Global Tectonics and Metallogeny

Fast Track Article

The Central European, Tarim and Siberian Large Igneous Provinces, Late Palaeozoic orogeny and coeval metallogeny

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With 3 figures and 4 tables

Abstract: The formation of the Central European and Tarim Large Igneous Provinces (LIPs) in the Early Permian coincided with the demise of the Variscan and the Southern Tianshan orogens, respectively. The Early Triassic Siberian LIP was formed in the wake of the Western Altaid orogeny in the Late Permian. These processes coincided with the development of the majority of known Late Palaeozoic and Early Mesozoic hydrothermal and magmatic ore deposits in the corresponding orogenic domains. Nickel-copper(-PGE) deposits followed directly from the evolution of the (ultra-)mafic melts which make up the LIPs. In Western Siberia, the diverse assemblage of associated noble and base metals in the Noril'sk-Talnakh Ni-Cu(-PGE) deposits suggests these metals also had their source in the mantle domain from which the (ultra-)mafic melts were generated. The same metals variably found their way into the hydrothermal ore deposits in the defunct Variscan and Southern Tianshan orogenic domains. These ore deposits have traditionally been viewed as a result of orogenic processes. However, their ages, together with the timing and nature of their by then intracontinental tectonic control cause uncertainty concerning the role of the orogens. In view of their mantle sources in their association with the Siberian LIP, the mantle contribution to these Late Palaeozoic hydrothermal ore deposits in the orogenic belts may have been more significant than previously thought. An orogenic contribution to melting of mantle complexes and to mineralisation may have resided in the earlier modification of subcontinental mantle domains by subduction of oceanic lithosphere. In all three cases, the controlling tectonic setting of orogenic cessation, LIP formation and mineralisation was dominated by translithospheric strike-slip deformation, possibly in combination with orogenic collapse and lithosphere delamination. In view of their recurrence, the orogen-lip sequences were probably not fortuitous. The controlling strike-slip faults were principal elements of the lithosphere-scale dynamic framework that led to the amalgamation of Pangaea. At this scale, the exceptionally large volume of the Siberian LIP may, in addition to the strike-slip dissection of the lithosphere, have been related to extension in the continental lithosphere of the margin of the Supercontinent (cf. Gutiérrez-Alonso et al. 2008). The peripheral extension was associated with compression in its centre. The explanation of these Large Igneous Provinces does not require the concept of an active mantle plume because deep-reaching strike-slip deformation, orogenic collapse and lithosphere delamination involved in the destruction of the orogenic edifices can have caused decompression melting in large domains of the subcontinental mantle.

Keywords: orogen-large igneous province sequence, translithospheric strike-slip, plumes, delamination, collapse, ore deposits, Late Palaeozoic, Early Mesozoic, Pangaea

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Introduction

The Late Palaeozoic, so-called orogenic, gold deposits in the Variscides and the Southern Tianshan were formed in a setting dominated by continent-scale, translithospheric strike-slip deformation (De Boorder 2012). The deposits are of the intrusion-related type and part of complex, deep-reaching systems involving upwelling asthenospheric mantle in localized extensional domains. These produced (ultra-)mafic decompression melts which lo-

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www.schweizerbart.de
DOI: 10.1127/0163-3171/2013/0008
0163-3171/2013/0008 $ 9.45

cally stalled at the Moho as gabbroic plutons in the upper mantle and the lower crust (Henk et al. 1997, Pirajno et al. 2008, Mao et al. 2008a, Zhang et al. 2008) with granulite facies aureoles (Tribuzio et al. 1999), and flood-basalts (Ziegler 1990, Stähle et al. 2001). Ubiquitous ignimbrite and rhyolite in pull-apart basins (Benek et al. 1996, Breitkreuz & Kennedy 1999, Schaltegger & Brack 2007), associated with the deep-reaching strike-slip zones (Arthaud & Matte 1977, Ziegler 1990, Henk 1999, Scheck et al. 2002, Bellot et al. 2003, Laurent-Charvet et al. 2003, Wang et al. 2009, De Jong et al. 2009), probably resulted from melting of the lower crust due to the high temperatures of trapped mantle magmas. Prior and/or coeval thinning of the lithosphere could have been due to lithosphere delamination (Marignac & Cuney 1999, Bierlein et al. 2006). In addition, orogenic collapse has often been advocated in the Variscides (e.g., Ménard & Molnar 1988, Diez Balda et al. 1995, Escuder Viruete et al. 1998, Fernández-Suárez et al. 2000, Echtler & Malavieille 1990, Echtler & Chauvet 1991–1992, Malavieille et al. 1990, Schulmann et al. 2002). Both in the Variscides and the Southern Tianshan, these processes destroyed the orogenic edifices and facilitated variable degrees of permeability of the lithosphere which permitted the emplacement of (ultra-)mafic magmas at diverse levels of the upper mantle and the crust. Their volumes are large enough for their qualification as large igneous provinces, namely the Central European and Tarim LIPs (Doblas et al. 1998, Dobretsov et al. 2010, Zhou et al. 2009, Tian et al. 2010). Considering that the gold deposits, together with the other Late Palaeozoic hydrothermal ore deposits, had earlier been viewed in relation with orogenic processes, the here implied association with large igneous provinces opens up a new perspective in global tectonics and metallogeny on the interaction between the crust and the subcontinental mantle. This leads to questions concerning the resemblance of the settings of the Early Permian Central European and Tarim LIPs and the Permo-Triassic Siberian LIP (Figure 1), similarities in associated metallogeny and the relevance of active mantle plumes.

LIP – orogen relations

There is consensus that the compositions of the vast volumes of mafic and ultramafic rocks of the continental large igneous provinces are indicative of melting in the asthenosphere and the continental lithospheric mantle. However, there still is uncertainty and disagreement concerning the mechanisms leading to melting, migration and emplacement of the melts. A substantial part of this controversy resides, on the one hand, in the role of inferred plume systems emanating from processes in the core and the core-mantle boundary (CMB) and, on the other, of upwelling of asthenospheric and/or lithospheric mantle following processes in the lithosphere. The mantle plume mechanism is sometimes stipulated as the initial assumption or paradigm underlying the subsequent explanation of observations (e.g., Begg et al. 2010, Borisenko et al. 2006, Dobretsov et al. 2010, Zhang et al. 2008). However, the resulting igneous rocks are thought to have obtained their chemical mantle signature only in the upper mantle (White 2010). The latter suggestion removes the material link with the Earth's core and reduces the professed plume to a heat source. Continental basalt melts were, contrary to oceanic basalts, contaminated by the hosting continents and the subcontinental mantle lithosphere (Arndt & Christensen 1992, White 2010). Recently, the controversy has been set out in Foulger (2010) and its reviews (Mantle Plumes 2013). Especially the large volumes of the flood-basalts and sills have been taken to suggest an origin of the melts within or in relation to mantle plumes from the CMB (e.g., Dobretsov 1997, Courtillot et al. 2003, Davies 1998, Yakubchuk & Nikishin 2004, Dobretsov et al. 2008, 2010, Pirajno et al. 2009, Saunders et al. 2005, 2007, Reichow et al. 2005, and references therein). Lithosphere delamination has been advocated as an alternative process to generate the melts were it not for the resulting, allegedly limited melt volumes (e.g., Arndt & Christensen 1992, White & McKenzie 1995, Silver et al. 2006, Pirajno et al. 2009, Begg et al. 2010). Both processes deliver the thermal anomaly required to melt parts of the upper mantle. The implication is that the effects of a thermal mantle plume and of delamination of the continental lithosphere by plate-related processes are not readily distinguishable. The two processes have also been invoked as sequential (e.g., Gladkochub et al. 2010), as complementary (e.g., Su et al. 2011) and accidentally coeval (Nikishin et al. 2002). As a consequence, the criteria for the recognition of CMB-sourced mantle plumes are still not operational beyond 'vast' or 'large' melt volumes. With the continued uncertainty concerning estimates of mantle plume temperature obtained from the petrology and geochemistry of the (ultra)mafic LIP rocks (Class 2008) and the limited resolution of seismic tomography in the deep mantle (e.g., Rickers et al. 2012), the lithosphere-driven processes cannot be dismissed despite the immense popularity of the plume hypothesis. This is the more so because the subcontinental mantle, if modified by fluxes from subducting oceanic lithosphere, need not require the very high temperature exclusively attributed to active mantle plumes in order to produce the magmas observed (Elkins-Tanton 2005, Ivanov 2007). The question then arises as to how the three LIPs fitted in their contemporary lithospheric framework. A first lead is in the isotope-geochronological estimates compiled in Tables 1, 2, and 3, which indicate

Table 1. Timing of Late Palaeozoic igneous complexes in Western Europe

Province	Lithology	Age Ma	Analytical method	References
Northern Variscides and Foreland				
Oslo Graben				
NE German Basin	mafic and felsic calc-alkaline magmatic activity (‘flare-up’) in Internal and External Variscides and northern Foreland	302-297	SHRIMP U-Pb zir	Benek et al. (1996), Breitkreuz & Kennedy (1999)
Harz Massif	layered gabbro-norite, accompanied by independent granites	297±4–293 ±2 ‘297–293’	U-Pb zir	Vinx (1982), Baumann et al. (1991)
Saar-Nahe Basin	diatremes of basaltic tuff and K-rich tholeiite			Nicholls & Lorenz (1973)
	basalt, basaltic andesite, rhyodacite, rhyolite, trachyte	296–293	^{40}Ar-^{39}Ar total gas	Von Seckendorff et al. (2004) and references, Lorenz & Haneke (2004)
	calc-alkaline basalt, andesite, rhyolite typical of volcanic arc settings	300±9	Sm-Nd dacite	Schmidberger & Hegner (1999) and references
South Alpine Zone				
Ivrea-Verbano Zone (IVZ)	(1) granulite (2) metaperidotite from Mafic Formation (3) metagabbro	(1) 299 ± 5 (2) 300 ± 6 (3) 293 ± 6	U-Pb zir	Vavra et al. (1999)
	ultramafic hornblendite and hornblende syenite dikes in layered Mafic Formation	223	K/Ar, ^{40}Ar-^{39}Ar hbl	Stähle et al. (2001)
Contact of Ivrea-Verbano and Strona-Ceneri Zones	dioritic rim of Mafic Complex	285 +7/–5	TIMS U-Pb zir	Pin (1986) quoted by Schaltegger & Brack (2007)
	contact metamorphic rim of Mafic Complex	274 ± 17	U-Pb mon	Bürgi & Klötzli (1990)
	mylonitic metapelite along contact	280–275	U-Pb zir	Henk et al. (1997)
	mafic and felsic dikes	285–275	Rb/Sr WR U-Pb zir	Mulch et al. (2002)
	Baveno granitoids	280–270	U-Pb zir	Schaltegger and Brack (2007) and references therein
Atesina Volcanic District	high-K calc-alkaline continuum of basaltic andesite to rhyolite and gabbro to monzogranite	~285–260	TIMS U-Pb zir	Rottura et al. (1998)
Southern Alps	felsic volcanics (silicic tuffs, ignimbrite, rhyodacite) and high-level intrusives	Athesina district 280±0.5 277.6±0.6 277±5 Lugano-Valganna Complex 281.3±0.5 282±1	TIMS U-Pb zir	Schaltegger & Brack (2007)
Austroalpine Zone separated from South Alpine Zone by the Insubric Line				
	Braccia-Fedoz gabbro associated leucogabbro	281±19 278–2.5/ +2.6	U-Pb zir	Hansmann et al. (2001)
	Sondalo gabbro	280±10 300±12	Sm/Nd WR	Tribuzzio et al. (1999)

Table 1. cont.

Province	Lithology	Age Ma	Analytical method	References
	Mt. Collon gabbro	284.2±0.6 282.9±0.6	U-Pb zir	Monjoie et al. (2001),
	Anzasca gabbro	288+2/–4	U-Pb zir	Bussy et al. (1998)
Dent Blanche-Sesia Unit, Western Austroalpine Zone	granites and gabbros	296–287	SHRIMP U-Pb zir	Bussy et al. (1998)
External Crystalline Massifs Aar and Gotthard Massifs	ferro-potassic granites	305–295		Bussy et al. (2000) Debon & Lemmet (1999)
Mont Blanc Massif	post-tectonic Mont Blanc felsic-mafic association	303±2	U-Pb zir	Bussy et al.(2000)
Northern Apennines	Mt. San Agostino granulite	291±9	Sm/Nd WR	Montanini &Tribuzio (2001)
Corsica-Sardinia Batholith	(1) A-type granites (2) stratified (ultra)mafic cplxs tholeiitic affinity	(1)290–286 (2) 290–280	SIMS-TIMS U-Pb zir	Cocherie et al. (2005)
Iberia				
Northwestern Iberia	post-tectonic tonalite-granodiorite-monzogranite association	295–285	U-Pb zir	(1) Fernández-Suárez et al. (2000) (2) Gutiérrez-Alonso et al. (2011)
Northern Portugal	sub-alkaline ferro-potassic granites (post-D3)	296–290	U-Pb zir	Dias et al. (1998)
	high-K calc-alkaline granitoids (late- to post-D3)	ca. 300	U-Pb zir	Dias et al. (1998)

Table 2. Late Palaeozoic igneous complexes in Central Asia.

Province	Lithology	Age Ma	Analytical method	References
Western Tianshan				
Kyzylkum, Alai and Kokshal segments	Post-collisional intrusions	295–280	SHRIMP-II U-Pb zir	Seltmann et al. (2011)
Kokshal segment	(1) Inylchek A-type granites (2) Terektinsky high-K calc-alkaline granitoids, on opposite sides of megashear	(1) 299–295 (2) 294–291	SHRIMP-II U-Pb zir	Konopelko et al. (2009)
	(1) Djangart, (2) Uch-Koshkon, (3) Mudryum and (4) Kok-Kiya A-type granites	(1) 296±4 (2) 279±8 (3) 281±2 (4) 281±3	SIMS U-Pb zir	Konopelko et al. (2007)
Eastern Tianshan				
Tarim-Junggar segment	High-K calc-alkaline and alkaline Borohoro granites	294–280	LA-ICP MS U-Pb zir	Wang et al. (2009)
	Cooling ages of biotite from mylonites in North Tianshan, Qingbulak-Nalati and Shangshuyuanzi Faults	285–245	^{40}Ar-^{39}Ar	Wang et al. (2009), Yin & Nie (1996), Zhou et al. (2001), Laurent-Charvet et al. (2003), De Jong et al. (2009)
	Cooling ages of mylonites in pre-Permian rocks	WR 285–255 bio 263.4±0.6 mus 253.3±0.3 bio 252.3±0.3	^{40}Ar-^{39}Ar laser step heating	De Jong et al. (2009)

Table 2. cont.

Province	Lithology	Age Ma	Analytical method	References
E Tianshan and Beishan	Mafic and ultramafic intrusions	278.6±1.2 –284±2.0	SIMS U-Pb zir	Qin et al. (2011)
Middle Tianshan and Beishan belts	Mafic and ultramafic intrusions	286–279	SIMS U-Pb zir	Su et al. (2011)
Tarim Basin				
North Tarim Uplift	Picrite-basalt-rhyolite suite	upper rhyolite 286±3.3 lower rhyolite 290±4.1	SHRIMP II and LA-ICP-MS U-Pb zir	Tian et al. (2010)
Keping area	Basalt	288±2.0 289.5±2.0	SHRIMP U-Pb zir	Yu et al. (2011)
Inner Mongolia				
Sonidzuoqi district	Basaltic andesite Rhyolite	289±3 287±3	SHRIMP U-Pb zir	Zhang et al. (2011)

Table 3. Timing of Permo-Triassic igneous complexes in northern Eurasia.

District	Lithology	Age Ma	Analytical method	References
Oslo Graben	Basalt, dolerite Syenite Syenite	310-300 c. 275 c. 250	^{40}Ar/^{39}Ar amph	Timmerman et al. (2009) and references therein
Chelyabinsk, E. Urals	?	242.2±0.6	^{40}Ar/^{39}Ar plagioclase	Reichow et al. (2009)
Vorkuta, N. Urals	Aphyric basalt	249.7±0.7	^{40}Ar/^{39}Ar plagioclase	Reichow et al. (2009)
Taimyr Peninsula	Plagioclase-phyric basalt flow	250.1±1.3	4^{40}Ar/^{39}Ar plagioclase	Reichow et al. (2009)
Bel’kov Island, New Siberian Islands	Gabbro (mafic to ultramafic complex)	252.3±2.4	U-Pb zir	Kuzmichev & Pease (2007)
Kolyuchinskaya Bay	Gabbro (intrusive in tholeiitic basalts)	252±4	U-Pb zir	Ledneva et al. (2011)
Noril’sk	?	250.3±1.1	^{40}Ar/^{39}Ar plagioclase	Reichow et al. (2009)
Putorana	?		^{40}Ar/^{39}Ar plagioclase	Reichow et al. (2009)
Angara-Taseevskaya syncline	Dolerite sills	240.9±1.8	^{40}Ar/^{39}Ar cleaned matrix	Ivanov et al. (2009)
Lower Tunguska River	?	248.9±1.2 251.8±1.5	^{40}Ar/^{39}Ar plagioclase	Reichow et al. (2009)
Kuznetsk Basin	Gabbro	250.6±0.4 251.8±0.6	^{40}Ar/^{39}Ar biotite	Reichow et al. (2009)
Donets Basin and Scythian Platform	Shonkinite, monzonite Andesite, trachyandesite	285-270 250-245	^{40}Ar/^{39}Ar plagioclase, amphibole, biotite, W.R.	Alexandre et al. (2004)

that the Central European, Tarim and Siberian LIPs emerged during or following the latest stages of the Variscides, the Southern Tianshan and the Western Altaids, respectively. In terms of orogeny, this stage is best characterised by their demise.

Tectonic setting of LIPs

In the Variscides, five processes and their combinations have been invoked to explain the demise of the orogen: delamination of the lithosphere, orogenic collapse, rollback of the subducting Palaeotethys oceanic plate, intracontinental mega-wrenching between Laurussia and Gondwana, and uplift by a superplume in conjunction with orogenic collapse. Many have suggested that collapse of the Variscan Orogen played an important role in its destruction (e.g., Ménard & Molnar 1988, Costa & Rey 1995, Diez Balda et al. 1995, Doblas et al. 1998, Echtler & Malavieille 1990, Echtler & Chauvet 1991–1992, Escuder Viruete et al. 1998, Fernández-Suárez et al. 2000, Gutiérrez-Alonso et al. 2011, Malavieille et al. 1990, Schulmann et al. 2002, Valle Aguado et al. 2005). Quantitative studies by Henk (1999) indicated that far-field forces and strike-slip deformation may have dominated. Ziegler et al. (2006) suggested collapse was initiated by the strike-slip deformation that had already been described and analysed by Arthaud & Matte (1977) and Bard (1997). In the Variscides, a relationship between orogenic collapse, the major strike-slip deformation across the orogen and its adjacent platforms, and the Early Permian volcanism was probably first proposed by Doblas et al. (1998) who extended the relation to an inferred breakup of Pangaea and the emergence of a mantle plume (see also Wilson et al. 2004, Timmerman et al. 2009). In view of the widely spread, relatively small complexes of primarily calc-alkaline volcanic complexes (Fig. 2), Doblas et al. (1998) coined the term ‘scattered igneous province’ for what Dobretsov et al. (2010) called the Central European LIP. Wilson et al. (2004) considered the option of a mantle plume but prefer, with reference to Van Wees et al. (2000), a complex combination of wrench-related lithospheric deformation, magmatic inflation of the lithosphere and thermal erosion at the base of the lithosphere.

In the Southern Tianshan, the interaction between orogeny and the Tarim LIP is still controversial. The termination of orogenesis is debated in conjunction with the apparent disparity in age estimates of the HP complexes (Gao et al. 1995, 1999, Gao & Klemd 2000, 2003, Klemd et al. 2005, Zhang et al. 2007, Xiao et al. 2010) as proxies for continent-continent collision and the closure of the oceanic basins north of the Tarim Block and the North China Continent (see also Biske & Seltmann 2010). These issues were discussed in detail by Wilhem et al. (2012) whose most relevant conclusion in the present context was the formation of the Turkestan suture between the Tarim and Kazakhstan continental blocks in the Late Carboniferous and the closure of the Solonker Ocean between Siberia and North China in the course of the Permian. Another important controversy concerns the geographical extent of the Tarim LIP in relation to the composition of the igneous complexes. Wan et al. (2013) concluded that the Tarim LIP affected only the region of the Tarim Basin. However, coeval mafic dyke swarms, (ultra)mafic intrusions, basalt flows and A-type granites in the Tianshan, north of the South Tianshan Suture, have also been viewed as elements of the same Tarim LIP, albeit in a different mantle province derived from metasomatized sub-continental lithospheric mantle with variable assimilation of crustal materials in a *non-orogenic setting* (e.g., Zhang et al. 2010a, b, Zhang & Zhou, 2013a, b). On the other hand, Wilhem et al. (2012) asserted that hydrous amphibole-bearing (ultra)mafic complexes amongst them are not an expected consequence of the plume activity supposedly underlying the Tarim LIP. Interestingly, mantle heterogeneity beneath the eastern Tianshan and Beishan was attributed by Su et al. (2011) to earlier subduction-processes. This concurs with the proposed role of subduction-related metasomatism and subsequent reactivation of the lithospheric mantle in the formation of postsubduction porphyry Cu-Au and epithermal Au deposits (Richards 2009, 2011) and mesozonal Au deposits (De Boorder 2012) as products of remelting of subduction-modified lithosphere.

In the Southern Tianshan, orogenic collapse has not been reported although Pirajno et al. (2008) recognized its feasibility in the accretionary-type orogens of the Altaids in conjunction with strike-slip faulting, and the emplacement of A-type felsic-mafic intrusions, flood-volcanism, (ultra)mafic intrusions and dyke swarms. Translithospheric strike-slip deformation has been advocated to have occurred in the Southern Tianshan in the course of the Permian (e.g., Allen et al. 1995, Laurent-Charvet et al. 2003, Charvet et al. 2007, Charvet et al. 2011, Yakubchuk et al. 2005, De Jong et al. 2009, Wang et al. 2009). Charvet et al. (2011) also suggested slab break-off following compressive deformation in the Central and Southern Tianshan. According to Vladimirov et al. (2008), the northwest-striking Char Suture in eastern Kazakhstan (Fig. 1) resulted from the Late Devonian-Early Carboniferous oblique collision of the Siberian and Kazakhstan plates. The Early Permian (ultra)mafic complexes along the northwest-striking Char belt are generally included in the Tarim Plume Event in view of their composition and their ages (Table 4). Their emplacement was controlled by strike-slip faults of the Char belt (Vladimirov et al. 2008). The prominent system of sinistral strike-slip faults with

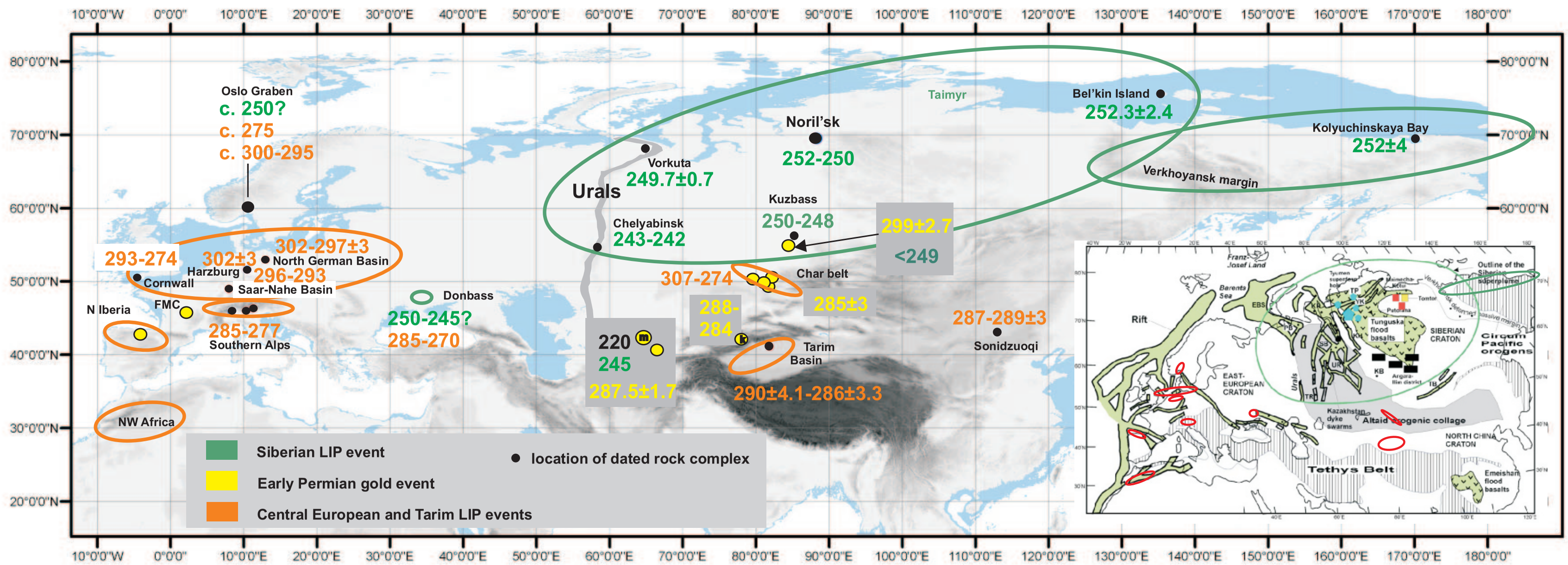

Fig. 1. Schematic overview of the distribution of Early Permian and Early Triassic Large Igneous Provinces in Europe and northern Asia, with estimates of the ages of igneous complexes (overall distributions schematically indicated with coloured ellipses) and gold deposits (yellow dots represent dated principal districts; m – Muruntau, k – Kumtor). For details, see Table 1-4. Inset shows the distribution of LIPs in relation to Permo-Triassic rift complexes as far as the eastern Atlantic; modified after Nikishin et al. (2002).

Table 4. Late Palaeozoic igneous complexes in the Char Belt.

Province	Lithology	Age Ma	Analytical method	References
Kalba batholith		290–274	U-Pb	Vladimirov et al. (2008) with reference to Travin et al. (2001)
Argimbai belt	Gabbro-plagiosyenite	293±2	SHRIMP II U-Pb zir	id.
	Picrite	278±3 280±3	^{40}Ar/^{39}Ar hbl, phlg	id.
Kalba-Naryn Zone	Kunush plagiogranite	307-299	SHRIMP II U-Pb zir	Vladimirov et al. (2008) with reference to Kruk et al. (2007)
Early Kalba cplx	Granodiorite-granite	295–274	U-Pb data	Vladimirov et al. (2008)
Late Kalba cplx	Granite-leucogranite	253–245	id.	id.
Monastyr cplx	Leucogranite	231–225	id.	id.
Irtysh/Erqishi Shear Zone	Mylonite	290–270, 285–270, 270–260	^{40}Ar/^{39}Ar mica, amphibole	Melnikov et al. (1998), quoted by Laurent-Charvet et al. (2003); Vladimirov et al. (2008) with reference to Travin et al. (2001)
	Gold-dominated deposits	285±3	^{40}Ar/^{39}Ar	Naumov et al. (2009)

widespread flower-structures is hosted by the northwest-striking Zaisan fold belt. In addition to these (ultra)mafic complexes, there are widely spread outcrops of granitoid rocks of the Kalba-Narym and Zharma-Saur batholiths. A zircon U-Pb SHRIMP-II age estimate indicates c. 293 Ma for a gabbro, with ^{40}Ar/^{39}Ar results of about 280 Ma for hornblende and phlogopite from picritic rocks. Vladimirov et al. (2008) concluded that an extraordinary heat source was required, not only to explain the (ultra)mafic complexes but also the accompanying felsic batholiths. They suggested the sources of the igneous complexes were located in a mantle plume, with reference to both the Tarim *and* the Siberian mantle plumes.

In western Siberia, Elkins-Tanton & Hager (2000) invoked removal of the mantle lithosphere in their explanation of the eruption of the Siberian flood-basalts. Elkins-Tanton (2005) suggested a role for lithospheric delamination in continental magmatism to explain the vast volumes of mafic melts of the Siberian LIP as an alternative to plume-related mechanisms. The Western Altaids, the western part of the Central Asian Orogenic Belt, are largely overlain by the West Siberian Basin; yet deep-

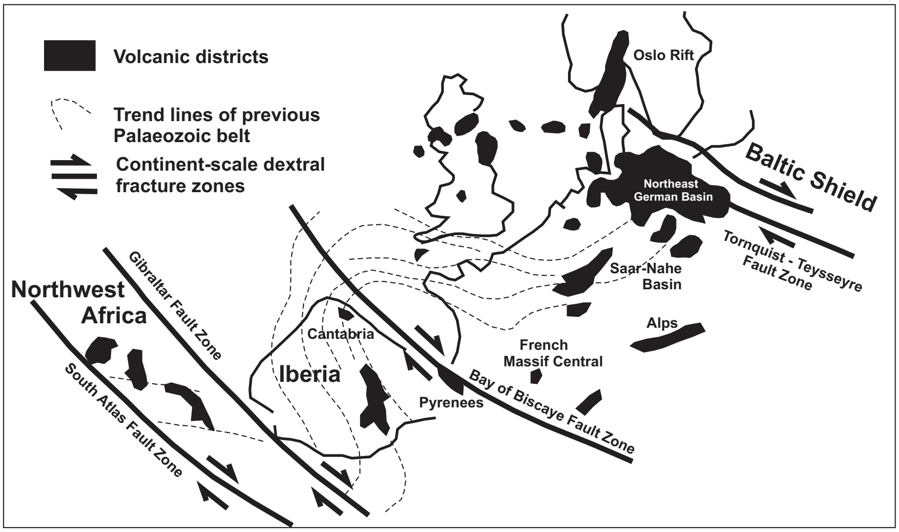

Fig. 2. Distribution of the complexes of the Central European Large Igneous Province; modified after Doblas et al. (1998).

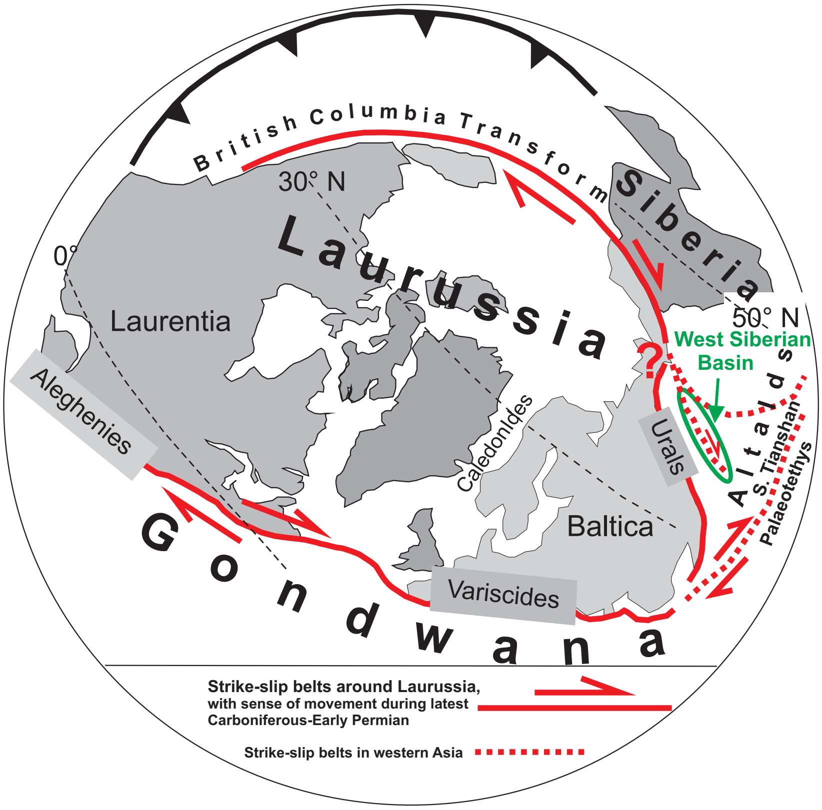

Fig. 3A. Overview of lithosphere plates during the Late Palaeozoic; modified after Sears (2012). Principal elements are the dextral British Columbia Transform along which the Siberian Craton moved to its current position, consistent with the dextral shear zones in the Urals and the West Altaid basement with the consequent pull-apart basins between the Baltic and Siberian Cratons (cf. Allen et al. 2006) as the roots of the West Siberian Basin.

reaching strike-slip deformation has been inferred between the Baltic and Siberian Cratons. Major strike-slip faults along the length of the basin are thought to have been responsible for the pull-apart nature of its rift basins (Allen et al. 2006 and references therein). The deformation was connected with the dextral strike-slip along the northeasterly striking Yenisey-Khatanga rift zone (Duzhikov & Strunin 1992). Consequently, a coherent translithospheric, transcurrent deformation belt of some 3000 km in length then dissected the region between the Baltic Shield to the west and the Siberian Craton to the east, and transected the northern margin of the Siberian Craton. Moreover, a Trans-Eurasian strike-slip fault has been inferred along the length of the Basin with links to the strike-slip faults in the Zaisan fold belt to the south, in eastern Kazakhstan (Şengör & Natal'in 1993, 1996, Allen et al. 1995, Yakubchuk 2004, Yakubchuk et al. 2005, Buslov et al. 2004). Vyssotski et al. (2006) pointed out that strike-slip faults are abundant in the sedimentary complexes of the West Siberian Basin. They drew an analogy with the South Permian Basin in northern Germany (see Wilson et al. 2004) where, as elsewhere in Western Europe, older structures were reactivated as deep-reaching strike-slip zones with concomitant production of mantle melts which variably invaded the crust. The strike-slip deformation in the West Siberian Basin has been correlated with the shear zones in the Urals (Allen et al. 2006). The inter-cratonic, intra-continental Western Altaid zone then comprises, in addition to the exposed Urals, (1) the western part of the Siberian LIP, (2) a largely hidden Altaid basement, (3) a major and complex Late Permian to Early Triassic rift system with pull-apart structures in a transcurrent shear belt of continental if not supercontinental proportions, and (4) a very substantial Mesozoic and Cenozoic, up to 15 km thick sedimentary complex. Nikishin et al. (2002) noted that collapse in the Urals coincided with development of the West Siberian Rift system and the onset of the flood-basalt extrusion. The flood-basalts and dykes in the northwestern part of the Craton domain to the east of the Basin most probably emerged along the Craton's margins because of easier access to shallow levels to the thicker lithosphere of its more cen-

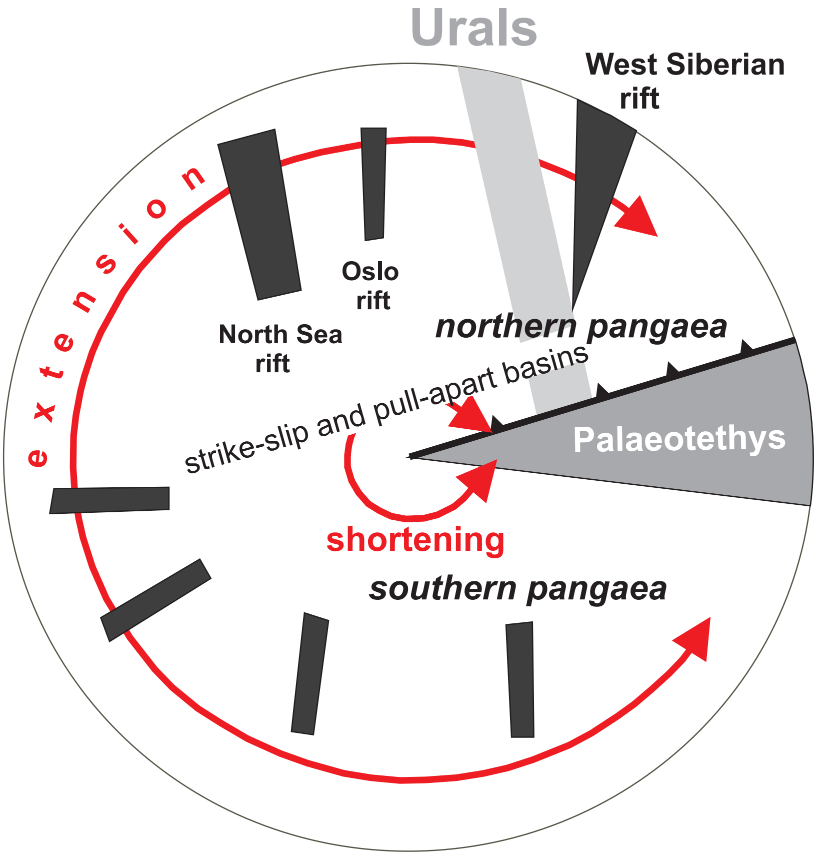

Fig. 3B. Schematic representation of the formation of the Pangaea supercontinent in relation to the closure of the Palaeotethys Ocean, with southern Pangaea subducting to the north underneath northern Pangaea; modified after Gutiérrez Alonso et al. (2008) whose model of 'self-subduction' involves transpression in the core of the supercontinent and extension in its periphery consistent with the translithospheric strike-slip zones in the central parts and the West Siberian Rift in the northern margin, consistent with the interpretation in Figure 3C.

tral parts (Begg et al. 2010). The flood-basalts and dykes in the southern part of the Craton have also been attributed to upwelling of mantle melts following detachment of subducted oceanic lithosphere of the Okhotsk-Mongol Ocean and evolution of a coeval mantle plume (Gladkochub et al. 2010).

While the Late Carboniferous-Early Permian strike-slip destruction of the Variscides and the Southern Tianshan rooted in the margins of Gondwana and Eurasia, the Permian-Early Triassic strike-slip deformation in the Western Altaids reflects the relative movements of the Baltic and Siberian Cratons. The nature and magnitude of this deformation, together with the displacement of the Siberian Craton along the dextral British Columbia Shear Zone (Fig. 3A) suggested by Sears (2012), probably compare in magnitude with the translation of Gondwana relative to Eurasia. The link between the shears in the Western Altaids and the British Columbia Zone, however, remains speculative in view of the uncertainties concerning the South Anyui Suture in the Chukotka Shelf of northern Siberia (Kuzmichev 2009). Yet, the suggested outliers of the Siberian LIP in the New Siberia Islands and Kolyuchinskaya Bay (Kuzmichev & Pease 2007, Ledneva et al. 2011, Fig. 1), may represent witnesses of this tectonic framework pointing to relatively small extensional domains, capable of pulling-up the local mantle. Buslov et al. (2010) attributed the Triassic flood-basalts in the Kuznetsk Basin to extension associated with the strike-slip deformation inferred by Allen et al. (2006) in West Siberia. According to Buslov et al. (2010), strike-slip faults were formed in the folded area separating the East European and Siberian Cratons which, with reference to Buslov et al. (2003, 2004), Dobretsov & Buslov (2011), Hetzel & Glodny (2002) and Laurent-Charvet et al. (2003), resulted from their Late Palaeozoic collision.

In summary, despite the Mesozoic and Cenozoic sedimentary cover of the Late Palaeozoic Western Altaid basement, deep-reaching strike-slip belts have been in-

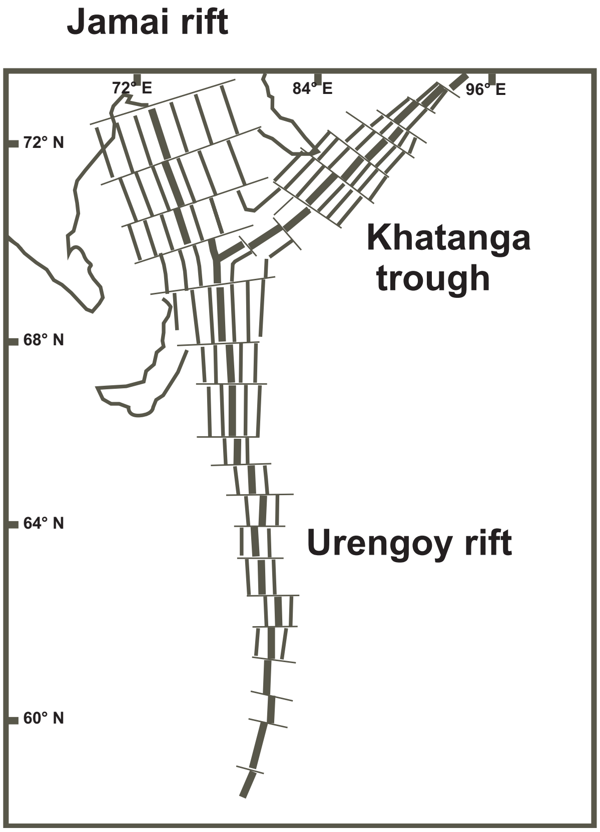

Fig. 3C. Interpretation by Aplonov (1995)of the magnetic anomalies in the region of the West Siberian Basin in terms of an aborted rift along the long axis of the West Siberian Basin and the northeast-striking Khatanga Trough, opening from north to south; modified after Aplonov (1995).

ferred from the magnetic anomaly map and from direct observations in the Urals and in the Altaids of Central Asia. These inferences constitute compelling indications of a geodynamic setting which is strongly comparable with the setting in the Variscan and Southern Tianshan regions in the Latest Carboniferous to the Early Permian. In all three cases, the old orogenic edifices were dissected by deep-reaching strike-slip deformation, possibly in combination with delamination and orogenic collapse, which reached into the subcontinental mantle with variable volumes of mafic and ultramafic melts finding a way into the crust and to the surface. Where stalled, the mantle melts transferred heat to the crust with the production of felsic melts and prominent ignimbrite flare-ups. This type of setting is consistent with the conclusions of Dewey (1988) concerning the possible formation of flood-basalt complexes in the course of orogenic collapse.

Setting of Variscan and S Tianshan gold deposits

The Late Carboniferous-Early Permian gold deposits in the Variscides and the Southern Tianshan have been interpreted as ‘orogenic’ (Bierlein & Crowe 2000, Bouchot et al. 1997, 2005, Goldfarb et al. 2005), ‘shear zone-hosted’ (Bellot et al. 2003, Drew et al. 1996), ‘intrusion-related’ (Sillitoe 1991, Drew et al. 1996) and ‘thermal aureole-hosted’ (Wall et al. 2004) deposits. At Muruntau, Cole (2001) suggested a dependence on both shears and intrusions. A recent model associated the mineralisation with translithospheric strike-slip zones and their extensional and compressional domains (De Boorder 2012). A relationhip with the hosting orogens was proposed to reside in lithosphere domains that were metasomatized during earlier subduction. The Late Carboniferous to Early Permian translithospheric shears were the most likely if not the only channels that could trigger decompression melting and tap these deep domains. The overall range of the estimated ages is from 311 to 277 Ma in the Variscides and from 293 to 269 Ma in the Southern Tianshan (De Boorder 2012). The shears of the northwest-striking Char belt, East Kazakhstan, to the north of the eastern part of the Southern Tianshan, host a number of Late Palaeozoic gold-dominated deposits coeval with the strike-slip deformation and the formation of the gold deposits in the Southern Tianshan between 288 and 282 Ma (Naumov et al. 2010). According to Naumov et al. (2010), Early Triassic ages of gold-dominated deposits in this belt may indicate reactivation and redistribution of primary ores, in line with observations by Wilde et al. (2001) at Muruntau and by De Jong et al. (2009) on fluid-rock reactions in the Southern Tianshan of northwestern China.

Associated metals

While an ore deposit may be known as a ‘gold’ deposit or a ‘tungsten’ deposit or ‘any metal’ deposit because of the metal’s economic significance, associated metals can quantitatively even predominate. The economic fame of the deposit, discarding the associated metals, is then easily turned into a tag which confuses questions concerning its origin and development. This overshadowing effect of economic significance is particularly manifest for the world class deposits. The Early Permian Muruntau district and the other prominent gold deposits in the South Tianshan are clear examples because with their dominating arsenic and tungsten contents they compare directly with the gold deposits of the French Massif Central. With their tungsten, tin and copper both districts compare with the tin-copper deposits in Cornwall. The bismuth-tellurium duo occurs not only in most Early Permian gold deposits but also in the Early Triassic giant nickel-copper deposits of the Noril'sk and Talnakh districts. These represent another instance of economic prominence with an important yet underexposed metal association. A possibly surprising but important aspect is the qualitative similarity of the diverse metal associations in deposits which were thought to have a primary relation with orogens on the one hand and with (ultra)mafic large igneous provinces on the other.

The Early Permian gold deposits in the Variscides and the South Tianshan show assemblages of associated metals including arsenic, tungsten, bismuth, tellurium, silver, antimony, copper, molybdenum, tin, nickel, lead, zinc and mercury (e.g., Boiron et al. 2003, Bouchot et al. 1997, 2005, Bril et al. 1991, Cole et al. 2000, Cole 2001, Graupner et al. 2006, 2010, Lescuyer 2005, Morávek et al. 1989, Rickleman et al. 2011, Romer & Soler 1995, Stanley et al. 1990, Wilde & Gilbert 2000). The differences are in volumes and grades rather than in kind. Elsewhere, several of these metals constitute their own acknowledged deposits which in turn contain small amounts of gold and/or other noble metals (e.g., Snee et al. 1988, Chen et al. 1993, Shail et al. 2003, 2009, Paniagua et al. 1988, Krupp 1989, Crespo et al. 2000, Munoz et al. 1992, Berger et al. 1994, Cole 2001, Mao et al. 2008a). Available age estimates show that these deposits formed at about the same time as the major recognised gold deposits. A comparable, disproportionate distribution is seen in metal assemblages associated with (ultra)mafic large igneous provinces.

At Noril'sk and Talnakh, the prominent Early Triassic Ni-Cu-PGE deposits contain a series of additional metals as there are gold, silver, bismuth, tellurium, antimony, cobalt, and mercury (e.g., Barnes et al. 2006, Spiridonov 2010) in alloys and sulphides. Elsewhere, some of these combined in deposits of other specific ore types, still in close association with the complexes of the Siberian LIP. Notable amongst these are the Co-Ni-As and Hg deposits (Borisenko et al. 2006, Goverdovsky et al. 2007, Dobretsov et al. 2010, Obolenskiy 2007) which were also formed in the Permian nominal gold districts of northern Iberia along the Bay of Biscay Fault Zone. Here, small coeval gabbroic bodies may represent a link to the Central European LIP.

Temporal coincidence of ore formation, termination of orogeny and inception of the Large Igneous Provinces

Central in the present discussion is the meaning of the close correspondence between the age ranges of the ore deposits, the cessation of orogeny and the inception of the respective large igneous provinces. Their coincidence in timing is the same in the three cases and leads to the relation between the demise of the orogen and the inception of the continental LIP and to the role of this relation in mineralisation. In this context, the Noril'sk-Talnakh district is important in four ways:

1. The setting of the Siberian LIP complexes is also defined by translithospheric strike-slip faults and large pull-apart basins which destroyed the Western Altaids orogen,
2. The consensus concerning the genetic relation of the Ni-Cu-PGE ores with the Siberian LIP complexes, including contamination by the continental lithosphere in general and by evaporite in particular,
3. The diversity of the other, hydrothermal, ore deposit types related to these complexes,
4. The diversity of the associated metals in the Ni-Cu-PGE deposits.

These four aspects of the Noril'sk-Talnakh district shed further light on the origin and the migration of the metals in both the Early Triassic *and* the Early Permian hydrothermal deposit types in the Central Asian and the West European theatres. In the Early Triassic Noril'sk-Talnakh district, the connection between the associated metals and the (ultra)mafic complexes has been clearly established. In the Permo-Carboniferous districts of Western Europe and Central Asia, several of these metals constitute ore deposits in their own right but their association with the LIP complexes, although locally inferred, is much less clearly, if at all, visible. Historically understandable without the only recently emerging more precise age estimates of ore deposits and hosting complexes, these deposits have been regarded in relation with their hosts as orogenic, late-orogenic, post-orogenic, post-collisional and post-tectonic. The underlying Central European and Tarim LIPs reinforce the similarity of the settings of the two Early Permian metal provinces with the Early Triassic Siberian setting. On the basis of the nature of metal and mineral associations, the differences are not necessarily essential. However, their hosting lithosphere domains were already orogenically defunct at the time of ore formation. As a consequence, the above temporal coincidences may well result from the same processes – there is no fundamental difference between the three orogen-LIP cases. They represent variations on a theme. Yet, the notably large volumes of the Siberian LIP remain puzzling if they have to be explained with the strike-slip mechanisms observed in Western Europe and Central Asia. At an even larger scale, however, the three events compare within the stress fields that shaped the Pangaea supercontinent.

The Pangaea context

Recently, Gutiérrez-Alonso et al. (2008) interpreted the closure of the Palaeotethys Ocean in terms of the amalgamation of Pangaea. Key elements of their thesis are the northward subduction of the Palaeotethys mid-oceanic ridge, the opening of the Neotethys Ocean, translithospheric strike-slip shear zones and associated pull-apart basins along the northern coasts of Palaeotethys, oroclinal bending of the Variscan Orogen in the core of the consolidating supercontinent and subsequent delamination of the thickened lithosphere of southwestern Europe. These elements played a role in the Early Permian gold mineralisation in the domains of the defunct Variscan and South Tianshan orogens (De Boorder 2012). At the scale of the Pangaea supercontinent, Gutiérrez-Alonso et al. (2008) distinguished a compressional stress regime in its core and an associated extensional stress field in its periphery (Fig. 3B). The Central European and Tarim LIPs and the gold mineralisation appear a logical consequence of the evolution of the stress field in the central parts of Pangaea. Major radial rift domains – 'peripheral seas' of the model – could account not only for the North Sea and Oslo Grabens in northern Pangaea, but also explain the West Siberian rifts (see Rasulov et al. 1997, Wilson et al. 2004). I submit that structures like an Ob Ocean (Fig. 3C) and the Urengoy and Jamai rifts (Allen et al. 2006, Rasulov et al. 1997) in the subsurface of the West Siberian Basin, together with the Khatanga Trough (Duzhikov & Strunin 1992) could qualify as such effects. The Siberian LIP was formed, not unlike the Central European and Tarim LIPs, in a framework of complex interaction of plate-scale processes which destroyed an orogen. The West Siberian orogen-LIP system is then distinguished from its Early Permian predecessors by an additional lithosphere breakup which accounts for the extraordinary volumes of the Siberian LIP melts.

Upward or downward control of LIPs and ores?

In the analysis of ore-forming processes, the interaction between mantle and crust has become increasingly important (e.g., Arndt & Christensen 1992, Begg et al. 2010, De Boorder 2012, De Boorder et al. 1998, Kerrich et al. 2005, Kerrich & Wyman 1994, Lorand et al. 1993, Morelli et al. 2007, Mao et al. 2005, 2008b, Pirajno 2000, 2009, White & McKenzie 1995). In this framework, the implications of proposed mantle plumes are often pitted against the dynamics of the lithosphere plates. In view of the temperature gradient between the core and the crust of the Earth (e.g., Davies 1998), hypothetical plumes emanating from the core cannot be refuted. Therefore, the mantle plume hypothesis will stay with us in its appealing simplicity and elegance despite the weakness of direct evidence (e.g., Class 2008, White 2010, Rickers et al. 2012). Time and again, however, lithosphere delamination has been invoked as the most plausible alternative for an active mantle plume (e.g., Begg et al. 2010, White & McKenzie 1995). However, this process has been just as often dismissed (e.g., Begg et al. 2010, White & McKenzie 1995) because it could not imaginably produce the observed large volumes of mantle melts, despite proposals to the contrary (e.g., King & Anderson 1995, Puffer 2001, Elkins-Tanton 2005, Ivanov 2007). The weakness of the active plume proposals is further emerging when indeed gravitational instability or delamination of the lower lithosphere are invoked as a secondary mechanism to explain the very magma volumes of the Siberian LIP (Saunders et al. 2007) – that is, the largest known continental large igneous province.

The antagonism is unproductive and impedes further understanding. A more rewarding approach aims at the mechanisms which directly generated the melts of the (ultra)mafic large igneous provinces and derivative ore deposits. Provided that mantle melting is initiated at depths of less than some hundred kilometres (Begg et al. 2010, White & McKenzie 1995), the segment of principal interest in metallogeny and mineral exploration is then in the relatively shallow subcontinental mantle. Consequently, given that after subduction had ceased continental mantle melts formed, if at all, on decompression, the 'top-down' processes are at a distinct advantage to explain the formation of LIPs and ore deposit types other than Ni-Cu-PGE deposits in the wake of orogeny.

The continent-scale, translithospheric strike-slip belts, with their drawn-out pull-apart conditions, which eventually helped destroying the preceding orogens, are observable and can be tested. At the cessation of orogeny these structures were the most adequate to access the bottom of the lithosphere and the subcontinental mantle domains that had earlier been modified by fluid-rock interaction in the course of subduction. The movements along these structures could trigger mantle melting and facilitate subsequent emplacement of the three LIPs during broadening extension, with invasion of the crust and emission at the surface. Active mantle plumes are not necessarily relevant.

Conclusions

- In Western Europe, Central Asia and Western Siberia, Late Palaeozoic and Early Mesozoic large igneous provinces formed in the course of the destruction of the orogenic edifices of the Variscides, the Southern Tianshan and the Western Altaids, respectively. This sequence, in three separate settings, is probably not fortuitous.

- The destruction of the orogens was most likely brought about by translithospheric, transcontinental, strike-slip dissection – possibly following or causing orogenic collapse and delamination of part of the lithosphere – and by rifting, all in relation to the amalgamation of Pangaea.
- The large-scale, deep-reaching deformation permitted upwelling of the sub-continental mantle.
- Early contamination of the mantle by subduction-associated fluxes may have been a factor in the production of the large volumes of (ultra-)mafic melts by lowering the melting temperature of individual mantle complexes.
- Orogenic collapse and delamination of the lithosphere could have led to thinning of the lithosphere and consequent shallow decompression melting.
- These melts did not require active mantle plumes as a heat source.
- The plume hypothesis cannot be refuted despite the weakness of direct evidence.
- The plate hypothesis cannot be disregarded because of the strength of direct evidence.
- Direct and indirect age estimates of ore deposits of different types (including gold-antimony-mercury, gold-mercury, mercury; tin-tungsten; tin-copper; copper-molybdenum) suggest a link with the above LIPs. The occurrence of precious and other base metals in the Ni-Cu deposits, as in the Noril'sk-Talnakh region, suggests that concentrations of those metal associations, generally considered to have been of orogenic affiliation, may have been derived directly from LIP-associated mantle sources as well.

Acknowledgements

Helpful suggestions by Franco Pirajno and Xiao Wenjiao are much appreciated. My sincerest thanks go to Professor Dr. R. Seltmann for his hospitality, his continuous interest in my work, his support and frank discussions.

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Received 18 March 2013
Accepted 10 August 2013