Verbano complex in northern Italy were also interpreted as a flood basalt complex by Stähle et al. (2001) in view of their volumes. Calc-alkaline affinity, enrichment in LILE relative to Nb, Ta and Ti in fragments of a deep-seated layered ultramafic complex in the subsurface of the French Massif Central are viewed as subduction-related signatures (Féménias et al., 2003) and traced in coeval complexes elsewhere in Europe (Benek et al., 1996; Cortesogno et al., 1998; Lorenz and Haneke, 2004; Schmidberger and Hegner, 1999; see also De Boorder, 2012). In the Alps of Switzerland and Italy, lower crustal (ultra)mafic complexes of Permo-Carboniferous age have been exhumed in the course of the Alpine orogeny. Such complexes were inferred by Schaltegger and Brack (2007) as a heat source of granites and felsic volcanics emplaced in pull-apart basins along both the southern and northern margins of the defunct Variscan Orogen. The Early Permian setting is summarized in Fig. 3A.

3. The Southern Tianshan and the Tarim LIP

The Southern Tianshan extends from the southern Urals eastwards to the eastern tip of the Tarim Basin, between the Kazakhstan, Yili and Junggar Blocks in the north and a string of lithosphere blocks or

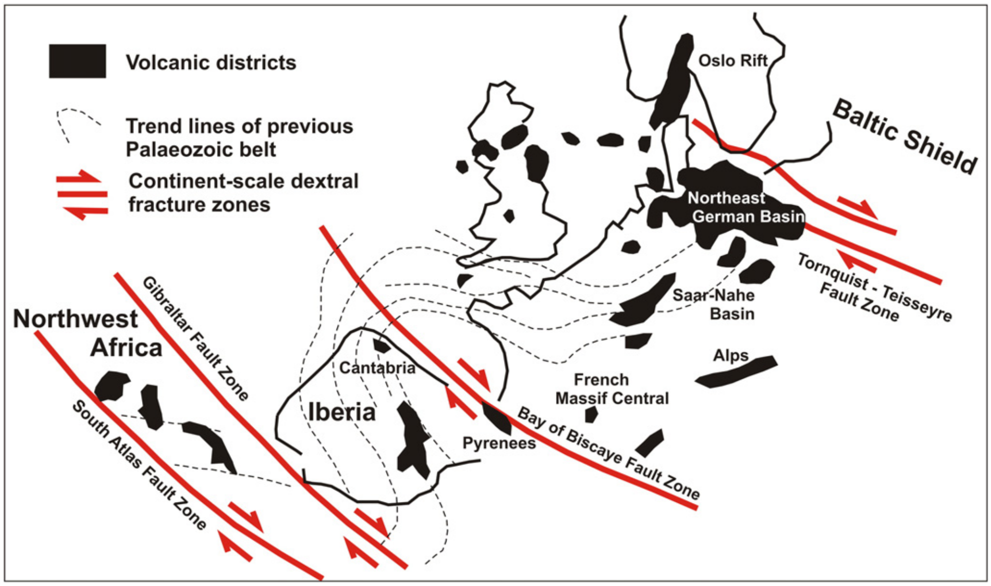

Fig. 2. Distribution of the complexes of the Central European Scattered or Large Igneous Province. Adapted from Doblas et al. (1998), and modified after De Boorder (2014).

microcontinents to the south, rifted off the northern margin of Gondwana and comparable to the Gondwana-derived fragments constituting the backbone of the Variscides to the west (Stampfli and Borel, 2002; Von Raumer, 1998; Von Raumer et al., 2003; Wilhem et al., 2012). From west to east these are the largely hidden Turan, Karakum, and Tarim blocks and the North China Craton which extends as far as the Pacific Ocean. These blocks are bounded to the north by an east–west-striking belt of deep-reaching strike-slip deformation (Fig. 4) largely taken up in the Southern Tianshan Orogen and extending westward to the Tornquist–Teisseyre Zone which separates the Baltic Shield from Phanerozoic Central Europe. This deformation belt is known as the Scytho-Turanian Fault which to the east is thought to extend to the Solonker Suture (Natal'in and Şengör, 2005).

To the south of this belt, the Tarim Basin, with over 10 km of Phanerozoic sediments and volcanics (Tian et al., 2010) overlying the Precambrian complexes of the Tarim Block, hosts the Permian volcanic complexes of the Tarim Large Igneous Province (Fig. 5). Coeval igneous complexes in the surrounding regions have been advocated to form part of this district (e.g., Konopelko et al., 2007, 2009; Zhang and Zou, 2013a,

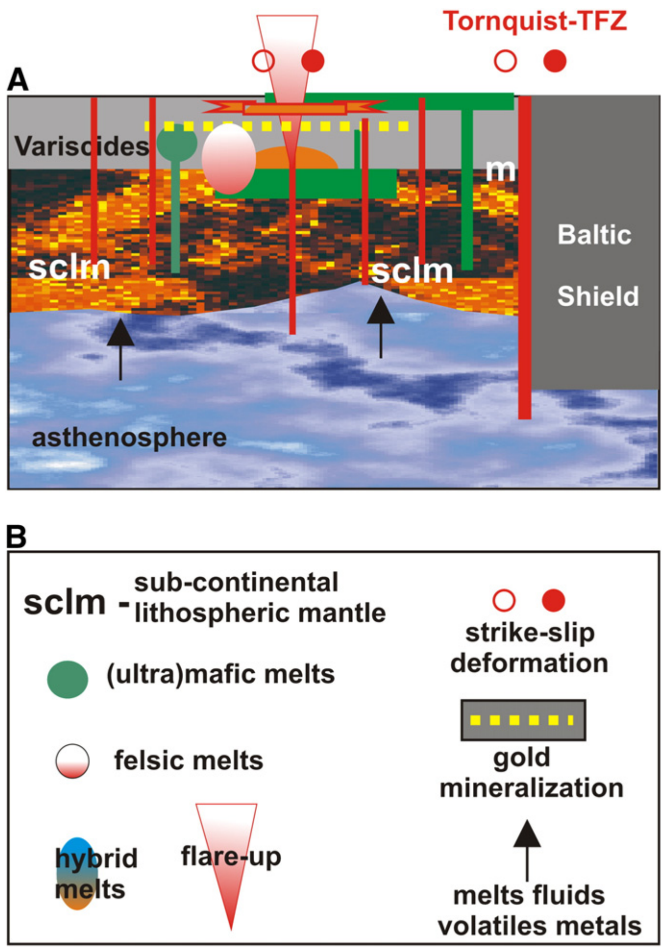

Fig. 3. A Schematic summary of the inferred post-Variscan setting. For legend see panel B. B. Legend for panel A and Figs. 5, 7, 9 and 11.

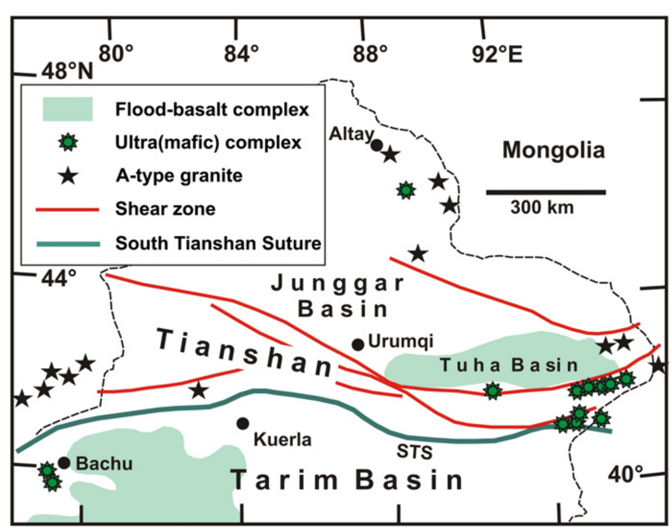

Fig. 4. Distribution of the Tarim Large Igneous Province in the northern Tarim Basin, the flood-basalts of the Tuha Basin, with ultra(mafic) and A-type granite complexes. Modified after Zhang and Zou (2013a,b).

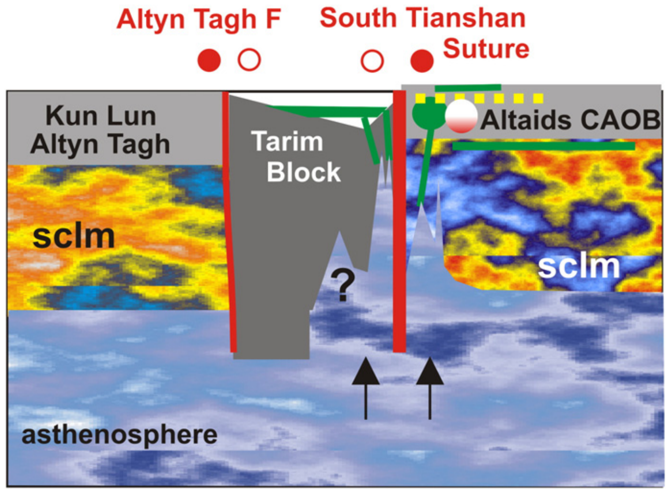

Fig. 5. Schematic summary of the inferred setting of the Tarim Large Igneous Province. For legend see Fig. 3B.

b; Zhou et al., 2009) despite the wide-ranging variety of the rocks. The knowledge of the lithologies and the extent of the volcanics in the Tarim Basin is based on outcrops along the northern margin, industrial drill cores and seismic and magnetic surveys. The dominating flood basalts, with a thickness in excess of 2500 m and covered by some 5 km of post-Permian sediments in the North Tarim uplift (Qin et al., 2011), generally have OIB-like affinity attributed to asthenospheric sources. Diversity is ascribed to heterogeneous mantle sources (e.g., Zhou et al., 2009). Cores from the North Tarim Uplift show a picrite–basalt–rhyolite sequence (Tian et al., 2010). Here, rhyolite is found to have originated by fractional crystallization of basalt melts and by assimilation of crustal complexes. Geochronological estimates of rhyolite units, in the lowest and highest levels of the ca. 1000 m sequence investigated deliver ages of 290 $\pm$ 4.1 and 286 $\pm$ 3.3 Ma, respectively. In addition to the bimodal volcanic complexes there are layered and zoned intrusions of gabbro–norite, A-type granitoid plutons, ultramafic complexes and dyke swarms.

Zoned gabbro–norite intrusions are known in the eastern Tianshan. They have been interpreted as Alaskan-type intrusions associated with the flood basalts (Mao et al., 2008a; Pirajno et al., 2008) but their origin is controversial. Magmatic hornblende in the gabbroic complexes would indicate crystallization from a hydrous magma which tends to set them apart from the Tarim flood basalts (Wan et al., 2013; Wilhem et al., 2012). Chemical characteristics in the igneous rocks of the eastern Tianshan are explained by modification of the underlying mantle domains during earlier subduction (e.g., Qin et al., 2011; Su et al., 2011). According to Su et al. (2012 and references therein), subduction-induced mantle heterogeneity beneath the Central Asian Orogenic Belt is probably of regional extent.

From studies of Permian plutonic complexes, A-type syenite-granites and coeval (ultra)mafic intrusions in the northern margin of the Tarim Basin, and from associated dyke systems and plutons and dyke swarms in the Southern Tianshan and the Junggar Basin to the north, Zhang and Zou (2013a,b) suggested the existence of two different mantle source domains. The Tarim domain, south of the South Tianshan suture, produced magmas from the Tarim Craton's lithospheric root after long-term interaction with the surrounding mantle ('enriched' continental lithospheric mantle) followed by melts from astenospheric sources leading to the formation of the (ultra)mafic Bachu Complex in the northern margin of the Tarim Basin. In the Tianshan domain, north of the South Tianshan suture, magmas were produced from its continental lithospheric mantle after preceding subduction-related metasomatism. At the same time, Zhang and Zou (2013b) argued the lowering of melting temperature of 'time-integrated enriched' continental lithospheric mantle with reference to the study by Xu (2001) concerning the destruction of the root of the North China Craton. The magmas of mafic dyke swarms, (ultra)mafic complexes and the continental flood basalts to the north of the Southern Tianshan Suture, in the western Central Asian Orogenic Belt (CAOB), were attributed to metasomatized mantle sources, presumably generated by subduction of the Turkestan Ocean. In both domains the heat source was attributed to one and the same mantle plume.

The generally observed lithological diversity is also exposed by the study of the ore deposits in the Southern Tianshan belt. In the ultramafic host complex of the Baishiquan Ni–Cu deposit, in the eastern part of the belt, the presence of ubiquitous hornblende and biotite suggests a parent hydrous magma (Chai et al., 2008). M. Zhang et al. (2011) found that the host complex of the Huangshandong Ni–Cu deposit, at some 50 km from Baishiquan, has a tholeiitic composition different from the alkaline basalts of the Tarim basin and more akin to the coeval volcanics in the Tuha Basin to the north. Gao et al. (2013) concurred with the above views of Chai et al. (2008) on the Baishiquan deposit. Sun et al. (2013) believed that the Huangshandong deposit formed from basaltic magmatism related to post-subduction delamination and asthenosphere upwelling instead of a deep-seated plume. Deng et al. (2014) found that the intrusion hosting the Huangshandong deposit is enriched in large ion lithophile elements and depleted in high field strength elements relative to N-MORB, and high Th/Yb ratios, suggesting that the primary magma of the intrusion was derived from partial melting of a metasomatized mantle source, modified by subducted slab-derived melt/fluid. The differences between the (ultra)mafic magmas to the south and to the north of the South Tianshan Suture may then be largely due to subduction metasomatism of comparable magmas to the north of the Suture. The geochemical diversity of the igneous complexes is thus increasingly clarified. The distribution of the ore deposits, dominantly Ni–Cu deposits associated with the gabbroic plutons, and the gold deposits in the deep-reaching shear zones between the two prominent mantle domains (e.g., Mao et al., 2008a) raise the problems of emplacement of the igneous complexes beyond the adoption of an active mantle plume (e.g., Sun et al., 2013). The solution may well have to be sought in the dynamics behind the Permian shear zones that dissected the South Tianshan orogen (Charvet et al., 2007; Laurent-Charvet et al., 2003; Pirajno, 2010) and the associated extensional domains as represented by pull-apart basins (De Boorder, 2012; De Jong et al., 2009; Pirajno, 2010; Wang et al., 2009).

Whereas an active mantle plume is still seen as the source of melts from the asthenosphere, the (ultra)mafic igneous complexes along the northern margin of the Tarim Basin and within the Tianshan domain are increasingly regarded as the result of partial melting of a subduction-modified subcontinental mantle (Fig. 5). In addition, (partial) destruction of the root of the Tarim Craton may have occurred as a result of its long-term compositional modification through interaction with the surrounding mantle. The emplacement of both ore deposits and igneous complexes may have depended on the deep-reaching shear zones and their associated extensional domains, considering that melting of the mantle complexes did not depend on the normally required high temperatures attributed to active mantle plumes.

4. The Emeishan LIP

The Emeishan Large Igneous Province in southwestern China extends ca. 600 km from north to south along the Jinshajiang–Ailaoshan Sutures (Fig. 6), (see Jian et al., 2009b), which forms the western limit of the province and from where the igneous rocks extend some 700 km eastward on the Yangtze Craton. Comparable complexes in northern Vietnam have also been attributed to the Emeishan LIP (Anh et al., 2011; Chung et al., 1997; Hoa et al., 2008; Kamenetsky et al., 2012; Wang et al., 2007). According to Shellnutt et al. (2010), this igneous province has been viewed as one of the best illustrations of a mantle plume production. Apart from the (ultra)mafic lithologies, domal uplift

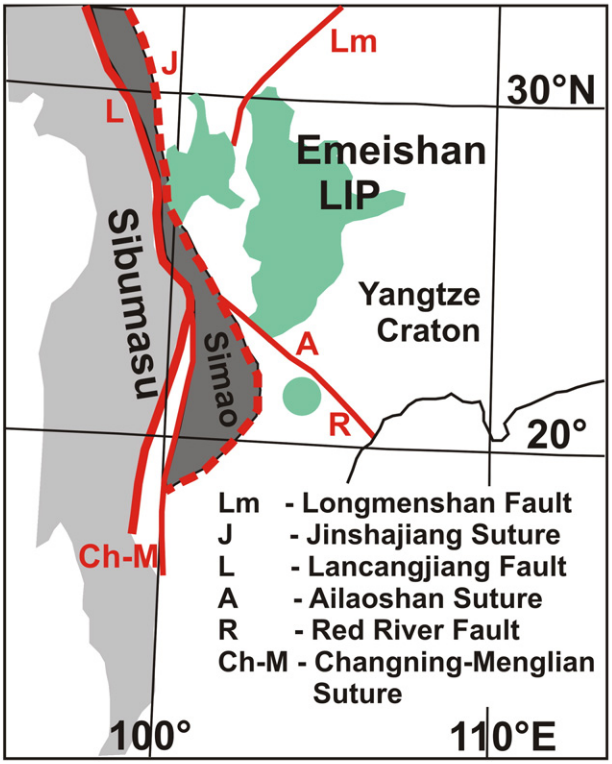

Fig. 6. Distribution of the Emeishan Large Igneous Province in relation to the principal sutures and fault zones of the region.
Modified after Jian et al. (2009b), Wang et al. (2007) and Kamenetsky et al. (2012).

of the region appears to have been an important argument in favor of a plume origin. This aspect is, however, still debated (He et al., 2010; Peate and Bryan, 2008). The age of the (ultra)mafic complexes is estimated at about 260 Ma (e.g., He et al., 2007). Zhou et al. (2008) distinguished two magma series, one comprising of high-Ti basalts and Fe-rich gabbroic and syenitic intrusions, and the other of low-Ti basalts and (ultra)mafic intrusions. Each has specific ore types, the first with giant Fe–Ti–V oxide ore deposits, the second with Ni–Cu–(PGE) sulfide deposits. The authors suggested that the two series resulted from melting of a heterogeneous mantle plume. Kamenetsky et al. (2012) also found low-Ti and high-Ti end members. Their investigation of melt inclusions in primitive olivine suggested that numerous parental magma batches were involved in the evolution of the complex of more differentiated basalts. Mantle sources for the low- and high-Ti end-members were suggested to have resided in peridotite and garnet pyroxenite, respectively. The similarity of Sr and Nd isotopic compositions was thought to represent a source in the sub-continental lithosphere rather than the convective asthenosphere or a deep mantle plume.

The tectonic setting of the Emeishan LIP is dominated by several north–south striking sutures in a complex, narrow bundle of thrusts and strike-slip faults with a dominantly sinistral sense of displacement along the current western margin of the province. Here, the very complex Jinshajiang–Ailaoshan Suture marks the closure of the Paleotethys Ocean along the western margin of the Yangtze Craton (Pirajno, 2013; Xiao et al., 2008). According to Xiao et al. (2008), OIB-type mafic volcanics are widely spread in the suture zone and involve a passive margin succession. Chemically and isotopically these volcanics compare to the complexes of the Emeishan LIP to the east. Xiao et al. (2008) attributed the Emeishan LIP to a mantle plume which caused the opening of the Jinshajiang Paleotethys Ocean in the Carboniferous and continued its activity along the western margin of the Yangtze Craton till the end of the formation of the Emeishan LIP. However, further geochronological studies by Jian et al. (2009a,b) have led to more detailed understanding of the region.

The temporal framework of the evolution of the western Yangtze Craton was reinforced by Jian et al. (2009a,b) with SHRIMP zircon dating of rock complexes in the various sutures and microcontinents (blocks). They reconstructed a Devonian–Permian plate tectonic cycle for the opening and closure of the Paleotethys Ocean. The final subduction of the Paleotethys Ocean is defined between 270 and 264 Ma with formation of the Changming–Menglian ophiolite along the main Paleotethys Suture and arc volcanism which partially overlapped in time with the formation of the Emeishan LIP between ca. 267 and 256 Ma. At this stage, the ensuing Paleotethys Orogen and the Emeishan Continental Large Igneous Province had a similar extensional history possibly controlled by a common tensional stress regime along a pre-existing tectonic boundary. Westward movement of the Yangtze craton was thought to have caused lithospheric pull-apart structures which the authors visualized with the model of Anderson (1994). Jian et al. (2009b) arrived at the association of the continental flood basalt province with a major orogeny in terms of the plate tectonic evolution of the Paleotethys Ocean and its continental framework. They attributed the generation of the Emeishan magmas to plate tectonic forces rather than the impact of a mantle plume. Kamenetsky et al. (2012) converged with this conclusion; they did not find evidence for the involvement of a mantle plume either.

As in the other continental, (ultra)mafic large igneous provinces, deposits of Ni–Cu and Ti–V are clearly associated with the igneous rocks of the Emeishan complexes. Interestingly, Zhang et al. (2006) found particles of native gold and native copper in olivine from picrite. The authors suggested, with reference to Hu et al. (2004), that gold deposits of Mesozoic age had formed in the Emeishan LIP. However, the account by Hu et al. (2004) deals with the porphyry deposits along the Red River–Jinshajiang strike-slip fault, which formed later in association with mantle-derived alkaline intrusions between ca. 40 and 30 Ma. In the Emeishan region itself the native gold and copper in olivine do illustrate a relation of the metals with the Late Permian ultramafic melts. Burnard et al. (1999) reported on fluids, with both mantle and crustal characteristics, in three shear zone-hosted gold deposits in the Ailaoshan Gold Belt. $^{40}Ar/^{39}Ar$ estimates arrived at an age of ~33 Ma for the Daping ores which may represent reworked concentrations (Sun et al., 2009). Other ore deposits of gold and copper allegedly related to complexes of the Emeishan LIP have been reported only from northern Vietnam (Hoa et al., 2008). These include Cu–Ni, Mo and Au–As–Sb–Hg associations in two major, NW–SE-striking rift zones, with estimated $^{40}Ar/^{39}Ar$ ages between 252 and 228 Ma. Whereas a relation between these rift structures and the movements along the Ailaoshan–Red River–Jinshajiang strike-slip fault zone stands to reason, the tectonic control of the ore deposits of northern Vietnam merits further investigation.

In addition to the proposals of active mantle plumes, documented, different mechanisms have recently come forward involving more shallow sources and correlation of the Emeishan Large Igneous Province with the aftermath of the Southwest Asian Paleotethys Orogen (Fig. 7) and a direct association between gold and copper with ultramafic complexes.

5. The Western Altaids and the Siberian LIP

The Western Altaids constitute the basement of the West Siberian Basin between the Urals and the Baltic Shield to the west and the Siberian Shield to the east. Its nature is inferred from bore holes, magnetometry and gravimetry, and outcrops around the Basin. The flood basalts of the Siberian LIP generally rest unconformably on the Western Altaids in which granitoid rocks have been found with Late Carboniferous and Permian ages (Aplonov, 1995) and on earlier Paleozoic sediments on the Siberian Shield (Czamanske et al., 1998). The basement

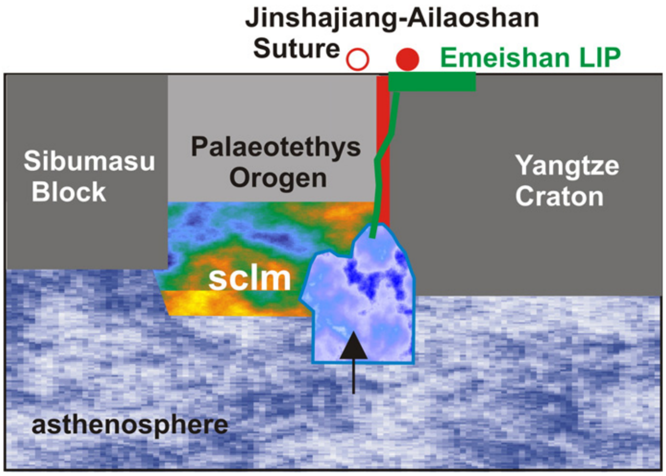

Fig. 7. Schematic summary of the inferred setting of the Emeishan Large Igneous Province in relation to the Yangtze Craton and the Southeastern Asian Palaeotethys Orogen. For legend see Fig. 3B.

of the West Siberian Basin is generally interpreted in terms of two oroclines between the Baltic Shield and the Urals to the west and the Siberian Shield to the east, including the Kazakhstan Block (Seltmann et al., 2014; Şengör and Natal'in, 1996, 2007; Yakubchuk et al., 2005).

The principal outcrops of the flood basalts are on the Siberian Shield. Comparable rocks have been recovered from bore holes in the West Siberian Basin and have been observed in the Urals and as far to the northeast as the New Siberia Islands (Kuzmichev and Pease, 2007) and Kolyuchinskaya Bay (Ledneva et al., 2011) on the Arctic coast (Fig. 1). To the south, they are known in the Kuznetsk Basin (Fig. 1). The province comprises of dominant low-Ti and subordinate high-Ti oceanic island basalts, dykes, sills and (ultra)mafic and felsic intrusives. The majority of the flood basalts have low concentrations of HFS elements relative to LIL elements (Ivanov, 2007). In continental basalts these patterns may point to sudden melting of arc or backarc sources trapped under a continental-plate suture (Puffer, 2001). Major basalt emissions on the Siberian Craton occurred at about 250 Ma and 240 Ma with contemporaneous granitic magmatism which continued into the Late Triassic. Earlier, minor basaltic pulses should not be excluded (Ivanov et al., 2013). In view of the large extent of the volcanics, the tectonic framework of the Siberian LIP is much a matter of continent-scale deformation. Its elucidation depends on the interpretation of continent-wide potential fields and on protracted, localized field work.

A relation between magmatism and deep-reaching strike-slip faults has been inferred as far as the northern margins of the Siberian Craton and the Taimyr Peninsula (Duzhikov and Strunin, 1992) and to the south in Central Asia (Buslov et al., 2003, 2004, 2010; Vladimirov et al., 2008). The interpretation of the magnetic anomaly map of the West Siberian Basin by Allen et al. (2006) portrays the rift structures in the basement of the Basin as pull-apart basins along deep-reaching strike-slip faults. In the reconstruction of the transformation of the Siberian Craton along the Laurussian margin by Sears (2012, and references therein), the British Columbia Transform plays an important role. A connection between the strike-slip deformation inferred in the West Siberian Basin and the British Columbia Transfer Shear should not be excluded (De Boorder, 2014). Whereas the deep-reaching pull-apart structures would clarify the relatively small occurrences, as in the Kuznetsk Basin, without much opposition, the vast volumes on the Siberian Craton and in the West Siberian Basin seem to require different or additional processes.

In the explanations of the sources of the vast volumes of (ultra)mafic flood basalts and intrusives the Siberian LIP is still at the center of the debate that pits the active mantle plume concept against plate tectonic mechanisms (e.g., Foulger, 2010; MantlePlumes, 2013). Prominent issues concern the volumes of the igneous complexes, the temperatures required to melt the mantle source rocks and the uplift of the lithosphere. Many authors have preferred an active mantle plume as the source of adequate temperatures. However, Ivanov (2007) and Ivanov et al. (2008) have invoked the role of earlier subduction of water as an agent to lower the melting temperatures of mantle complexes on the basis of the occurrence of primary mica and amphibole in the volcanic and plutonic rocks and experiments on high water capacity of the mantle transition zone. Gladkochub et al. (2010) advocated a similar mechanism in combination with a mantle plume for the mafic complexes in the southern part of the Siberian Shield. Saunders et al. (2007) invoked mantle delamination processes in support of explanations of the very large volumes of the Siberian LIP, following Elkins-Tanton and Hager (2000) and Elkins-Tanton (2005). Whereas plume-related magmas obtain their mantle signature only in the upper mantle (White, 2010), the scrutiny by Class (2008) of petrological, geochemical and geophysical approaches to mantle dynamics emphasized the need for their integration to resolve the uncertainties in the dynamics of the mantle in order to ascertain the existence of active mantle plumes emanating from the core–mantle boundary. The diagnostic strength of uplift or subsidence of the lithosphere in relation to mantle plume activity appears to have been reduced with the studies of Burov and Guillou-Frottier (2005) and Sobolev et al. (2011) which suggested that uplift is not necessary and that either could occur. In western Siberia if not western Asia, the vast production of (ultra)mafic magmas seems to require proportionate processes over and above the formation of the rift basins that decorate the translithospheric strike-slip shears. Enlarging the scale of the problem to continental proportions, namely to Pangea, a system of multiple plumes and a superplume has been advocated (e.g., Doblas et al., 1998; Dobretsov, 1997). Recently, however, Gutiérrez-Alonso et al. (2008) formulated the amalgamation of Pangea in terms of the closure of the Paleotethys Ocean, involving prominent, translithospheric, transcurrent, compressional strike-slip deformation in the central parts of the growing supercontinent and the evolution of extensional structures in the marginal parts. De Boorder (2014) proposed the West Siberian Basin, also with reference to Aplonov (1995), as one of these marginal extensional intracontinental domains between the Siberian and Baltic Cratons, superimposed on the belt of the amalgamating Western Altaids and its translithospheric, transcurrent deformation (Fig. 8). Paleozoic metasomatism of the subcontinental mantle of the Siberian Craton and its surroundings by subducted fluids (see Gladkochub et al., 2010; Ivanov, 2007; Ivanov et al., 2008), lowering the melting temperature, could have been an important process for later massive melting.

As set out in the Introduction, the formation of the Early Permian metal deposits in the Variscides and the Southern Tianshan at the same time as the orogenic domains *and* their neighboring platforms were invaded and flooded by the magmas of the Central European and Tarim LIPs, suggests interaction of the (ultra)mafic LIP magmas with the remnants of the orogens. Such a relation appears reinforced by the indications of earlier subduction-related metasomatism of the subcontinental mantle, which in turn provided for large-scale melting and deep-seated production of fluxes in the subcontinental mantle upon decompression along translithospheric strike-slip deformation (Fig. 9) during or after thinning of the lithosphere. The notably large-scale, semi-synchronous events require a trigger mechanism that most probably has to be sought at the scale of the lithosphere plates. However, because of erosion, subsidence, sedimentation and younger orogenesis, the relevant depth levels of the Late Paleozoic complexes are only accessible to a limited extent. Therefore, further understanding is pursued in a potentially comparable system of largely Mesozoic age centered on the North China Craton.

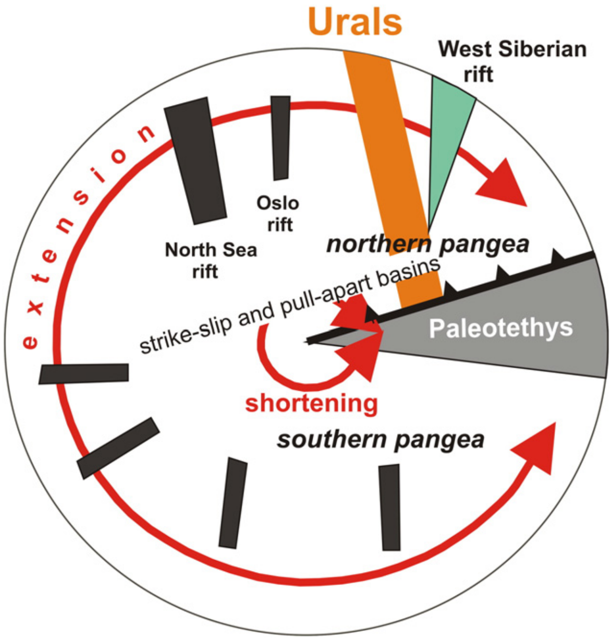

Fig. 8. Schematic representation of the formation of the Pangaea Supercontinent in relation to the closure of the Palaeotethys Ocean with southern Pangaea subducting to the north below northern Pangaea, adapted from Gutiérrez-Alonso et al. (2008) who coined the term 'self-subduction'. Their model includes transpression in the core of the supercontinent and extension in the periphery consistent with the translithospheric strike-slip zones in the central parts and the West Siberian rift in the northern margin. Modified after De Boorder (2014).

6. The North China Craton, the Jiaodong Gold District and the Giant Igneous Event

6.1. The partially thinned Craton

The Early Cretaceous Jiaodong gold district is part of a much larger metallogenic province in eastern Asia which developed during the breakdown of the lithospheric root of the eastern part of the North China Craton. The causes and mechanisms of the partial loss of the root and relations with the prominent gold deposits are still being discussed and have been comprehensively reviewed, summarized and expanded in Zhai et al. (2007) and recent papers (e.g., Dong et al., 2013; Guo et al., 2013; Li and Santosh, 2014; Li et al., 2012, 2013, 2014; Tan et al., 2012; Windley et al., 2010). Here, the comparison of the associated Early Cretaceous magmatism with the large igneous provinces of Eurasia is inspired by its designation as a ~130–120 Ma Giant Igneous Event (Wu et al., 2005) along the eastern Asian continental margin. The complexes of this Giant Igneous Event are generally thought to neither constitute a large igneous province nor directly relate to a mantle plume. Despite the distinct involvement of mantle processes with upwelling of the asthenosphere, the generating mantle environment is considered shallow rather than deep and to have produced a scattered igneous province rather than a large igneous province (Pirajno, 2013). Liu et al. (2008) concluded that the destruction of the roots of the North China Craton was not a 'local' event but part of regional crustal detachment and lithosphere thinning in East Asia. The suggestion by Wu et al. (2005) was taken up by Windley et al. (2010) in their Fig. 1 in which the coastal belt between 50° and 25° N is indicated as a delamination zone in the lithosphere. The concept of the destruction or removal of part of the lithospheric root of the North China Craton is solidly anchored in the study of xenoliths of Ordovician, Mesozoic and Cenozoic kimberlite pipes, implying the removal of some 120 km in the Mesozoic (e.g., Deng et al., 2004; Fan et al., 2000; Griffin et al., 1998; Menzies et al., 1993, 2007; Windley et al., 2010). Although alongside these discussions the association with the mineralization in the region seems clear cut because of the temporal overlap of the processes, the direct relations between the two are only beginning to emerge.

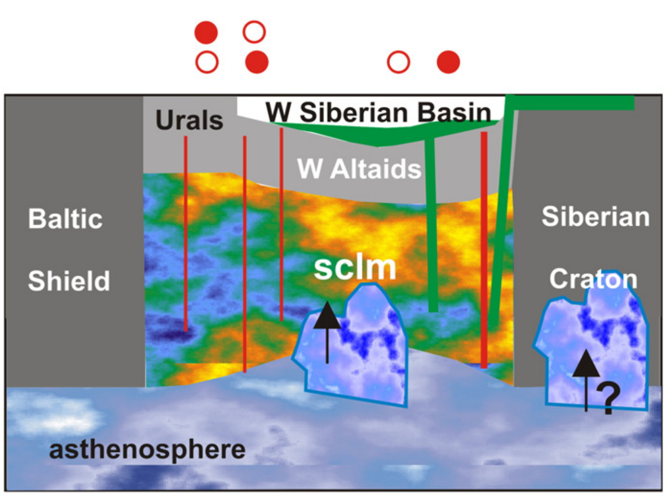

Fig. 9. Schematic summary of the inferred setting of the Siberian Large Igneous Province in relation to the West Siberian Basin and the Siberian Craton. For legend see Fig. 3B.

6.2. The setting of the North China Craton

The Craton is hemmed in by three subduction zones (Solonker, Dabie and Pacific) and disturbed by the far-field effects of the Mongol–Okhotsk suture and the Late Jurassic–Early Cretaceous collapse of the Mongolian plateau with the formation of the Yanshan belt on the northern margin of the North China Craton (Meng, 2003, challenged by Windley et al., 2010). The lithosphere destruction remained limited to the eastern part of the Craton. Cope and Graham (2007) noted that the eastern and western parts of the North China Craton had a similar history during most of the Paleozoic, including a regional Silurian–Devonian disconformity suggesting that both parts were elevated and stable till the Early Jurassic. The margins of the eastern block are generally seen in the Solonker and Dabie Sutures in the north and south, respectively, with the Tan–Lu Fault in the east and the so-called Gravity Lineament (see Wang et al., 2006) to the west.

Prior to closure of the Paleotethys Ocean in the Solonker and Dabie Sutures, subduction of the oceanic lithosphere and its inherent water content had taken place since the Early Viséan (~340 Ma, Stampfli and Borel, 2002). The subduction of the Pacific plate below Asia added further water to the continental mantle, and may have affected a belt of ~3000 km along the coast, eventually reaching ~1000 km inland. Windley et al. (2010, and references therein), building on the ideas of Maruyama et al. (2004) and Maruyama et al. (2009), documented a role for hydro-weakening of the North China Craton root by the introduction of water-bearing complexes during subduction of the Paleotethys plate along the above sutures and the westward subducting Pacific plate. Although they draw the extent of the delamination to the north and to the south, they do not offer an explanation beyond the North China Craton.

6.3. Timing and setting of the gold mineralization

Li et al. (2006) showed that the gold mineralization in the eastern part of the Jiaodong district coincided with the emplacement of widespread mafic to intermediate dykes and was younger than the granites. In the Pengjiakuang gold deposit they dated ($^{40}Ar/^{39}Ar$) sericite from auriferous alteration at 120.9 ± -0.4 to 119.1 ± 0.2 Ma, and biotite from the adjacent Queshan granite at 120.9 ± -0.4 to 119.1 ± 0.2 Ma. At Rushan they estimated mineralization-associated sericite between 109.3 ± 0.3 and 107.7 ± 0.5 Ma whereas biotite from the hosting monzogranite formed between 129.0 ± 0.6 and $126.9 +/- 0.6$ Ma. In parallel, Mao et al. (2008b) emphasized that the gold deposits of western Jiaodong were coeval with 121–114 Ma lamprophyre and dolerite dykes. Retrograde alteration fluids in lamprophyres and dolerites were found to be the same, as part of a potassium- and carbon dioxide-rich system, and younger than the granitic complexes. An extensively documented study by Tan et al. (2012) of the Guocheng deposit, Jiaodong, found three geodynamic events from lead isotope systematics. Starting with the find of mantle complexes that were metasomatized by subduction in the Paleoproterozoic, they specified the following elements:

> "(1) repeated injection of basic magma from metasomatized SCLM into a crustal reservoir of felsic composition along with sulfide melt exsolution, possibly enriching the hybrid magma in sulfur and ore metals,
> (2) late stage aqueous fluid exsolution destabilized magmatic sulfides and thus incorporated their metal and sulfur endowment,
> (3) buoyant rise of magmatic-hydrothermal fluids into zones of structural weakness, where focused ore precipitation occurred, and
> (4) ongoing extension facilitated prolific mafic and felsic magmatism."

This proposal compares closely with the suggestions by Li et al. (2006) and Mao et al. (2008b): gold, dolerite, lamprophyres are coeval and younger than the granitoids. In more absolute terms, there is a range of some ten milion years. This window broadens again with the estimates by Li et al. (2012) of 155–119 Ma for the gold deposits in the Xiaoqinling district in the southern North China Craton. In a comprehensive study of the geodynamic setting of the gold mineralization, Guo et al. (2013) provided an overview of eleven earlier models. They expanded suggestions by Yang et al. (2012) and involved thinned subcontinental and metasomatized mantle, underplated mafic magmas and upwelling asthenosphere from the stagnant Pacific plate in the transition zone below the Tan–Lu Fault Zone as a major corridor for magmatism and metallogeny. The Pacific slab has been found by seismic tomography along the mantle transition zone below eastern Asia (Huang and Zhao, 2006; Zhao et al., 2010; Zhu et al., 2011) but the existence of a corresponding orogen in the coastal belt of Eastern China has, apart from the Sulu segment, not been documented in published vertical sections. The suggestions by Zhu et al. (2011) (their Fig. 4; see also Li et al., 2012) concerning the destabilizing interaction of the relatively steep, westward subduction of the Pacific lithosphere and mantle convection extend the proposals by Guo et al. (2013) with the stagnant or stalled segment in the mantle transition zone and its implications in terms of dehydration and degassing (Huang and Zhao, 2006; Ivanov, 2007; Ohtani and Zhao, 2009; Pirajno, 2013). Oxidizing conditions at depth, related to partial melting in the stalled slab (Sillitoe, 1997, with reference to McInnes and Cameron, 1994) liberating gold from sulfides, would have augmented the mineralizing potential. The recently proposed model by Goldfarb and Santosh (2014) builds on earlier proposals by Goldfarb et al. (2007) but is not consistent with the seismic tomography results (e.g., Huang and Zhao, 2006; Zhao, 2004, 2009; Zhao et al., 2010). There is no indication that steepening of the crust (lithosphere) ever occurred just above the Tan–Lu Fault whereas according to the tomography the steepening of the oceanic crust occurs currently at the trench east of Japan.

6.4. Giant Igneous Event

Wu et al. (2005) studied the widespread Mesozoic igneous rocks (Fig. 10) of eastern China, initially with zircon U–Pb SHRIMP, LA-ICP-MS and TIMS dating of dolerite, diorite and granite from the Liaodong Peninsula. Comparison with published data from other regions, (including the Xing'an–Mongolian (Xingmeng) Orogenic Belt in NE China, the Yanliao region, the Jiaodong Peninsula, the Dabieshan, and the eastern Yangtze Craton) led them to define a Giant Igneous Event between ~132 and ~120 Ma. In the Great Xing'an Mongolian ranges the ages

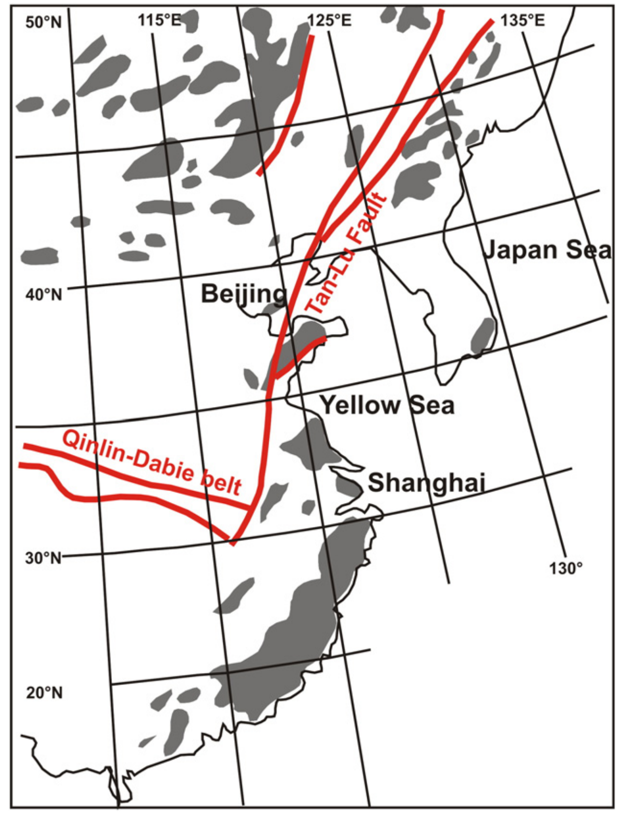

Fig. 10. Schematic distribution of Late Jurassic and Early Cretaceous Giant Igneous Event. Modified from Windley et al. (2010).

spread between 137 and 105 Ma. They attributed the magmatism to a combination of continental breakup, rapid plate motion, including subduction of the Pacific plate, lithospheric delamination, asthenospheric upwelling and crustal melting in an extensional setting. Wu et al. (2005) defined an overall extensional setting on the basis of coeval A-type granites, dyke swarms and metamorphic core complexes with large-scale gold mineralization, magmatic underplating, lower crustal granulite metamorphism and extensional to strike-slip deformation. Fan et al. (2003) found the late Mesozoic volcanic rocks of the northern Da Hinggan Mountains (Xing'An Ranges) enriched in LIL elements and depleted in HFS elements and inferred their derivation from a metasomatized lithospheric mantle. They concluded that these complexes formed independent of subduction of the Pacific plate and could not be related to a mantle plume. Mesozoic mafic volcanism occurred largely along the northern and southern margins of the North China Craton and intrusive ultramafic–mafic complexes were mainly formed in the center of the craton (Zhang, 2007; Fan et al., 2007; Huang et al. (2007) reported on the geochemistry of mantle-derived rocks. They concluded that depletion of HFS elements and enrichment in LIL elements cannot be attributed to enrichment by ancient fluid or melt and they preferred interaction between lower continental crust and lithospheric mantle or upwelling asthenosphere. Garnetiferous assemblages resulting from metamorphic reactions in the Craton's root may have acted as sinkers leading to delamination.

In the absence of precise geochronological constraints for the volcanism in the Great Xing'an of northeastern China, Wang et al. (2006) conducted a $^{40}Ar/^{39}Ar$ study of mainly basalts and basaltic andesites (see Fig. 10 for the distribution of Late Jurassic–Early Cretaceous volcanics, after Windley et al., 2010). On the basis of their compilation with published data from surrounding regions, including the study by Wu et al. (2005), Wang et al. (2006) concluded that magmatism took place from ~160 Ma till ~113 Ma in four distinct pulses which migrated from west to east and which they related to the closure of the Mongol–

Okhotsk Ocean and eastward delamination of the lithosphere from the western edge of the China–Mongolia Block. In view of the distribution of the Late Jurassic–Early Cretaceous volcanics and their ages, they preferred a relation with the Pacific lithosphere. However, the overlap in time with Mongol–Okhotsk-related processes hampers a definitive solution. Moreover, it is unclear to what extent the zonation observed by Wang et al. (2006) affected the North China Craton south of latitude 40° N. The Cenozoic lavas, Early Tertiary tholeiites, Late Tertiary and Quaternary alkaline to peralkaline basalts are thought to stem from upwelling asthenosphere in the wake of craton destruction (Windley et al., 2010).

6.5. Triggers

In view of the constraints in time of the plate tectonic processes, destabilizing dynamic control of igneous and mineralizing processes is to be expected. The triggers of the various processes have been sought in relatively abrupt events like the collision of continental blocks as there are the Yangtze and North China Cratons and/or the North China and Siberian Cratons (e.g., Wang et al., 2006), the reversal of movement along the Tan–Lu Fault Zone (e.g., X. Wang et al., 2011), the change in the orientation of Pacific plate movement from orthogonal to parallel to the continental Asian margin (Goldfarb et al., 2007), changes in the stress field along the Tan–Lu Fault (Goldfarb and Santosh, 2014; Yang and Santosh, 2014), the rise of the Ontong Java Plume (Ernst and Jowitt, 2013; Goldfarb et al., 2007 and references therein) and the Kerguelen Plume (Li and Santosh, 2014 and references therein). Windley et al. (2010) suggested post-collisional thrusting on the Solonker and Dabie Sutures, largely in the Jurassic, led to extension and thinning in the Cretaceous with major extension on the hydro-weakened crustal root of the eastern part of the Craton.

6.6. Open questions and one certainty

Uncertainties surrounding the post-Triassic evolution of the North China Craton follow directly from a history of events for the eastern North China Craton by Windley et al. (2010, their Fig. 3). It spans some 130 my in time between about 220 and 90 Ma. They include processes between the Siberian and Yangtze Cratons on the one hand and between the Pacific and the Ordos Basin in the west on the other. The overall mechanical and chemical interaction of the principal continental blocks with the intervening subducted oceanic lithosphere across eastern Asia, and the subduction of the Pacific plate affecting the entire theater, appears unavoidable. The concentration in time of extension, root loss, peak magmatism and mineralization within the same twenty million years is bound to hamper unscrambling the essentials. Moreover, the differences in timing of gold mineralization in the northeast (e.g., Li et al., 2006; Mao et al., 2008b) and the southwest (e.g., Li et al., 2012) of the North China Craton raise several options: diachronous mineralization processes or mineralization in two different systems, North China Craton destruction or Dabie–Sulu–Qinlin aftermath? Is the gold mineralization along the northern margin of the North China Craton indeed a matter of North China Craton destruction or did it follow from the orogenic processes in the Permo-Triassic, or from the major strike-slip dissection along the Solonker and Dabie Sutures? Should a Late Jurassic–Early Cretaceous orogen still be consistently delineated in eastern continental Asia, the question arises: ‘How and to what extent do orogenic gold deposits depend on the nature of an orogen?’ Also, three belts of metamorphic core complexes in different parts of eastern Asia with different setting, together have their peak development between 140 and 110 Ma, yet owe their existence to different causes in different parts of eastern Asia (Windley et al., 2010). These were formed during root loss of the eastern North China Craton, gold mineralization, and deep strike-slip deformation along the coastal belt. Of fundamental significance is the nature of the interaction between Pacific lithosphere and the cratons, especially since these have generally not yet been explicitly identified in the interpretations of the seismic tomography.

The tomographic imagery of the eastern and northeastern Pacific seaboard shows the systemic leveling of the Pacific oceanic lithosphere in the Mantle Transition Zone (Zhao et al., 2010) but the cratonic blocks can only vaguely be made out and detached roots remain a matter of speculation. Yet, with the delamination belt suggested along the Pacific coast (Windley et al., 2010; Wu et al., 2005) and the gold mineralization extending northward to the eastern Stanovoy block (Goldfarb et al., 2007), lithosphere destruction would have affected not only the North China Craton but also the intervening complexes, as for instance in the Great Hinggan of northeastern China with its prolific Early Cretaceous volcanics and its different types of ore deposits (Zhang et al., 2008; Zhang et al., 2010; Zhou et al., 2012).

For the destruction of the root of the eastern block of the North China two different mechanisms have been recognized (e.g., Windley et al., 2010): mechanical removal (delamination) and chemical replacement (thinning). The lack of expression in the seismic tomographic sections of remnants of the root at deeper levels might suggest that some form of ‘digestion’ took place by replacement at scales smaller than the resolution of the seismic tomography, especially along the boundaries of the micro-blocks in the Craton (Li and Santosh, 2014). After some 35 my of quiescence, the earlier calc-alkaline volcanism in the Greaty Xing'an, north of the Craton, was succeeded from about 65 Ma by Cenozoic tholeiites and alkaline basalts in such quantities that they qualify as flood basalts. The meaning of the gap in time is intriguing but remains unclear as long as the causes of the Giant Igneous Event on and off the Craton (Wang et al., 2006; Wu et al., 2005) have not been balanced. The first flood basalts extruded some fifty million years after the apparent 120–110 Ma peak in gold production in the northeast of the North China Craton.

The only certainty about the appearance of the gold mineralization is that it occurred late in the history of the loss of the cratonic root during interaction with magmas from a hydrous and probably oxidizing domain in the asthenosphere.

6.7. Comparison of the Giant Igneous Event with the LIPs

Perhaps the most notable difference between the Early Cretaceous Giant Igneous Event on the North China Craton and the recognized Permian Tarim, Emeishan and Early Triassic Siberian Large Igneous Provinces is the absence of extensive flood basalts. However, in this respect it compares to the Permian Central European Province. Only in the Cenozoic, flood basalts formed in variable volumes across the North China Craton and surrounding regions. Yet, there are also substantial regions covered by Early Cretaceous basalt, rhyolite, andesite and dacite, that make up some 100,000 km^2 which, in turn, resemble the ignimbrite, rhyolite, andesite and basalt complexes of Central Europe where underplating (ultra)mafic magmas are thought to have provided the heat to melt segments of the crust. In the absence of further estimates of volumes and extent, and of the duration of extrusion between ca. 160 and 110 Ma, the East Asian Province probably fails the formal criteria of the large igneous provinces (Ernst and Buchan, 2002). Characteristic Ni–Cu–PGE ores have not been reported and the Early Cretaceous metallogeny on the North China Craton was dominated by mesozonal gold deposits. Moreover, there is consensus concerning the absence of an active mantle plume (see Pirajno, 2013; Windley et al., 2010). Recognizing these differences, a comparison with the Eurasian Late Paleozoic and Early Mesozoic LIPs and their explanations shows that the above failures of the North China Craton–Great Igneous Event duo tend to clarify some aspects of the established LIPs.

The Central European Large Igneous Province of Dobretsov et al. (2010) was also known as a scattered igneous province (Doblas et al., 1998; Perini et al., 2004), as is the Great Igneous Event in eastern Asia (Pirajno, 2013). In Europe, however, there was no craton involved.

Translithospheric strike-slip deformation dissected the Variscan orogen and collapse may have been involved in its demise prior to the emplacement of the LIP complexes. The felsic and (ultra)mafic complexes show indications of metasomatism of the lithosheric mantle related to earlier, probably Devonian to Early Carboniferous subduction processes. The Early Permian volcanism of ignimbrite, rhyolite, dacite, andesite and minor tholeiitic basalt is not unlike the Late Jurassic–Early Cretaceous volcanism in eastern Asia. As in the Jiaodong region, an association of lamprophyre and hornblende gabbro intrusions with diverse ore deposit types may relate to melting of mantle complexes that were enriched by metasomatism during earlier subduction.

The Tarim igneous complex is mainly built by tholeiitic basalts. Its estimated volumes and extent tend to qualify as a large igneous province although large parts are covered by kilometers of post-Permian sediments. Indications of metasomatism of the source rocks have been noticed along the northern margin of the Tarim Basin and within the Tuha Basin to the north. In the gabbro–norite plutons in the eastern Tianshan, water-rich magmas may have been involved. Extensions of the main complexes in the Tarim Basin to the west and to the east have been emplaced along the easterly-striking, translithospheric strike-slip zones which dissect the Southern Tianshan (e.g., Konopelko et al., 2007, 2009; Seltmann et al., 2011). The eccentric position of the bulk of the volcanic complexes away from the Southern Tianshan on the Precambrian Tarim Block resembles the position of the Emeishan LIP on the Yangtze Craton and of the bulk of the Siberian LIP on the Siberian Craton. The sources of the magmas are generally agreed to stem from the (heterogeneous) asthenosphere and have long been attributed to an active mantle plume. With the recently considered equivalence of 'asthenosphere' and 'mantle plume' as a source of heat by Arndt (2013), the predominance of the plume mechanism was reduced. At the same time, Zhang and Zou (2013b) invoked the mechanism proposed by Xu (2001) for the destruction of the North China Craton by thermo-mechanical and chemical erosion, to explain the Tarim LIP with the (partial) destruction of the root of the Tarim Craton. The implication is that, again, a long inferred active mantle plume model is no longer required for the production of a prominent large igneous province.

The Siberian LIP is renowned as one of the largest continental igneous provinces and is generally explained as the result of an active mantle plume. Lithosphere delamination has been suggested as an alternative (e.g., Arndt and Christensen, 1992; Begg et al., 2010; Elkins-Tanton, 2005; White and McKenzie, 1995) were it not for the presumably too small lava volumes produced that way. Whereas volumes and extent are exemplary, the mechanism of delamination was cited by Saunders et al. (2007) to explain the very volumes of the Siberian complexes. Following Bercovici and Karato (2003), water from the mantle transition zone introduced by subduction, has been invoked by Ivanov (2007), Ivanov and Balyshev (2005) and Ivanov et al. (2008) as a factor to lower the melting temperature of the source complexes of the Siberian LIP. We see the same process proposed in the case of the partial foundering of the North China Craton root (Pirajno, 2013; Windley et al., 2010), inclusive of a process of consequent eclogitization and the production of a sinker of the failing lithosphere as suggested by Elkins-Tanton (2005). In the case of the Siberian LIP, translithospheric, transcurrent shear (e.g., Czamanske et al., 1998) together with peripheral rifting of Pangea (Gutiérrez-Alonso et al., 2008) may have played a role in the production of the exceptionally large lava volumes (De Boorder, 2014).

The Emeishan LIP in southwestern China has been extensively documented. Generally the LIP has also been attributed to an active mantle plume (Shellnutt et al., 2010). However, in a comprehensive petrological and geochemical study, Kamenetsky et al. (2012) concluded from Sr and Nd isotopic compositions that the sources of the complex resided rather in the sub-continental lithosphere than in the asthenosphere. Jian et al. (2009a,b) deduced a direct relation with the Paleotethys Orogen, with lithosphere-scale pull-apart deformation in the wake of orogeny.

The North China Craton and the gold deposits of Jiaodong and elsewhere in the eastern block of the Craton demonstrate the significance of the destruction of a segment of the continental lithosphere followed by upwelling of the asthenosphere. Early to Middle Paleozoic subduction of the (Paleotethys) oceanic lithosphere was probably responsible for the long-term introduction of water into the subcontinental mantle and the consequent changes of its composition and rheology. In Eastern Asia, the subducted slab of the Pacific oceanic lithosphere stalled in the hydrous Mantle Transition Zone and may have released gold and other metals in an oxidizing and particularly hydrous environment (Fig. 11). Inferred subduction-related metasomatism of the sources of the Permo-Triassic LIP and SIP complexes suggests that similar processes played a role in the Paleozoic of Eurasia, albeit in relation to orogens that lost their root by gravitational and/or far-field forces. The results are comparable but unique in each case. Yet, Jiaodong and the North China Craton have their very own place and setting within the scala of wrecked lithosphere segments.

7. Conlusions

1 Orogenic gold districts can form independently of orogenesis.
2 The stalled Pacific lithosphere slab in the mantle transition zone below eastern Asia may have released gold and other metals because of its oxidation within a notably hydrous environment, especially below the North China Craton.
3 A scattered igneous province need not be distinguishable from a large igneous province.
4 Scattered igneous provinces and large igneous provinces can form independent of active mantle plumes.
5 Each continental large or scattered igneous province has its multi-scale characteristics, dependent on its setting; yet, in the Late Paleozoic and Mesozoic of Eurasia there was always a variable interaction involved between the asthenosphere and the continental lithosphere plates upon destruction of a principal segment of the continental lithosphere. It was at this stage that unpredictably prolific and diverse ore deposits tended to be formed. These include the ore types known as orogenic, late- and post-orogenic, post-tectonic, anorogenic and post-peak metamorphic deposits of meso- and epizonal gold, arsenic–tungsten–gold, mercury–antimony–gold, mercury and nickel–cobalt–arsenic which, together with the LIP-associated nickel–copper–PGE, have also been asserted to have been associated with the Eurasian Permo-Triassic and mantle plumes.

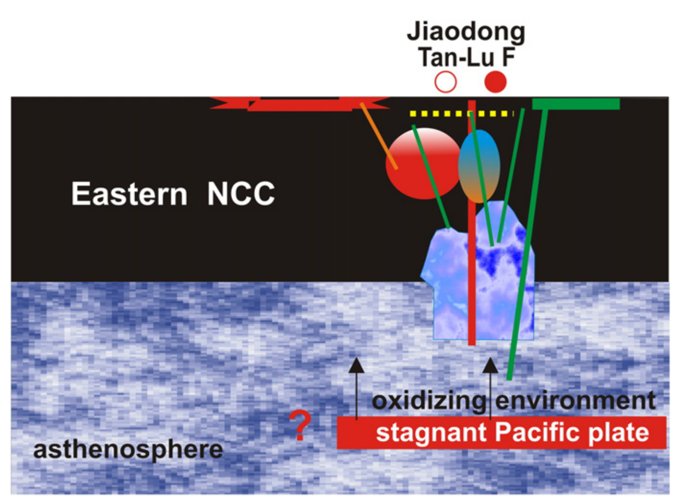

Fig. 11. The eastern block of the North China Craton with its gold deposits (Jiaodong district), the trans-lithospheric strike-slip deformation (Tan–Lu Fault Zone) and the stalled subducted Pacific lithosphere with its oxidizing potential on partial melting, within the Mantle Transition Zone.

6 Prolonged subduction of oceanic lithosphere can be an important factor in mantle processes affecting the rheology and the solidus temperature of mantle complexes by introduction of water leading to hydro-weakening, metasomatism and melting of mantle complexes. Active plumes from the core–mantle boundary are not a prerequisite for the voluminous melting of mantle complexes.
7 The formation of mesozonal gold districts involved emplacement of the asthenosphere at higher levels; translithospheric strike-slip deformation is probably the most effective mechanism to provide the necessary permeability.
8 The flood basalts of eastern Asia, theoretical sources of Ni–Cu–PGE deposits, only emerged after 35 million years of magmatic quiescence. The meaning of this gap is not clear.

Acknowledgments

I deeply appreciate the invitation by the Guest Editors, M. Santosh and F. Pirajno, to contribute to this issue of Ore Geology Reviews on the Jiaodong gold province. My sincere thanks go to Reimar Seltmann for his hospitality, his continuous interest in my work, his support and frank discussions over the years. I am grateful for the repeated encouragement by Franco Pirajno. The reviews by Reimar Seltmann and Neil Phillips are much appreciated.

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