Paleozoic large igneous provinces of Northern Eurasia: Correlation with mass extinction events

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ABSTRACT

This paper assesses data from recently described major Paleozoic large igneous provinces (LIPs), mostly in Northern Eurasia. The 10 LIPs reviewed form a unimodal distribution in terms of volume. Eight LIPs have an initial modal volume greater than 0.1×10^6 km^3. The rift associated basalts of 2 LIPs from the end of the Late Cambrian Period and the end of the Late Ordovician Period do not occupy a large volume. Some of the provinces were discovered or rediscovered relatively recently and dating is still approximate, but most provinces fit a simple model in which volcanism persisted on the order of 10–20 Myr, often resulting in continental break-up. Correlation between LIP ages and the ages of geological events in the Paleozoic Era that reflect mass extinctions and oceanic anoxia agrees with correlations suggested by Courtillot (1994) and Courtillot and Renne (2003) for the Cenozoic and Mesozoic eras, considering that the absolute dating of some Paleozoic LIPs needs to be strengthened in the future.

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1. Introduction

Enormous lava eruptions formed large igneous provinces (LIPs) with millions of cubic kilometers emplaced in relatively short time intervals. Such magmatic events have been most likely initiated by the uplift of hot material from the core–mantle boundary and occurred several times during the Cenozoic and Mesozoic eras in the history of the earth. Many LIPs can be linked to continental rifting and breakup as well as noticeable climatic perturbations. Mesozoic–Cenozoic hotspot volcanism (i.e., the surface manifestation of mantle plumes) and LIPs preferentially occur in the two major large regions, away from subduction zones — the African and Pacific low shear velocity provinces (Courtillot et al. (2003), Li and Zhong (2009), and references therein). Paleozoic and Precambrian LIPs are typically deeply eroded; they may occur in completely subducted oceans and therefore cannot be identified or well described. Usually such LIPs are represented by giant dyke swarms, sill provinces, and layered intrusions. Courtillot (1994) suggested that major mass extinctions are caused by the global changes triggered by gigantic magma eruptions in the past. Courtillot and Renne (2003) reviewed the occurrence of the 15 large continental basalt provinces in Cenozoic and Mesozoic eras and correlated them to major mass extinctions and paleoclimatic episodes as well as to the geological period boundaries.

In this paper I assess the Paleozoic LIPs from 300 to ~550 Ma discovered to date and correlate their formation to the largest mass extinctions. Courtillot (1994) and Courtillot and Renne (2003) published such correlations for the last 260 Myr and included the Viluy trap event (~365 Ma) from Kravchinsky et al. (2002). The mechanism responsible for correspondence of a particular mass extinction to an igneous event in such a correlation for the Paleozoic Era should be verified in detail in the future (see discussion of the possible mechanisms in Archibald et al., 2010). This paper suggests a correlation for the whole Phanerozoic Eon. Paleozoic LIP allocations often appear ambiguous because of sporadic descriptions of Paleozoic volcanic provinces and poor availability of reliable dates for the formation of such provinces.

Discovery, dating, and identification of Paleozoic LIPs are complex processes that can take decades of energetic multidisciplinary studies to accomplish. Multiple geological processes that follow the eruption events (accretion with other continents, metamorphism, burial under thick sedimentary covers, etc.) can destroy or hide ancient LIPs partially or completely. Therefore it is unlikely that we will uncover Paleozoic LIPs larger or equal in size to Mesozoic or Cenozoic LIPs. Magmatic events that occur in the ocean, such as the formation of the Mesozoic Java Plateau in the Pacific Ocean, might be almost entirely erased by subsequent subduction processes. Nevertheless, because of discovery and description in the literature of more Paleozoic LIPs during the last decade it has become possible to correlate the timing of the gigantic magmatic events with major Paleozoic mass extinctions. Kuzmin et al. (2010) reviewed recent advances in age determination and localization of the Northern Eurasia igneous provinces and summarized both international and Russian sources.

Recently, Li and Zhong (2009) suggested that circum-supercontinent subduction may lead to the formation of antipodal superplumes like

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African and Pacific plumes observed today. Superplumes could gradually move with their coupled supercontinents toward equatorial locations through true polar wander events, eventually leading to the breakup of the supercontinents. This would indicate that some of the antipodal plumes occurred in the ocean as did the Java Plateau formation. When magmatic signatures are absent at the continent, traces of such plumes can be sought in the remaining fragments of ophiolite zones or oceanic islands.

2. Paleozoic large igneous provinces

Recently, Bryan and Ernst (2008) defined that an LIP should primarily be composed of mafic rock with areal extent $>0.1 \times 10^6$ km^2 and an igneous volume of $>0.1 \times 10^6$ km^3. The maximum extent of magmatic activity is about 50 Myr with eruption of the major magmatic volumes during short pulses of 1–5 Myr. Most of the large igneous provinces discussed in this study are located in Eurasia (Fig. 1 and Table 1) which occupies ~36.2% of the total land area of the earth and has been intensively studied in the last decade.

Cenozoic and Mesozoic LIPs and several Late Paleozoic LIPs (Siberian Trap Province and Emeishan traps) have been described by Courtillot and Renne (2003) and Courtillot and Olson (2007). I start my brief assessment with the Skagerrak-Centered LIP that was formed at the Moskovian/Kasimovian boundary and finish with the oldest Volyn province (end of the Ediacaran Period). Table 1 lists Paleozoic LIPs of Northern Eurasia. The references in Table 1 provide detailed descriptions of the igneous provinces and their age constraints. Ages of the major mass extinctions are taken from Benton (2001) and Rohde and Muller (2005) (Fig. 2). The figure illustrates the promising correspondence between the major mass extinctions and LIPs occurrence.

Kuzmin et al. (2010) demonstrated that the Siberian continent and its surroundings have been situated above the African hot mantle plume during the entire Phanerozoic Eon moving from equatorial latitudes to the present day Icelandic hot spot position. The Permo-Triassic Siberian trap eruption occurred above the Icelandic hot mantle upwelling which was situated roughly at its present day hot spot location. The present day African plume is defined as the African large low shear velocity province (LLSVP) and considered to be a prolongation of the Pangean superplume (Li and Zhong, 2009). The African LLSP extends from equator to high latitudes and is manifested by the hot spots (Courtillot et al., 2003). Siberia left the plume zone only in the Late Mesozoic Era. As a result, the Siberian Platform and surrounding terranes contain traces of many major Paleozoic LIPs (Table 1). The dataset would be improved with more reliable dating,

nevertheless, it already suggests that the correlation between LIPs and mass extinctions may have continued into the Paleozoic Era. The Kalkarindji LIP from the end of the Early Cambrian, situated in Australia, does not have an age analogue in Eurasia but is included because it is correlated with the mass extinction at the end of the Cambrian Period.

Torsvik et al. (2008) described the Skagerrak-Centered Large Igneous Province (SCLIP) that occupies an area of more than 0.25×10^6 km^2 and a volume of more than 0.5×10^6 km^3. In a Pangea A type reconstruction, Torsvik et al. (2008) restored the center of the SCLIP eruption using a new reference frame, and tested the idea that a Skagerrak plume rose from the core–mantle boundary (CMB) to its ~300 Ma position. The major eruption interval took place in very narrow time interval 297 ± 4 Ma. The rift formation coincides with the Moskovian/Kasimovian boundary and the Carboniferous Rainforest Collapse (Sahney et al., 2010). The largest Skagerrak graben developed as an intracontinental rift.

The Late Carboniferous–Early Permian Barguzin–Vitim LIP demonstrates a zonal structure and covers an area of over 0.15×10^6 km^2 (Kuzmin et al., 2010). The age of the basite intrusions is 302–275 Ma (Litvinovsky et al., 1992; Yarmolyuk et al., 1997). Kuzmin et al. (2010) considered that the heating effect of the basaltic magmas on the upper crust resulted in an abundant crustal anatexis and caused formation of the granitoid batholiths. The central part of the province is occupied by the largest Angara–Vitim batholith composed of granitoids of different composition. The age of the batholith formation is determined to be 305–275 Ma using U–Pb and Rb–Sr data (Yarmolyuk et al., 1997; Tsygankov et al., 2007). The rift zones containing alkaline rocks are found at the batholith's periphery: Uda–Vitim, Synnyr, and Eastern Sayan. One more zone, Saizhen, is situated along the axial part of the batholith. The U–Pb, Rb–Sr, and Ar–Ar ages of the rifting magmatism are slightly different in different zones (Kuzmin et al., 2010). The Synnyr zone has an age of 300–285 Ma, the Saizhen zone has an age of 290–288 Ma, and the Uda–Vitim zone has an age of 290–275 Ma. It is still unknown if the major volume of magmatic activity is associated with one of the zones or is more or less equally distributed among the zones.

The Viluy LIP covers most of the present day north-eastern margin of the Siberian Platform. The triple-junction rift system was formed during the Devonian Period (Kuzmin et al., 2010); the Viluy rift is the western remaining branch of the system and two other branches form the modern margin of the Siberian Platform. The Viluy rift is 800 km long and 450 km wide (Kiselev et al., 2006). Volcanic rocks are covered with post Late Devonian–Early Carboniferous sediments. The earliest magmatic rocks in the area erupted in the Silurian Period
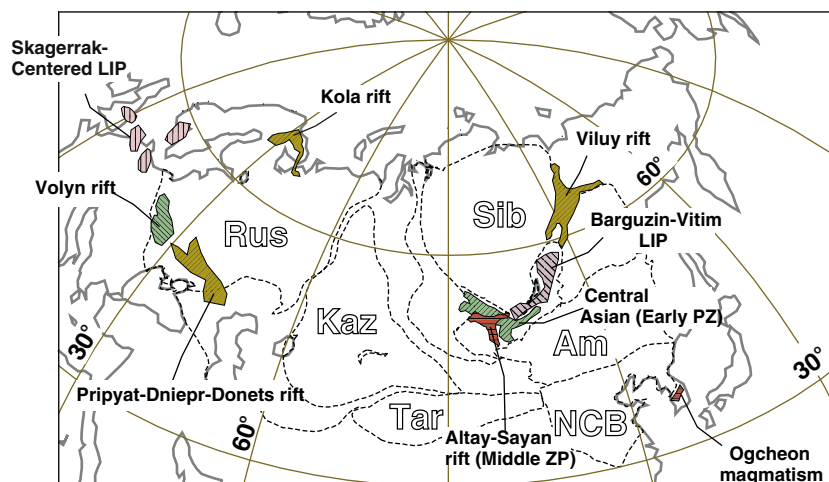

Fig. 1. Location of the Paleozoic large igneous provinces in North Eurasia (see Table 1 for details). Am - Amuria terrane; Kaz - Kazakhstan terrane; NCB - North China Block; Rus - Russian platform; Sib - Siberian platform; Tar - Tarim platform.

Table 1
Paleozoic intraplate magmatic provinces.

	Large igneous province (LIP)	Location	Mean age (age range) for LIP (Ma)	Age of mass extinction event (Ma)	Corresponding geological event	Area (10⁶ km²)	Volume of basalts (10⁶ km³)	Key references for the LIP's description
1	Siberian traps and West-Siberian rift system	Siberian platform, West Siberian plane	250 ± 1	250	End Permian	>4	>3	Courtillot and Renne (2003); Kuzmin et al. (2010)
2	Emeishan traps	China	259 ± 3	258	End Guadalupian	>0.5	>1 (?)	Courtillot and Renne (2003)
3	Skagerrak-Centered	Northern Europe	297 ± 4 (285–310)	296–310	Carboniferous Rainforest Collapse (Moscovian and Kasimovian stages)	0.25	0.5	Torsvik et al. (2008)
4	Barguzin–Vitim	Baikal Folded Belt, Trans-Baikalia, Mongolia	(275–310)	296–310	Carboniferous Rainforest Collapse (Moscovian and Kasimovian stages)	0.15	0.3	Kuzmin et al. (2010)
5	Viluy	East of Siberian platform	(350–380)	342	End Tournasian	>1	>1	Kravchinsky et al. (2002); Kuzmin et al. (2010); Courtillot et al. (2010)
				363–367	End Famennian–end Frasnian			
6	Pripyat–Dniepr–Donets	Russian platform	(364–367)	360–375	End Frasnian	>1	>1.5	Kusznir et al. (1996); Wilson and Lyashkevich (1996)
7	Kola/Kontogero	Russian platform (Kola peninsula)	(363–370)	360–375	End Frasnian	>0.1 (?)	>0.1 (?)	Kramm et al. (1993); Downes et al. (2005)
8	Altay–Sayan	South of Siberian platform	(393–408)*	410–430	End Silurian (?)	0.35	0.1	Kuzmin et al. (2010)
					Late Silurian extinctions (?)			
9	Unknown (Ogcheon area indicates mantle plume)	South Korea	(430–480)*	440–450	End Ordovician	–	–	Cluzel (1992)
10	Central Asian intraplate magmatism (LIP?)	South of Siberian platform	(470–510)*	497–502	End Late Cambrian/ Dresbachian (?)	>0.025	>0.05	Vrublevskii et al. (2009); Yarmolyuk et al. (2002; 2003)
11	Kalkarindji	Australia	(503–510)	510	End Early Cambrian	>1	>0.15	Glass and Phillips (2006)
12	Volyn (LIP)	Ukrainian Shield	(545–580)*	542–545(?)	End Ediacarian (?)	>0.2	>0.3	Elming et al. (2007)

Note: Absolute dating of the Paleozoic LIPs that needs to be strengthened in the future is marked with the asterisk.

(Gaiduk, 1987). A gently sloping depression filled with carbonate–clay sediments was formed in the Middle Devonian Period along the axis of the forthcoming Viluy rift. A system of grabens and minor depressions developed in the Viluy rift structure during the Frasnian age accompanied by an enormous volume of basalt intrusions. The intensity of tectonic movements and volcanic activity gradually declined during the Early Carboniferous Period. The gigantic volume of magmatic material in the three branches of the Viluy rift is at least 1×10^6 km³ (Kuzmin et al., 2010). On the basis of paleomagnetic data, Kravchinsky et al. (2002) suggested that the major stage of Viluy trap magmatism could have occurred in a relatively short time interval around the Frasnian–Famennian boundary and that this stage correlates well with the mass extinction during this time. Scarce Ar–Ar data indicate that the magmatism age ranges within 380–350 Ma (Kiselev et al., 2006). Recent absolute dating of samples using both K/Ar and ^{40}Ar/^{39}Ar techniques (Courtillot et al., 2010) demonstrated that the major phase of Viluy magmatism could indeed have been restricted to the period 360–370 Ma. Their preliminary result indicates possible proximity between this magmatism and the age of the Frasnian–Fammenian mass extinction now considered to have occurred ~376 ± 3 Ma and/or at the end of the Devonian ~361 ± 3 Ma (Gradstein et al., 2005; Kaufmann, 2006). Courtillot et al. (2010) suggested that the Viluy magmatism could have occurred as a series of several major pulses, as is now found to be possible in several flood basalt provinces (Courtillot et al., 1999; Chenet et al., 2009).

Several other large trap occurrences are now well known in the Late Devonian. Volcanic activity was accompanied by rifting and kimberlite magmatism in the Pripyat–Dniepr–Donets (PDD) aulacogen. Two-thirds of the rifting in this area of the Russian Platform occurred rapidly between 367 and 364 Ma (Kusznir et al., 1996; Wilson and Lyashkevich, 1996). Major and trace element and Sr–Nd isotopic analyses of the most primitive basic and ultrabasic magmas strongly suggest that magmatism was triggered by the upwelling of a mantle plume in the Late Frasnian. The 2000 km-long NW–SE trending PDD rift transects the southwestern part of the Russian Platform. Two Precambrian basement structures, the Ukrainian Shield to the north and the Voronezh Massif to the south, enclose the PDD rift defining its dome structure at more than 1000 km in diameter. The minimum size of the rift system is ~1×10^6 km² and the volume is at least 1.5×10^6 km³.

An extensional tectonic regime prevailed in the northern part of the Russian Platform during the Devonian Period. There are formations of this age in the Pechora Basin and tectonic grabens in Novaya Zemlya, the Kola Peninsula (Kola Alkaline Carbonatite Province), and possibly the eastern Barents Sea (Gudlaugsson et al., 1998). Voluminous alkaline magmatism occurred in the Kola Peninsula from 380 to 360 Ma, coinciding with the subsidence of the NE–SW trending Kontogero graben (Kramm et al., 1993), and contemporaneous with Late Frasnian–Famennian (363–370 Ma) alkaline magmatism in the Dnieper–Donets rift on the southern margin of the Russian Platform and Viluy magmatism in Siberia. The Kola Alkaline Province is characterized by features that resemble typical manifestations of plume magmatism (Downes et al., 2005; Kogarko et al., 2010). The total volume of magma that formed the Kola magmatic province is estimated to be at least 15,000 km³ (Arzamastsev et al., 2001), but this does not take into account the possibility of an eroded lava cover. If the magmatism was extended to the surrounding areas and eroded parts were taken into account, the volume could reach at least 0.1×10^6 km³.

Clearly, the end of the Devonian Period was a time of extremely widespread trap magmatism and rifting in the Russian and Siberian platforms, which were situated above the hot mantle plume (Kuzmin et al., 2010). Sedimentary constraints on the age of rifting and available geochronological data appear to be compatible with the idea that much of the magmatism was short-lived and coeval near or at the time of the Frasnian–Famennian boundary. This is the time of the largest mass-extinction event before the end of the Paleozoic Era (Benton, 2001; Rohde and Muller, 2005).
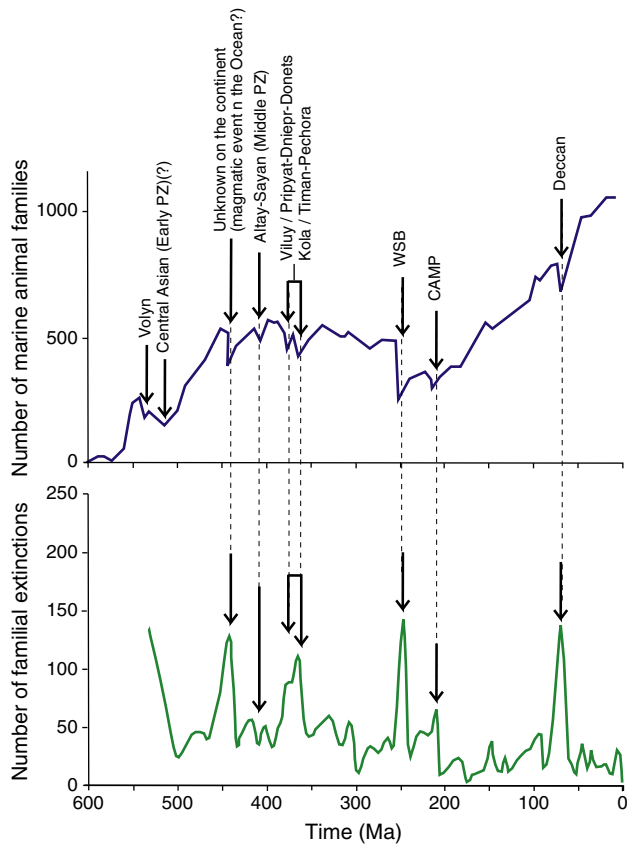
Fig. 2. Number of marine well-sceletonized animal families (top) and extinction rates for the marine animal families (modified from Benton, 1993, 2001, and Rohde and Muller, 2005). Only major extinctions are marked with the names of the correspondent large igneous provinces from Table 1. WSB — West Siberian trap basalts, CAMP — Central Atlantic Magmatic Province.

Recently, Kuzmin et al. (2010) summarized characteristics of the magmatic province called the Altay–Sayan LIP which is located in the south-western folded area of Siberia (Fig. 1 and Table 1). The region encompasses a total area of 0.35×10^6 km^2 (the Minusinsk basin, Tuva, Eastern and Western Sayan, and north-western Mongolia). The magmatism on different sites of the igneous province occurred more or less simultaneously and the peak of its activity was reached during a relatively narrow time span from 408 to 393 Ma in the triple-junction graben system (Kuzmin et al., 2010). Enormous lava eruptions of basic composition (basalts, esitobasalts, tephrites, and trachybasalts) and phonolites, trachytes, and comendites accompanied rifting. Intrusives of teschenites, alkali granites, and syenites were formed at the same time (Yarmolyuk and Kovalenko, 2003). Magmatic activity was abruptly reduced in the Middle Devonian Period. Kuzmin et al. (2010) estimated that more than 0.1×10^6 km^3 of magmatic rocks were formed from 490 to 400 Ma with a short duration peak of magmatic activity 408 to 393 Ma. This age interval coincides with the end of the Silurian Period.

The Ogcheon metamorphic belt in South Korea has always been interpreted to be an oceanic suture zone. Cluzel (1992) was first to demonstrate that the basalts in the belt are of intraplate magmatic origin. The Ogcheon belt is composed of Cambrian to early Ordovician quartzite and carbonate platform sequence overlain by a thick volcano-sedimentary sequence; the volcanic rocks have been ground into sediments. Cluzel (1992) concluded that the Ogcheon metavolcanics and associated metasediments were indicators of an Ordovician–Silurian intracontinental rift. Most of the basic volcanic rocks were emplaced as hypabyssal metavolcanic complexes (sills, dykes, and laccoliths) while the acidic volcanic sequences are mainly pyroclastic flow

or fall deposits and volcano derived sedimentary rocks. Taking into account both the overall characteristics of the sedimentary environment and the petrological and geochemical features of the volcanic component, the sequences appear to have evolved in an intracontinental rift and do not represent oceanic remnants as previously thought. Unfortunately, age is estimated only on the basis of stratigraphy and relation with sediments. Absolute dating gives only ages of metamorphic events. There are no other clearly described remnants of intraplate magmatic events of large scale from the end of the Ordovician Period to the beginning of the Silurian Period. Li and Zhong (2009) discuss that two mantle plumes most likely have been coexisting during most of the Phanerozoic Eon. Perhaps LIP(s) formed in the end of the Ordovician Period are analogous to the present day Java plateau in the Pacific Ocean. In such case we may search for the remains of these LIP(s) in the suture zones of present day continents only. Subduction processes could destroy a large part of such an oceanic LIP plateau. Discovery of the Ogcheon basalt magmatism offers hope of finding of the LIP remains of the Ordovician–Silurian age.

Yarmolyuk et al. (2003) identified a large area of mantle plume related magmatism south of the present day Siberian platform in the Central Asian magmatic province with age from Late Cambrian to Early Ordovician. They used geochronological and geochemical data from picritic, gabbroid, and alkali basalt associations to characterize the age of the plume magmatism. Vrublevskii et al. (2009) obtained new ^{40}Ar–^{39}Ar and Sm–Nd data from a volcanic complex that demonstrate that the magmatic province developed mostly between 510 and 470 Ma. The time interval is still too large to conclude firmly the correspondence to the mass extinction at the end of the Cambrian Period. More study is required in order to precisely evaluate the size and volume of the LIP and the timing of the major magmatic event.

The vast scale of mantle derived magmatism and sequential granite massif formation was caused by the influx of a mantle plume under Central Asia. Kuzmin et al. (2010) summarized the data that demonstrate that gigantic granite massifs were formed in a few phases by both the mantle plume and subduction related magmatism. Basic magmatism is present in Central Asian terranes of various thickness and evolutionary histories in the lithosphic mantle: Gorny Altay, Salair, Western Sayan, Kuznetsk Ala-Tau, Gornaya Shoria, Western Mongolia (island arc terrains), and Eastern Sayan (island arc and old rifting terrains) (Yarmolyuk et al., 2003; Vrublevskii et al., 2009). The approximate size of the province is $>0.3 \times 10^6$ km^2 and the magmatic volume (excluding granite massifs) is $>0.15 \times 10^6$ km^3 (estimated after Vrublevskii et al., 2009).

Another Cambrian extensive basaltic volcanism occurred across northern and western-central Australia, the so-called Kalkarindji continental flood basalt province, during the Early Cambrian Period. Glass and Phillips (2006) described the basalts as geochemically distinctive, having unusually uniform elevated incompatible element signatures (high Th/U, La/Sm, and Rb/Ba) compared to most other continental flood basalt provinces. A relatively homogeneous continental crustal signature characterizes the Kalkarindji basalts. High-precision ^{40}Ar/^{39}Ar analyses of plagioclase feldspar from basalt flows yield ages of 508 ± 2 Ma and 505 ± 2 Ma, identical to the previous U–Pb zircon ages for dolerites. Glass and Phillips (2006) concluded that these ages indicate that basaltic volcanism coincided with the Early–Middle Cambrian boundary and suggested a temporal link between eruption of the Kalkarindji basalts and the faunal mass extinction event at the end of the Early Cambrian (Early Toyonian). The size of the province is $>1 \times 10^6$ km^2 and the total magmatic volume is $>0.15 \times 10^6$ km^3.

In Ukraine the Ediacaran age volcanic rocks are subdivided into the Volyn, Mogilev–Podolia, and Kanilov series of sedimentary and volcanogenic rocks, which are exposed in the Peridniester region and near the town of Rivne. The basalts of the Volyn series, and their equivalents, occur on the western margin of the Ukrainian Shield which is part of the Russian Platform, and occupy some 0.2×10^6 km^2 of the

subsurface from Moldavia to Lithuania (Bialowolska et al., 2002). The traps are located on the southwestern erosional boundary of the Ukrainian Shield. The maximum thickness of the basalts is 225 m and their distribution is controlled by NW–SE trending faults. The isotopic and geochemical characteristics of these basalts are very similar to those of basalts from other continental trap provinces (Bialowolska et al., 2002). The Ediacaran volcanic activity in the Volyn area was discontinuous, and the basaltic sheets are interbedded with tuffs and sedimentary rocks of different types. The effusive rocks of the Volyn series are derivatives of weakly differentiated tholeiitic magma. Elming et al. (2007) reviewed the available dates and performed $^{40}Ar/^{39}Ar$ studies of whole rock on a few lave flows concluding that the basalt eruption occurred 590–545 Ma. It is still the only reliable data from the Volyn trap province and it is not known when the major eruption occurred. I suggest the large eruption occurred during the end of Ediacarian Period when a major mass extinction occurred (~545 Ma).

3. Discussion

Fig. 3 suggests that the correlation between LIPs and mass extinctions suggested by Courtillot (1994) and Courtillot and Renne (2003) may be prolonged into the Paleozoic Era, although the ages of many basalt provinces are based on a relatively small number of studies. Question marks on Fig. 3 highlight more problematic correlations where the age error bar is too large or the size of the province is not large enough. It is not expected that these data will soon be improved, as most Paleozoic LIPs have been largely "erased" by the tectonic and geological processes they provoke.

Kidder and Worsley (2010) reviewed recent studies confirming that LIPs can trigger HEATT (haline euxinic acidic thermal transgression), a mechanism that can force a climate conversion from greenhouse to hothouse. The authors proposed that HEATT led to an increase in primary productivity and thus dominance of primitive green algae and/or cyanobacteria. Progressive euxinia caused restrained primary productivity of the photic zone resulting in eukaryotic mass extinction. Kidder and Worsley (2010) suggested that the 16 Late Paleozoic–Mesozoic mass extinctions were caused at least in part by the HEATT process and provided convincing evidence that HEATT was a factor in 11 of the most severe extinctions. Less reliable data sets for the other five mass extinctions also suggest HEATT-related causes.

Kidder and Worsley (2010) were not able to associate most of the Early–Middle Paleozoic extinctions with LIPs because such magmatic provinces are not well described in the literature. Fig. 3 of this study links such extinctions with Eurasian magmatic provinces, assuming that the LIPs from Table 1 are manifestations of possibly even larger events in the ocean. In Eurasia, only the Cambrian Central Asian area of intraplate magmatism does not satisfy the definition of an LIP because of its diminutive size (Yarmolyuk et al., 2002, 2003; Vrublevskii et al., 2009). The event occurred in the ocean and the remains are limited to the magmatic realm exposed in the fragments of the Tuva–Mongolian composite terrane (Kuzmin et al., 2010).

Courtillot and Olson (2007) proposed that the Ordovician Moyero Long Reversed Superchron (~30 Myr) preceded the extinction event caused by a large-scale mantle plume at the end of the Ordovician Period. An end-of-Ordovician LIP has not been discovered on the continent. Possibly the province could be reconstructed piece by piece from relics of the Ordovician oceanic islands or small terranes. Cluzel (1992) described one such terrane, the Ogcheon belt metavolcanics in southern Korea. Metasediments associated with the metavolcanics were emplaced in an Ordovician–Silurian intracontinental rift. The size of the belt is negligible compared with the LIP definition; nevertheless it suggests that such an event occurred.

Lefebvre et al. (2010) modeled the existence of a low latitude mantle superplume using data from carbon, alkalinity, and phosphorus cycles coupled with an energy-balanced climate model in order to explain both the mid-Ashgill (Katian) global warming event and the subsequent Late Ordovician (Hirnantian) glaciation. Li and Zhong (2009) suggested that an antipodal plume, similar to the present day Pacific plume, led to the breakup of supercontinent Rodinia around
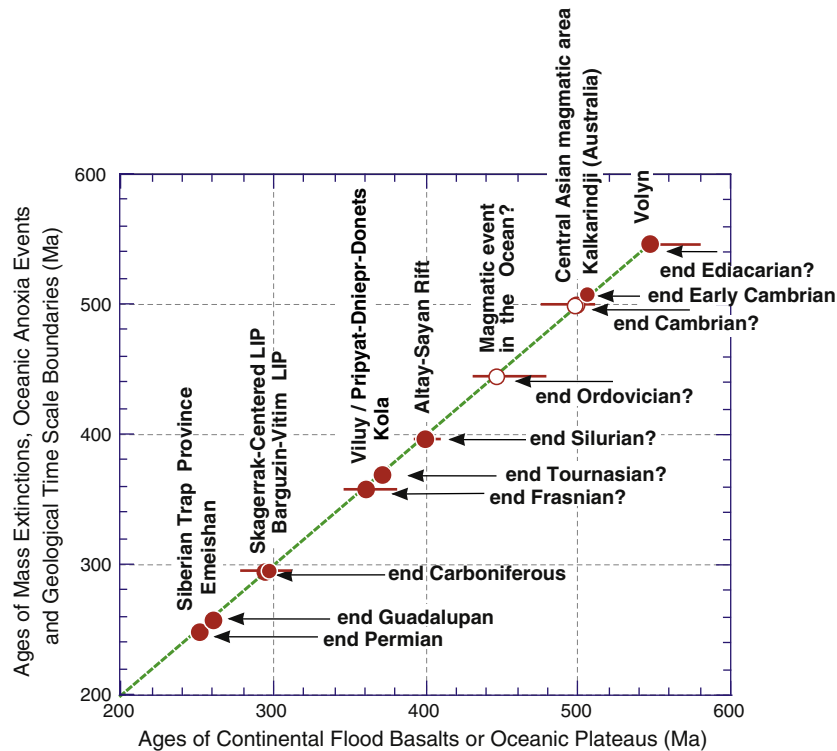

Fig. 3. Correlation between LIP age (horizontal axis), and age of mass extinctions and oceanic anoxia events (vertical axis) for Paleozoic Eon. Uncertainties are observable only when they are bigger than the diameters of the circles corresponding to particular events. Open symbols correspond to volcanic areas not large enough to be considered LIPs.

750 Ma. Possibly the magmatic rocks generated by the plume were subducted or in part preserved in the Late Proterozoic–Early Paleozoic orogenic metamorphosed zones and cannot be easily identified today. After Rodinia's breakup the continents began moving in different directions from the antipodal plume that "pushed" them away. Kuzmin et al. (2010) proposed that the present-day African plume could have existed throughout the Phanerozoic eon. By analogy, the plume under Rodinia could have survived long after Rodinia's break-up, initiating magmatic events such as the Late Ordovician pulse.

There is increasing agreement between LIP ages and mass extinctions and oceanic anoxia. All large Paleozoic volcanic eruptions presently discovered in Northern Eurasia appear to correspond to several major divisions in the geological time scale, and future work will focus on individual correlations.

Acknowledgements

References

Archibald, J.D., Clemens, W.A., Padian, K., Rowe, T., Macleod, N., Barrett, P.M., Gale, A., Holroyd, P., Sues, H.D., Arens, N.C., Horner, J.R., Wilson, G.P., Goodwin, M.B., Brochu, C.A., Lofgren, D.L., Hurlbert, S.H., Hartman, J.H., Eberth, D.A., Wignall, P.B., Currie, P.J., Weil, A., Prasad, G.V.R., Dingus, L., Courtillot, V., Milner, A., Milner, A., Bajpai, S., Ward, D.J., Sahni, A., 2010. Cretaceous extinctions: multiple causes. Science 328, 973–973.

Arzamastsev, A.A., Bea, F., Glaznev, V.N., Arzamastseva, L.V., Montero, P., 2001. Kola alkaline province in the Palaeozoic: evaluation of primary mantle magma composition and magma generation conditions. Russian Journal of Earth Sciences 3, 1–32.

Benton, M.J., 1993. The Fossil Records 2. Chapman & Hall, London. 845 pp.

Benton, M.J., 2001. Biodiversity on land and in the sea. Geological Journal 36, 211–230.

Bialowolska, A., Bakun-Czubarow, N., Fedoryshyn, Y., 2002. Neoproterozoic flood basalts of the beds of the Volhynian Series (East European Craton). Geological Quarterly 46, 37–57.

Bryan, S.E., Ernst, R.E., 2008. Revised definition of large igneous provinces (LIPs). Earth-Science Reviews 86, 175–202.

Chenet, A.L., Courtillot, V., Fluteau, F., Gérard, M., Quidelleur, X., Khadri, S.F.R., Subbarao, K.V., Thordarson, T., 2009. Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section. Journal of Geophysical Research 114, B06103.

Cluzel, D., 1992. Ordovician bimodal magmatism in the Ogcheon belt (South Korea): intracontinental rift-related volcanic activity. Journal of Southeast Asian Earth Sciences 7 (2/3), 195–209.

Courtillot, V., 1994. Mass extinctions in the last 300 million years: one impact and seven flood basalts? Israel Journal of Earth Sciences 43, 255–266.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., Besse, J., 1999. On causal links between flood basalts and continental breakup. Earth Planet. Sci. Lett. 166, 177–195.

Courtillot, V., Olson, P., 2007. Mantle plumes link magnetic superchrons to phanerozoic mass depletion events. Earth and Planetary Science Letters 260, 495–504.

Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events. Comptes Rendus Geosciences 335 (1), 113–140.

Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle. Earth and Planetary Science Letters 205 (3–4), 295–308.

Courtillot, V., Kravchinsky, V.A., Quidelleur, X., Renne, P.R., Gladkochub, D.P., 2010. Preliminary dating of the Viluy traps (Eastern Siberia): eruption at the time of Late Devonian extinction events? Earth and Planetary Science Letters 300, 239–245.

Downes, H., Balaganskaya, E., Beard, A., Liferovich, R., Demaiffe, D., 2005. Petrogenetic processes in the ultramafic, alkaline and carbonatitic magmatism in the Kola Alkaline Province: a review. Lithos 85, 48–75.

Elming, S.A., Kravchenko, S.N., Layer, P., Rusakov, O.M., Glevasskaya, A.M., Mikhailova, N.P., Bachtadse, V., 2007. Palaeomagnetism and ^{40}Ar/^{39}Ar age determinations of the Ediacaran traps from the southwestern margin of the East European Craton, Ukraine: relevance to the Rodinia break-up. Journal of the Geological Society of London 164, 969–982.

Gaiduk, V.V., 1987. Viluy Middle Paleozoic Rift System. Geotectonics 3, 66–76 (in Russian).

Glass, L.M., Phillips, D., 2006. The Kalkarindji continental flood basalt province: A new Cambrian large igneous province in Australia with possible links to faunal extinctions. Geology 34 (6), 461–464.

Gradstein, F.M., Ogg, J.G., Smith, A.G., 2005. A Geologic Time Scale 2004. Cambridge University Press, Cambridge.

Gudlaugsson, S.T., Faleide, J.I., Johansen, S.E., Breivik, A.J., 1998. Late Palaeozoic structural development of the south-western Barents Sea. Marine and Petroleum Geology 15, 73–102.

Kaufmann, B., 2006. Calibrating the Devonian time scale: A synthesis of U-Pb ID-TIMS ages and conodont stratigraphy. Earth Science Review 76, 175–190.

Kiselev, A.I., Yarmolyuk, V.V., Egorov, K.N., Chernyushov, R.A., Nikiphorov, A.V., 2006. Middle Paleozoic basite magmatism of the north-west part of the Viluy Rift: composition, sources, geodynamics. Petrology 6, 660–682.

Kidder, D.L., Worsley, Th.R., 2010. Phanerozoic large igneous provinces (LIPs), HEATT (haline euxinic acidic thermal transgression) episodes, and mass extinctions. Palaeogeography, Palaeoclimatology, Palaeoecology 295, 162–191.

Kogarko, L.N., Lahaye, Y., Brey, G.P., 2010. Plume-related mantle source of super-large rare metal deposits from the Lovozero and Khibina massifs on the Kola Peninsula, Eastern part of Baltic Shield: Sr, Nd and Hf isotope systematics. Mineralogy and Petrology 98, 197–208.

Kramm, U., Kogarko, L.N., Kononova, V.A., Vartiainen, H., 1993. The Kola alkaline province of the CIS and Finland: precise Rb–Sr ages define 380–360 Ma age range for all magmatism. Lithos 30, 33–44.

Kravchinsky, V.A., Konstantinov, K.M., Courtillot, V., Valet, J.-P., Savrasov, J.I., Cherniy, S.D., Mishenin, S.G., Parasotka, B.S., 2002. Palaeomagnetism of East Siberian traps and kimberlites: two new poles and palaeogeographic reconstructions at about 360 and 250 Ma. Geophysical Journal International 148, 1–33.

Kusznir, N.J., Kokhuto, A., Stephenson, R.A., 1996. Synrift evolution of the Pripyat Trough: constraints from structural and stratigraphic modeling. Tectonophysics 268, 221–236.

Kuzmin, M.I., Yarmolyuk, V.V., Kravchinsky, V.A., 2010. Phanerozoic hot spot traces and paleogeographic reconstructions of the Siberian continent based on interaction with the African large low shear velocity province. Earth-Science Reviews 102, 29–59.

Lefebvre, V., Servais, Th., François, L., Averbuch, O., 2010. Did a Katian large igneous province trigger the Late Ordovician glaciation? A hypothesis tested with a carbon cycle model. Palaeogeography, Palaeoclimatology, Palaeoecology 296, 310–319.

Li, Z.X., Zhong, S., 2009. Supercontinent–superplume coupling, true polar wander and plume mobility: plate dominance in whole-mantle tectonics. Physics of the Earth and Planetary Interiors 176, 143–156.

Litvinovsky, B.A., Zanvilevich, A.N., Alakshin, A.M., Podladchikov, Yu.Yu., 1992. Angaro–Vitim Batholith — Largest Granitoid Pluton. Nauka, Novosibirsk, p. 141. In Russian.

Rohde, R.A., Muller, R.A., 2005. Cycles in fossil diversity. Nature 434, 208–210.

Sahney, S., Benton, M.J., Falcon-Lang, H.J., 2010. Rainforest collapse triggered Pennsylvanian tetrapod diversification in Euramerica. Geology 38, 1079–1082.

Torsvik, T.H., Smethurst, M.A., Burke, K., Steinberger, B., 2008. Long term stability in deep mantle structure: evidence from the 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP). Earth and Planetary Science Letters 267, 444–452.

Tsygankov, A.A., Matukov, D.I., Berezhnaya, N.G., Larionov, A.N., Posokhov, V.F., Tsyrenov, B.Ts., Chromov, A.A., Sergeev, S.A., 2007. Late Paleozoic granitoids of western Transbaikalia: magma sources and stages of formation. Russian Geology and Geophysics 48 (1), 156–180.

Vrublevskii, V.V., Izokh, A.E., Polyakov, G.V., Gertner, I.F., Yudin, D.S., Krupchatnikov, V.I., 2009. Early Paleozoic alkaline magmatism of the Altai mountains: ^{40}Ar–^{39}Ar geochronology data for the Edel'veis Complex. Doklady Earth Sciences 427 (5), 846–850.

Wilson, M., Lyashkevich, Z.M., 1996. Magmatism and the geodynamics of rifting of the Pripyat–Dnieper–Donets rift, East European Platform. Tectonophysics 268, 65–81.

Yarmolyuk, V.V., Kovalenko, V.I., 2003. Batholiths and geodynamics of batholith formation in the Central Asian folded belt. Russian Geology and Geophysics 44 (12), 1260–1274.

Yarmolyuk, V.V., Vorontsov, A.A., Kovalenko, V.I., Zhuravlev, D.Z., 1997. Isotope inhomogeneity of sources of Late Paleozoic intraplate magmatism in the Central Asia (based on Sr and Nd isotope data for basalts of bimodal associations). Russian Geology and Geophysics 38 (6), 1178–1183.

Yarmolyuk, V.V., Kovalenko, V.V., Kovach, V.P., Kozakov, V.P., Kotov, I.K., Sal'nikova, E.B., 2002. Isotopic composition, sources of crustal magmatism, and crustal structure of Caledonides of the Ozernaya zone, Central Asian foldbelt source. Doklady Earth Sciences 387A (9), 1043–1047.

Yarmolyuk, V.V., Kovalenko, V.I., Kovach, V.P., Kozakov, I.K., Kotov, A.B., Sal'nikova, E.B., 2003. Geodynamics of caledonides in the Central Asian foldbelt. Doklady Earth Sciences 389 (3), 311–316.