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Original paper

An overview of the association between lamprophyric intrusions and rare-metal mineralization

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Abstract. Granite-related rare metal districts in orogenic settings are occasionally associated with lamprophyre dikes. We recorded 63 occurrences of lamprophyres in bimodal dike suites of about 200 granite bodies related to rare metal deposits. Most lamprophyres occur in Paleozoic and Mesozoic metallogenic provinces in the northern hemisphere. Lamprophyres which are associated with rare metal deposits are calc-alkaline (kersantites, minettes, spessartites) or more rarely alkaline lamprophyres (camptonites, monchiquites) which occur in the roof zone of complex granitic bodies as pre-granitic, intra-granitic, intra-ore or post-ore dikes. Most lamprophyres are spatially associated with dominant felsic dikes and/or with mafic dikes represented by diorites or diabases. Diorites and lamprophyres occasionally exhibit transitional compositions from one to another. Lamprophyres share common geochemical characteristics of highly evolved granitoids such as enrichment in K and F, increased abundances of Li, Rb, and Cs and enrichment in some HFSE (e.g. Zr, U, Th, Mo, Sn, W). Lamprophyres in rare metal districts testify to accessibility of the upper crust to mantle products at the time of rare metal mineralization and possible influence of mantle melts or mantle-derived fluids in the differentiation of granitic melts in the lower crust.

Key-words: lamprophyres, rare metals, Sn, W, Mo, bimodal dikes, mantle metasomatism

1. Introduction

Many rare-metal (RM) deposits are closely spatially and temporarily associated with granitoids or equivalent effusive rocks (e.g. Lindgren 1933; Abdullaev 1954; Rundkvist et al. 1971; Tauson 1977; Tischendorf 1977; Taylor 1979; Beskin et al. 1979; Popov et al. 1981; Štemprok 1990; Seifert, Kempe 1994; Robb 2005; Pirajno 2009). Most researchers interpret this association as genetic (granitoids produce mineralizing solutions, e.g. Abdullaev 1954, Tischendorf 1977; Lehmann 1990) while some Russian geologists (e.g. Yu. A. Bilibin and P. I. Lebedev in Abdullaev 1954) distinguish also paragenetic relationships (intrusions and mineralizing solutions use identical host structures). Most RM deposits were formed during Paleozoic and Mesozoic orogenies in an approximate 120–80 Ma interval (Rundkvist et al. 1971). However, the occurrences of lamprophyres in bimodal dike suites of RM districts are relatively rare (Štemprok 1995[1]) in contrast to the districts hosting mesothermal gold deposits (Rock 1991). Mesothermal gold deposits spatially related to granitoids, which range in age from Archean to Tertiary, include often abundant lamprophyres in their bimodal dike suites (Rock et al. 1989; Ashley et al. 1994). Their role was interpreted as evidence for mantle melts or volatiles involved in the origin of ore-bearing fluids (Rock et al. 1989). Mafic intrusions supply some of the components, including metals and heat to drive hydrothermal systems.

The districts with granites and RM deposits host lamprophyres in various sequential positions in relation to associated granites (e.g. Seifert 2008). RM deposits in the Erzgebirge metallogenic province are interpreted as mantle-derived mineralization (Seifert 1994, 2008; Seifert, Sandmann 2006). Uncertainties surrounding the genesis of lamprophyres make their occurrence in the ore districts with highly evolved RM granites even more difficult to explain. Rock (1991) noted that in the European Variscides the space-time relationship between lamprophyres and ores seems to be stronger than that between granitoids and ores.

Lamprophyres which are of mantle (< 100 km) origin in subduction zones and continental rift settings are reported also as components of bimodal dike suites in a number of hydrothermal Pb-Zn, Sb-Hg, Ag-Sb and fluorite deposits (Abdullaev 1957; Mikhaleva, Tychinskii 1972; Indolev 1979; Mikhaleva 1989; Rock 1991). Significant is the association of Sn-W, Sn-sulfide, and Ag-Sb deposits with Paleozoic and Mesozoic magmatism in the Erzgebirge, Central Asia, and Yakutia which includes granitoids and abundant mafic dikes (Obolenskaya 1971; Seifert 2008; Pavlova, Borisenko 2009; Vasyukova 2010; Seifert et al. 2011).

This paper examines the regional distribution of lamprophyres in bimodal dike suites of RM granites coeval with the origin of granites as based on literature data and the authors' own work. Many of the present models on the genesis of copper porphyry and tin porphyry deposits (e.g. Dietrich et al. 1999; Hattori, Keith 2001; Maughan et al. 2002; Sinclair 2007) reflect the growing recognition of the effect of mafic magmas on crustal felsic melts. The presence of lamprophyres also indicates a possible reaction of crustal material with lamproite melts suggested by Prelevic et al. (2004) as primary magmas in the genesis of K-lamprophyres.

[1] Lamproite dikes in the paper title refer to lamprophyre dikes (M.Š.)

We attempt to answer the question whether the association between RM- bearing granites and lamprophyres is coincidental; for example, if the lamprophyres intruded fractures that had been used by earlier granitoids or genetic with the origin of lamprophyres induced by a single long lasting magmatic event and lamprophyric magmatism contributed to concentration of rare metals in the crust. Our information is based on current descriptions of RM districts focused on the studies of ores and lamprophyres and enclosing or near-by granitoids.

2. Nomenclature of lamprophyres

The exact definition of lamprophyres still generates confusion (Wooley et al. 1996; Le Bas 2007) which is understandable in view of the identical mineralogy of calc-alkaline lamprophyres with abarokites and shoshonites and partly with diorites and andesites. Many authors note common transitions of lamprophyres to intermediate and mafic dikes, which accords with a common heteromorphism of lamprophyres and between various types of lamprophyres (e.g. minettes and kersantites; Metais, Chayes 1963, 1964; Rock 1991). The main petrographic types of calc-alkaline lamprophyres are kersantites as biotite-plagioclase lamprophyres with some late crystallizing alkali feldspar or quartz, and minettes characterized by phlogopite and alkali feldspar. No petrological model can account for the derivation of minette from kersantite and vice versa (Turpin et al. 1988).

We use the definition of lamprophyres as mesocratic to melanocratic igneous rocks with phenocrysts of dark mica and amphibole or both, set in a matrix of the same minerals and with feldspars restricted to the groundmass (Wooley et al. 1996). Hence, the calc-alkaline lamprophyres (CAL family after Rock 1991) include petrological types of genetically identical rocks like minettes, vogesites, kersantites and spessartites. Camptonites and monquichites, which are reported rarely from RM districts, belong to the class of alkaline lamprophyres (AL after Rock 1991) characterized by foids and glass in addition to feldspars in the matrix and by the presence of sodic amphiboles. The small thickness of some lamprophyre dikes precludes their correct identification in strongly weathered regions and also in intensively hydrothermally altered domains of some ore-bearing districts.

The importance of examination of lamprophyres in RM districts stems in our opinion from an unusually high volatile content (H_2O, F, CO_2, Cl) which differs them from most other mafic dikes. They have many other peculiar structural features (Shchukin 1974; Rock 1991) such as a complex morphology with varying changes of dike courses and thicknesses, a considerable small-scale variability in their petrological composition, gradual transitions to other mafic dikes like diabases and diorites, presence of abundant xenoliths of deep crustal and country rocks, chemical composition close to alkaline gabbroid rocks (Obolenskaya 1971; Rock 1991), and spatial association with granites, diabases and dolerites, alkaline complexes, ultramafic rocks and potassic rocks (Wimmenauer 1973). Many features of their emplacement can be explained by high volatile content which facilitates rapid forceful way along narrow fractures. This allows lamprophyre to “drill their passage” even into resistant rocks (Rock 1991). In case of RM districts these properties can explain penetration of lamprophyric dikes to apical parts of complex upper crustal granite bodies and into their country rocks.

Calc-alkaline and alkaline lamprophyres are geochemically characterized by (1) low SiO_2 typical of mafic to intermediate compositions (48 to 55 wt.%); (2) high contents of alkalies comparable to granitoids and rare alkalies in the range of fractionated acid igneous rocks; (3) increased contents of some trace elements close to their concentrations in mafic rocks (Ti, Co, Ni, V) or even higher (Cr) or in acid igneous rocks (Zr, Sr, Mo, Pb); (4) increased contents of volatile elements (P, F) and water. Lamprophyres contain abundant secondary minerals from the alteration of primary minerals. Products of some deuteric processes coincide with the products of thermal and hydrothermal alterations in alumosilicate rocks by contact metamorphism of granitoids, or greisenization of mafic rocks (Štemprok 1987) or with hydrothermal alterations in tin and copper porphyry-systems (Sinclair 2007).

3. Classification of primary Sn, W, and Mo deposits

The most modern classifications of Sn and W deposits consider geological position, shape of ore bodies, mineralogical characteristics and hydrothermal alterations (cf. Štemprok 1978). Sinclair et al. (2011) distinguished within the group of Sn and W deposits felsic and intermediate intrusion-domains. Sn and W deposits usually occur as veins and/or stockworks in the apical zones of felsic-intermediate intrusions and are associated with greisen-type alteration, breccia pipes, pegmatites and skarns. The classification of the ore deposits of Northeast Asia metallogenic belts related to magmatic processes by Rodionov et al. (2004) distinguished between deposits related to intermediate and felsic intrusions: (A) pegmatite, (B) greisen and quartz vein, (C) alkaline metasomatite, (D) skarn, and (E) porphyry and granitoid-pluton hosted deposits. The latter group includes cassiterite-sulfide-silicate vein and stockwork, porphyry Cu-Mo(±Au, Ag), porphyry Mo(±W, Bi) and porphyry Sn deposits. Most Russian classifications used the mineral characteristics to denote the type of deposits (Khruschov 1961; Magakyan 1974; Denisenko 1978; Povilaitis 1981). A simplified classification of the Sn, W, and Mo ores used in this study as adapted from Štemprok (1978) is shown in Table 1.

4. The source of literature data

We base our data on the collection by Štemprok (1998) on magmatic zonation of RM granitoids in orogenic belts, which considered differentiation ranges of magmatic bodies. This database included the protocol of 20 principal characteristics registered for each of the granitoid body and contained about 300 entries for around 200 mostly complex granitoid bodies. A second database is the collection of Seifert (1994, 2008), which describes the association of lamprophyres and rare metal, Ag-base metal, U, and Au mineralization in the Erzgebirge and surrounding metallogentic provinces and areas for comparison worldwide.

TABLE 1

Simplified classification of RM deposits related to felsic and /or intermediate intrusive magmatism.

Ore type	World map (Sinclair et al. 2011)	Metal	Dependence on granite contact	Form of ore body	Alteration	Main ore minerals
pegmatite	granitic pegmatite	Sn	independent	lenses, dikes		cassiterite
skarn	skarn	W, Sn, Mo	contact dependent	lenses, stratiform bodies	skarnization	scheelite, cassiterite, molybdenite
greisen, vein	greisen, vein, stockwork	Sn, W, Mo	contact dependent	veins, zones of alteration, stockworks	greisenization, sericitization	cassiterite, wolframite, molybdenite
tourmaline and chlorite metasomatite	vein, stockwork, breccia pipe	Sn, W	contact dependent	veins, zones of alteration	tourmalinization, chloritization	cassiterite, wolframite, scheelite
quartz feldspar metasomatite	vein, stockwork	Mo	contact dependent	stockworks, zones of alteration	feldspathization, sericitization	molybdenite
porphyry ore	stockwork	Mo, Cu	granite and/or porphyry contact dependent	stockworks, zones of alteration	silicification, sericitization	molybdenite, chalcopyrite
sulfidic ore	vein, stockwork, carbonate replacement	Sn	independent	veins, stratiform bodies	sericitization, chloritization	cassiterite, stannite

The above mentioned databases were used to identify the presence of lamprophyres in the dike suites of RM districts. Many of these data made the petrographic description before the introduction of the IUGS classification of lamprophyric rocks (Le Maitre 1989). Thus, the assignment of a dike rock to lamprophyres was in many cases based on field petrological criteria. We considered it important in our study to identify the dike association accompanying lamprophyres. There is no unique terminology for the classification of felsic dikes among various schools of geologists. The term "quartz porphyry" is currently used for some dikes of rhyolitic composition and textures and classified as "subvolcanic rhyolitic" dikes.

For location of many RM districts we used the world map of distribution of tin and tungsten deposits (Sinclair et al. 2011) which records 1063 primary tin and tungsten deposits and important ore occurrences. This map proved to be indispensable in locating some of RM deposits which lack any detailed description of geographical position in the original literature.

A relative age of lamprophyres described by the association of intrusive rocks and hydrothermal deposits is derived from cross-cutting relationships such as Etyka in Transbaikalia (Levitskii et al. 1963), U deposits in the western Erzgebirge (Ačejev, Harlass 1968) and for late-Variscan ore deposits in the Erzgebirge-Vogtland region and surrounding areas (Seifert 2008). The bracketing role of lamprophyre dikes with the products of granitoid magmatism and mineralization is very important as some rocks have been dated by geochronological methods (e.g. Abushkevich 2005; Seifert 2008; Pavlova et al. 2008; Seifert et al. 2011). The lamprophyric dikes can be pre-granitic, intra-granitic or post-granitic as shown in Figure 3 but also pre-ore, intra-ore, and post-ore (example Erzgebirge, cf. Seifert 2008). Recent data include also the dating by isotopic geochronology of lamprophyres which may confirm their contemporaneity with the associated RM granites in many ore provinces (e.g. Abushkevich 2005; Seifert 2008; Cheng et al. 2008; Pavlova, Borisenko 2009; Cheng, Mao 2010) (Tab. 2).

TABLE 2

Selected granite-related RM districts hosting lamprophyres.

Area	Deposits	Metals	Age of felsic magmatism (Ma)	Age of lamprophyres (Ma)	Reference
Seward Penninsula, USA	Lost River	Sn, W, Be	*115 - 75	*90 - 84 (?)	Sainsbury (1969), Dobson (1982), *Amato et al. (2003)
Red Mt., USA	Urad-Henderson	Mo	23 - 30	29.8±1	Wallace et al. (1978)
Iberian Penninsula, Portugal	Covas	W	Paleozoic	*c. 283	Conde et al. (1971), *Bea et al. (1999)
Cornwall, UK		Sn, Cu, W	*290 - 280	*Chyweeda: 292.9±3.4	Leat et al. (1987), *Darbyshire, Shepherd (1985), Shail, Wilkinson (1994)
Massif Central, France	Echassière, Puy-les-Vignes	W, Sn, Be	Paleozoic		Weppe (1951), Burnol et al. (1974)
Erzgebirge/Krušné hory, Germany/Czech Republic	*Ehrenfriedersdorf, **Gottesberg-Mühlleithen, ***Marienberg-Pobershau, Pöhla, Krupka, Sachsenhöhe	Sn, W, Mo	*322±5, **325.7±3.7 - 320±3, **312.5±4.6, ***321±3	*330-340(?), **320±3 - 316±2.7, ***327.8±0.5 - 309.5±6.9	Seifert, Kempe 1994, Štemprok, Seltmann (1994), Baumann et al. (2000), */**/***cf. Seifert (2008)
Northern Caucasus, Russia	Kti-Teberda	W	280 - 250		Makeev et al. (1983)
Uzbekistan	Karman, Karnab, Lapaz *Ingichke	Sn, W Sn, W	Paleozoic, Carboniferous	Carboniferous, 200 - 180	Smirnov et al. (1978), Lugov et al. (1986), *Denisenko (1986)
Tadjikistan	Kumarkh (Gissar Range) *Chorukh-Dairon (Mogoltau) **Trezubetz (SE Pamir)	Sn, W W, Mo Sn, W	Permian Permian Cretaceous	Permian, Cretaceous	Smirnov et al. (1978), *Mamadzhanov (2001), **Pavlova et al. (2010)
Central Kazakhstan (Kalba Narym)	Atasu West, Bainazar, Kaiba, Maikul	W, Mo, Sn	Paleozoic		Zhilinskii (1959), Shcherba (1960)
Kyrgyzstan	*Trudovoe (SE Tien Shan) **Kurgan (Talas Range) **Kumyshtag (Talas Range)	Sn, W Sn, Ag, Pb, Zn Ag, Sb, Pb, Zn	312 - 270 Paleozoic Paleozoic	295 - 250 280 280	*Dzhenchuraeva et al. (2007), **Pavlova, Borisenko (2009)

cont. TABLE 2

SE Altai, Russia NW Mongolia	Yustid Achitnur (*Chuya complex)	W, Mo Sn, W	355 Mesozoic	*246 - 235	*Pavlova, Borisenko (2009), Vasyukova (2010)
Kuznetsk Alatau, Russia	Sorskoe	Cu, Mo	Paleozoic		Makeev et al. (1983)
W. Transbaikalia, Russia	Dzhida	W, Mo	Mesozoic		Povilaitis (1960), Makeev et al. (1983)
Southern China	*Dachang, *Geiju, **Yaoganxian	Sn, Cu, Pb, Zn, Sb, Ag, W	95 - 90 77.4±2.5 - 85.0±0.85 169 - 178	82	*Cheng Yanbo et al. (2008), Cheng Yanbo, Mao Jingwen (2010), **Kaneda, Takeuchi (1988)
Northeastern Mongolia	Baga Khairkhan, Buren Tsogtin, Ikhe Khairkhan, Khara Yamatin	Sn, W, Mo	Mesozoic		Kovalenko et al. (1971), Marinov et al. (1977)
Eastern Transbaikalia, Russia	Belukha, Bogdatskoe, Bugdatin, Bukuka, Etyka, Khapcheranga, Orekitan, *Orlovka	Sn, W, Ta, Mo	Mesozoic	*153.3±3.8	Barabanov (1961), Levitskii et al. (1963), Ontoev (1974), Smirnov et al. (1978), Makeev et al. (1983), Lugov et al. (1986), *Abushkevich (2005)
Maritime (Primore), Russia	Bachelai, Vostok 2, Kandoma, Yamutin, Zabytoe	Sn, W, Mo	Mesozoic		Izokh et al. (1957), Ivanov et al. (1980), Makeev et al.(1983)
Yano-Kolyma, Russia	*Deputatskoe **/***Menkechenskoe Ilintas Burgochan, Dyakhtardakhskoe	Sn, W, Ag, Pb, Zn Sn, W, Ag, Pb, Zn Sn, W, Ag Sn, W	112-108 123-119 Mesozoic Mesozoic	>113, 106±1.2 >120 and <119 Mesozoic-Cenozoic	*Pavlova et al. (2009), Pavlova, Borisenko (2009), **Layer et al. (2001), ***Indolev, Nevoisa (1974), Flerov (1976), Smirnov et al. (1978)
Tasmania, Australia	Blue Tier batholith area	Sn, W	Paleozoic	Mesozoic	Mc Clenaghan & Baillie (1975), Higgins et al. (1985)
Chukotka, Russia	Agylkin, Egugskoe, Iul´tin, Pervonachol´noe, Pyrkakai, Svetloe, Valkumei	Sn, W	Mesozoic		Zagruzina (1965), Lugov et al. (1986)

Some data, however, show that intrusion of lamprophyres may not be coeval with RM granites and RM mineralization. For example, at the Kitsault porphyry molybdenum deposit in British Columbia lamprophyre dikes are almost 20 Ma younger than the intrusive complex that is related to the deposit (Steininger 1985). In the Blue Tier batholith in Tasmania the Paleozoic Sn(-W) mineralization described by Groves and Taylor (1973) is apparently independent of the intrusion of lamprophyres described by Mc Clenaghan and Baillie (1975) in the vicinity.

5. Geographical distribution of rare metal districts

RM granites occur in extensive, relatively narrow linear metallogenic zones within major orogenic belts (Fig. 1). The distribution of RM deposits and occurrences are irregular in linear belts and form metallogenic provinces (Rundkvist et al. 1971; Magakyan 1974; Kerrich et al. 2005). They are predominantly related to the Mesozoic and Cenozoic orogenic belts in western North and South America around the western margin of the Pacific Ocean and to the Tethyan orogenic belts in southern Asia. They are less

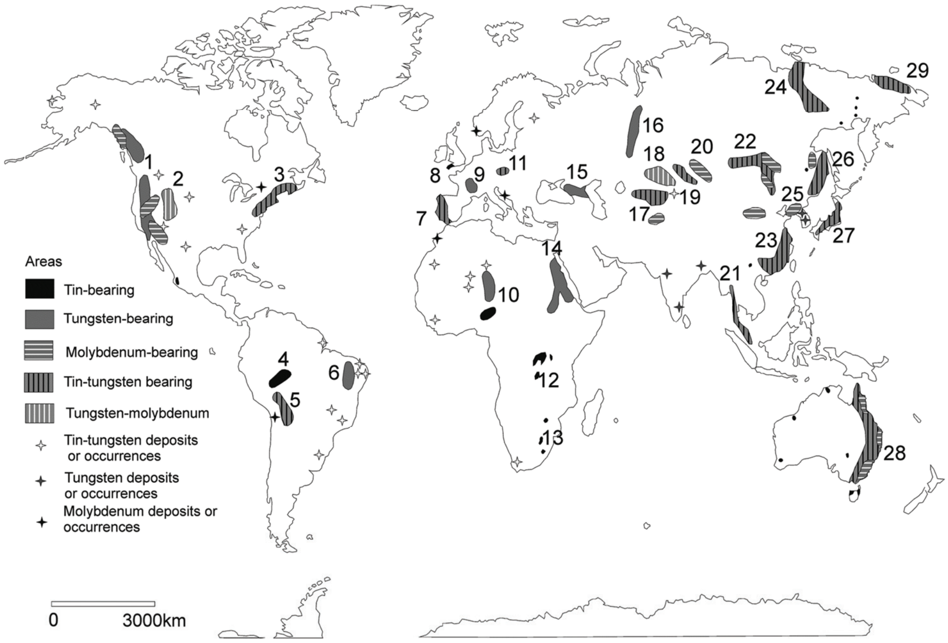

Fig. 1. Tin-, tungsten- and molybdenum-bearing areas and important deposits of the world. Compiled from Krushchov (1961), Taylor (1979) and Povilaitis (1981). Areas (provinces): 1 – North American Cordillera, 2 – Colorado Plateau, 3 – Appalachians, 4 – Rhondonia, 5 – Bolivian, 6 – East Brazilian, 7 – Iberian, 8 – Cornwall (Sn–W), 9 – Massif Central, 10 – Nigeria, 11 – Central Europe, 12 – Central Africa, 13 – Bushveld, 14 – East African, 15 – North Caucasian, 16 – East Uralian, 17 – South Tien Shan, 18 – Central Kazakhstan, 19 – Kalba–Narym, 20 – Gornyi Altai, 21 – Burma–Malaysia, 22 – Transbaikalian–Mongolian, 23 – South–eastern China, 24 – Verkhoyansk–Kolyma, 25 – Korean peninsula, 26 – Sikhote–Alin, 27 – Japanese Islands, 28 – Eastern Australia, 29 – Chukotka.

significantly distributed in Paleozoic provinces (Caledonides and Variscides) of Europe, Central Asia, Eastern Australia and eastern North America and very subordinately in Precambrian terranes. The RM provinces are characterized either by the predominance of a single metal in the ores such as Sn or W or more commonly by the combination of two metals, such as Sn-W or Mo-W, while the combination of Sn-Mo is very rare.

6. Lamprophyres in rare metal districts

The Sn, W, and Mo districts with felsic and/or intermediate intrusions hosting lamprophyres are shown in Figure 2.

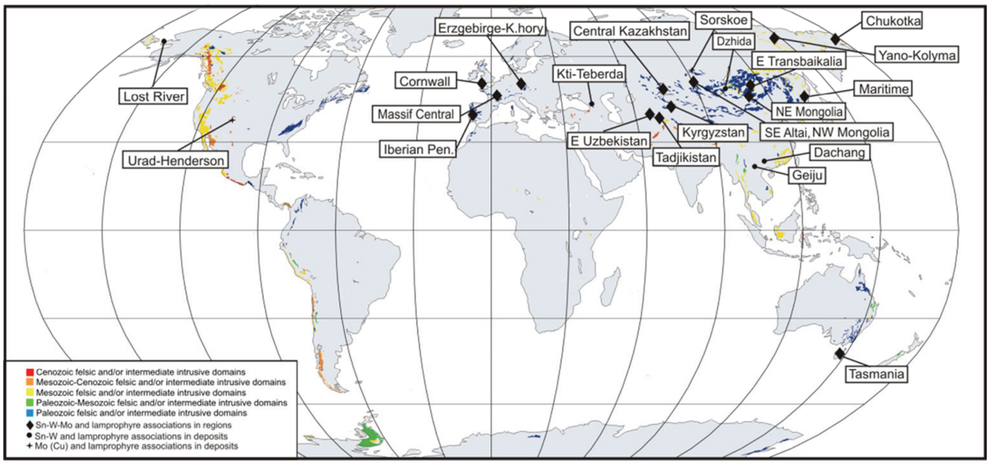

Fig. 2. Lamprophyres in Sn-,W-, and Mo districts within felsic and/or intermediate intrusive domains. Simplified from Geological map of the World, Geological Survey of Canada, by Kirkham and Chorlton (2005).

6.1. North American Cordillera

At *Lost River* Sn deposits in Alaska (USA) are associated with small stocks of Late Cretaceous biotite granites at six widely spaced localities in the Seward penninsula in Alaska. At the Lost River tin-tungsten-fluorite deposit (Sainsbury et al. 1968; Sainsbury 1969; Hudson, Arth 1983) the granites are accompanied by the dikes of diabases and lamprophyres and rhyolitic (quartz-porphyry) dikes. The lamprophyres contain granite xenoliths but no granitic dikes are known to contain lamprophyre xenoliths, indicating that the lamprophyres are younger. Amato et al. (2003) report Late Cretaceous dike swarms in Seward Penninsula where the dike swarm in the Kigluaik Mountains has the age between 90 and 84 Ma ($^{40}Ar/^{39}Ar$ method). The intrusion of the mafic dike suite marks Cretaceous extension of the region.

In the Red Mountain area, Colorado, USA the Urad-Henderson molybdenum deposits are associated with the mid-Tertiary Red Mountain intrusive centre, which formed in the interval of 27 to 30 Ma in at least 23 intrusive events (Shannon et al. 2004). The porphyry Mo systems at Climax and Henderson include a lamprophyre-leucogranite dike suite

(Bookstrom et al. 1988). Wallace et al. (1978) and Geraghty et al. (1988) described early separate or composite lamprophyre dikes associated with later rhyolite stocks and dikes. The age of kersantite in the Red Mountain intrusive suite belonging to the swarm of radial dikes was dated at 29.8 ± 1Ma (Ar/Ar) (Table 2).

6.2. Western European Variscides

In *South-West England* (mainly in Cornwall) minette dikes are spatially associated with the Cornubian batholith (Leat et al. 1987). The granite related mineralization of the vein type (Sn tourmaline-chlorite assemblages) is related to this batholith which hosts also "elvans" (K-rich rhyolitic rocks). Lamprophyres are petrographically identified as phlogopite or olivine-phlogopite minettes (Manning 1998). Fortey (1992) identified lamprophyres as calc-alkaline minettes, olivine minettes and analcime-bearing lamproites. Hughes (1997) distinguished two groups of minettes: the first group of Exeter Volcanic Rocks (EVR) following the Variscan trend (shoshonites and minettes), the second group called the Cornish Minette Rocks (CMR) following the Caledonian trend (minette with no shoshonite associates). Both of the groups show a spatial association with the granites of the Cornubian batholith (Darbyshire, Shepherd 1985) but none of the dikes cut the granite at the surface outcrops. Highly potassic mantle derived magmatism is approximately coeval with the earliest granites (Leat et al. 1987). The late Stephanian K-Ar age for the Chyweeda lamprophyre at 292.9 ± 3.4 Ma agrees with the age of highly potassic lavas in SW England as given by Hawkes (1981) at 295.2 ± 2.6 Ma.

In the French *Massif Central* the Late Paleozoic granite of Collete forms a major stock with a satellite minor granite cupola of Echassière, which is spatially associated with bimodal dike suite including a kersantite (Burnol et al. 1974). In *the Iberian Penninsula* of c*entral Spain*, upper Carboniferous peraluminus granitoids (330 to 290 Ma) are preceded by intrusion of mafic-ultramafic hybrid magmas and are postdated by dike swarms of camptonitic lamprophyres (~ 283 Ma; Bea et al. 1999). A tungsten skarn deposit in a spatial association with granites at Cova (15 km south of Vila Nova de Cerveira) hosts lamprophyres as the latest stage of Variscan magmatism (Conde et al. 1971).

6.3. Central European Variscides

Lamprophyre dikes occur in the *Krušné hory/Erzgebirge - Smrčiny-Fichtelgebirge* anticlinorium (Kramer 1976; Seifert 1994, 2008) of the Central European Variscides in a spatial relationship with the late-Variscan Krušné hory/Erzgebirge granite batholith (Seifert 1994; Seifert, Baumann 1994; Seifert, Kempe 1994; Novák et al. 2001; Štemprok et al. 2008) and Smrčiny/Fichtelgebirge pluton. The lamprophyres in the Erzgebirge are independent of the regional distribution of Variscan granites on the surface (cf. Watznauer 1964; Seifert 2008) but are closely related to deep-seated NW-SE and NE-SW fault zones and lineaments (e.g. Gera-Jáchymov and Warmbad-Chomutov fault zones; Kramer 1976, 1988; Seifert 1994; 2008; Štemprok et al. 2008).

The lamprophyric intrusions in the Erzgebirge are divided by Seifert (1994, 2008) using criteria of relative age relationships to late-Variscan granites, aplites, rhyolitic dikes, and late-Variscan mineralization stages as well as petrographic and geochemical criteria (L1 – L3, Fig. 3):

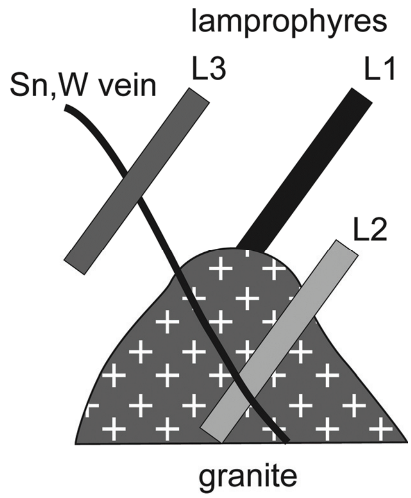

Fig. 3. Scheme for the sequence of pre-granitic (L1), intra-granitic (L2), and post-granitic lamprophyres (L3) in relationship to late-collisional granites of the Erzgebirge/Krušné hory (type "Eibenstock granite") (cf. Seifert 1994, 2008).

(1) L1-type lamprophyres are mostly represented by kersantites, which are intruded by the late-collisional Ehrenfriedersdorf granite and crosscut by aplites, which are possibly associated with deeper magma chambers of topaz-albite granites. L1 are crosscut and overprinted by Sn-W mineralization and show Sn contents of up to 230 ppm (Fig. 4).

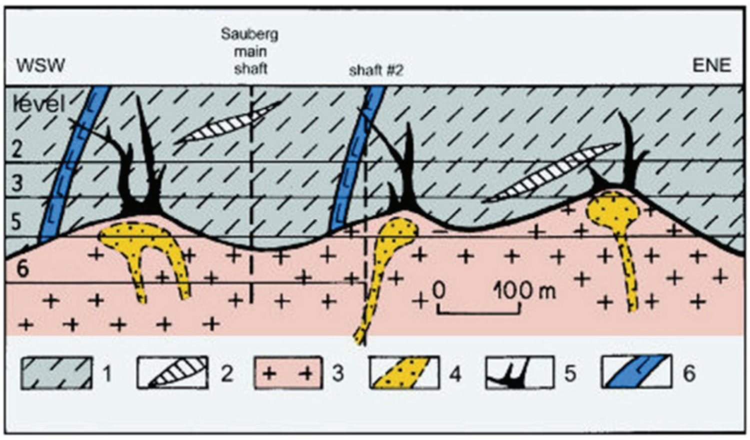

Fig. 4. Schematic cross-section through the central part of the tin district Ehrenfriedersdorf/central Erzgebirge (Seifert and Kempe 1994, modified in Seifert 2008). 1 – quartz-micaschist; 2 – skarn lense; 3 – late-collisional granite; 4 – Sn-greisen; 5 – aplite and greisenized aplite (schematic, different generations), 6 – lamprophyric dike (type L1).

(2) L2-type lamprophyres postdate the late-collisonal granite intrusions and occur widely in the Sn-Ag-U district Marienberg-Pobershau, and are dominated by mica-minette dike intrusions with strike lengths up to 7 km and a thickness up to 10 m. L2-type lamprophyres are crosscut by Sn(-W), Ag-polymetallic and U vein-type mineralization but they crosscut the main hidden Marienberg-Pobershau-Satzung granite complex (Fig. 5). L2-type lamprophyre intrusions are located in the most rare-metal, Ag-base metal, and U districts of the Erzgebirge (cf. Seifert 2008).

Fig. 5. Geology of the Sn deposit Sachsenhöhe/eastern Erzgebirge (in Seifert 2008, modified according to W. Schilka, pers. comm. 2000, and archive material). 1 – biotite gneiss; 2/3 – muscovite(–biotite) gneiss; 4 – explosive breccia; 5 – syenogranite; 6 – monzogranite; 7 – albite granite; 8 – lamprophyre (type L2); 9 – greisenization; 10 – Sn(-W-Bi) vein–like greisen zone; 11 – "kb ore–type" vein; 12 – vein with post–Variscan mineralization; 13 – fault; 14 – old adit.

(3) L3-type lampropyhres are identified in the Pobershau Sn-Ag-Cu ore field and are represented by feldspar- to low-phyric kersantitic lamprophyres. Based on the data from Müller (1848) and Seifert (1994, 2008) the L3-type lamprophyres in the Pobershau ore field show post-Sn mineralization age (Fig. 6).

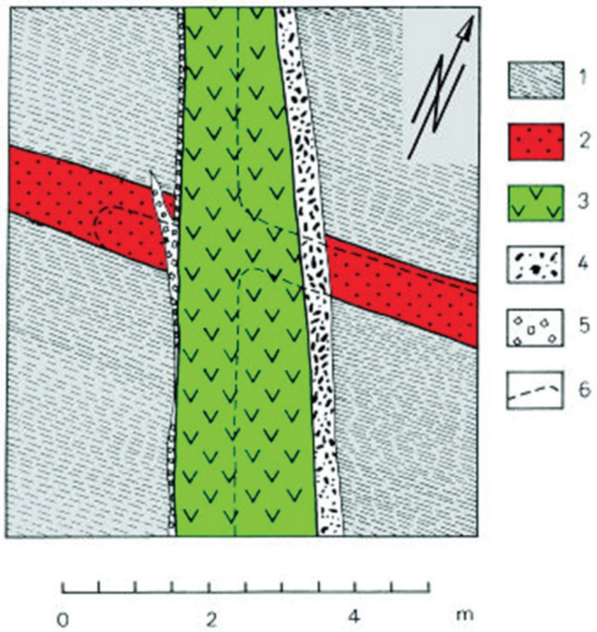

Fig. 6. Schematic picture showing an East-West striking cassiterite-quartz vein crosscut by a NNW-SSE lamprophyric dike, Pobershau Sn-Ag district/central Erzgebirge (in Seifert 2008, modified according to Müller 1848 and Seifert 1994). 1 – paragneisses of the Rusová unit; 2 – quartz-cassiterite vein (main type of the Sn veins in the Pobershau district; Sn-Li-F association); 3 – lamprophyric dike (type L3); 4 – brecciated quartz vein with Fe- and Mn-oxihydroxides; 5 – gneiss-, Sn-vein-, and lamprophyre-fragments cemented by quartz; 6 – old adit.

In the *Western Erzgebirge and Vogtland* area, lamprophyres occur in the Nejdek-Eibenstock granite massif and in the metamorphic host rocks as single dikes or minor dike swarms (Kaemmel 1961; Baumann, Gorny 1964; Seifert 2007). At the Mühleithen-Gottesberg Sn-W-U district Seifert (2007, 2008 and references therein) described low-phyric mica-minette dikes crosscutting Eibenstock-type granites of the Western Erzgebirge pluton and crosscut by (explosive) breccia pipes and subvolcanic felsic intrusions. The Sn veins and greisen and U veins are younger than the emplacement of the lamprophyric intrusions (cf. Seifert 2007).

In the *Eastern Krušné hory/Erzgebirge*, lamprophyric dikes (kersantites, minettes, spessartites) occur mainly in gneisses and crystalline schists, and are a component of the dike suite which also consists of aplites, microgranites and granite porphyries (Novák et al. 2001; Pivec et al. 2002; Seifert 2008). A kersantite dike in the exocontact of a granite cupola at the Sn-W deposit Preisselberg in the district Krupka is shown in Figure 7. Xenoliths of lamprophyre embedded by Li-mica alkali feldspar granite were observed at the Krupka Sn district (Štemprok et al. 1994). This indicates also the presence of intra-granitic lamprophyres.

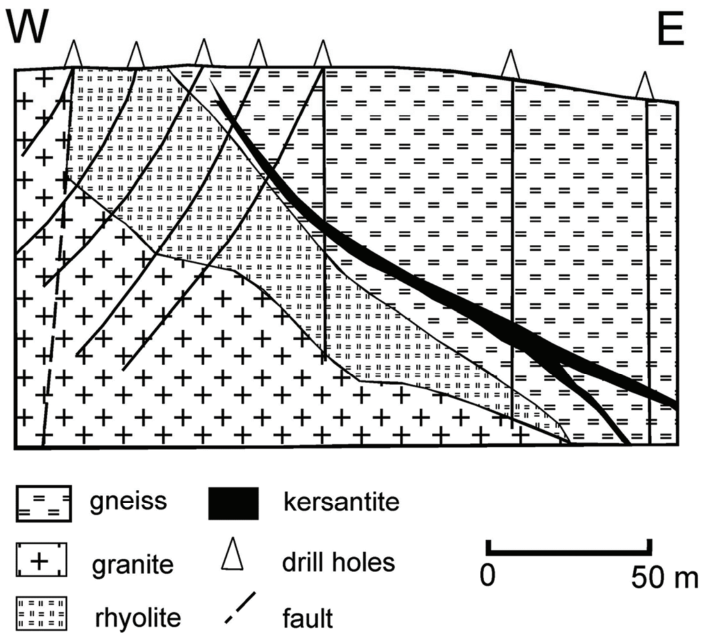

Fig. 7. Cross section of the Preisselberg Sn-W-Mo deposit in the Krupka district (Eastern Krušné hory/Erzgebirge) with a lamprophyric dike near the contact of the late-Variscan granite intrusion (from Novák et al. 2001).

6.4. The Caucasus

In the Main Ridge of the *Caucasus (Russia)* at the Kti Teberda deposit, scheelite veins and impregnations occur in orthoamphibolites (Kremenetsky et al. 2000) and are intersected by the Late Paleozoic Dupukh pluton of two-mica granites. The deposit was formed in two main mineralization stages separated by intrusion of diabase and lamprophyric dikes (Denisenko 1986).

6.5. Central Asian fold belts

The Talas ore district in the *Kyrgyz Tien Shan* encompasses numerous Sn-sulfide, Ag-Sb, Ag-Pb, and Sn-Ag ore deposits (Pavlova et al. 2008; Pavlova, Borisenko 2009, Pavlova, Borovikov 2010). Tin occurrences are located around multistage granite plutons of Neoproterozoic to Paleozoic ages intruding Proterozoic/Paleozoic terrigenous-carbonate sediments. All the Ag-Sb and Sn-Ag ore bodies are superimposed on earlier lamprophyres, syenites, and extrusive mafic rocks. The Sn-W deposit Trudovoe (SE Tien Shan) hosts Late Palaeozoic lamprophyres (Dzhenchuraeva et al. 2007).

In the SE Altai (Russia) and NW Mongolia in the Yustid granite massif, Sn-W deposits occur at the contact between the granite and the host Devonian terrigenous rocks.

The RM mineralization is connected with both the main stages of felsic magmatism: the Yustid complex (352 ± 6Ma) with Sn-W mineralization, and the amazonite dike with cassiterite mineralization (265.9 ± 3.5 Ma) (Pavlova, Borisenko 2009). The youngest ages for Mo-W greisen mineralization in Ulanul (Mongolia) and Kalguty (Russian Altai) was measured between 220 and 200 Ma (Pavlova, Borisenko 2009). The Early Mesozoic magmatism is represented by dike swarms of intermediate and mafic rocks (minette, kersantite, bostonite, dolerite), small intrusions of syenite and granosyenite and later leucogranitic intrusions and by ongonite dikes (Vasyukova 2010).

In Uzbekistan, scheelite skarn deposits like Ingichke occur at the contact zone of late-Variscan granites (Smirnov et al. 1978; Denisenko 1986) which hosts lamprophyres in the bimodal dike suite.

In Tajikistan in the Mogoltau Mts, the Middle Paleozoic Muzbek complex (quartz diorites, granodiorites) and Late Palaeozoic Chorukh-Dairon complex (Mamadzhanov 2001) are associated with W (scheelite) and Mo mineralization. In the SE Pamir the Sn-W deposit Trezubetz and the Ag-Sb deposit Akjilga host Cretaceous and Eocene lamprophyres, respectively (Pavlova et al. 2010).

In *central Kazakhstan and Kalma Narym* region lamprophyres are reported in the bimodal suite of granitoid plutons carrying RM mineralization by Zhilinskii (1959) and Shcherba (1957, 1960). In the *Southern Altai* in the Late Paleozoic Kalba massif, Shcherba (1957) documented granite porphyries and lamprophyres representing the products of the latest magmatic stages. Mafic dikes in Western Kalba include spessartites and kersantites, but also gabbrodiabases, diorites, diabases, and gabbronorites (Shcherba 1957). Lamprophyres occur in zones of Meso-Cenozoic tectonic activation. Thus, some of them may be related to tectonic events later than Palaeozoic magmatism which produced RM mineralization.

In the Altai-Sayan in Russia, the Cu-Mo stockwork of the Sorskoe deposit (Krementsky et al. 2000) occurs in the Kuznetsk Alatau region. The deposit is accompanied by bimodal suite of dikes consisting of pegmatites, diorites, diabases and spessartites (Makeev et al. 1983).

6.6. Asian Mesozoic provinces

In *south-eastern China* lamprophyres occur in association with Mesozoic granites in the Sn-polymetallic district of Dachang in north-western Guangxi province (Mao et al. 1995; Cai et al. 2006). In the Geiju area in the Yunnan province of south-western China, the Sn-polymetallic deposits are also spatially associated with Mesozoic granites. Mafic dikes which include lamprophyres and alkaline rocks (Cheng et al. 2008; Cheng, Mao 2010) are coeval with Sn-polymetallic mineralization.

In *Western Transbaikalia (Russia),* within and in the vicinity of the Gudzhir granite stock of Jurassic age at Dzhida, three closely spaced deposits are described (Smirnov et al. 1978; Troshin 1978): (1) Pervomaiskoe stockwork molybdenite deposit, (2) huebnerite-cassiterite mineralization of the Inkurskoe deposit, and (3) huebnerite-sphalerite-galena veins of the Kholton deposit. With the latter deposit, dikes of mafic and intermediate intrusive rocks are spatially associated, described as bostonites, lamprophyres and diorites (Troshin 1978). The earlier descriptions identified kersantites and spessartites as dikes (Povilaitis 1960), which chronologically separated the earlier molybdenite from the younger essentially huebnerite mineralization. The magmatic sequence in relation to the ore mineralizations was reintepreted by Efremova (1983). Reyf in Kremenetsky et al. (2000) classified the dikes separating the Mo and W mineralizations as quartz-microsyenites (Phase V).

The magmatism of *Eastern Transbaikalia* in Russia was studied in detail by Russian geologists (e.g. Troshin 1978; Kozlov 1985; Mikhaleva 1989). Granitoid intrusions comprise diorites and monzogranites and are associated with lamprophyres (Troshin 1978). Mikhaileva and Tychinskii (1972) noted a spatial and temporal association of lamprophyres (spessartites, vogesites, minettes, monchiquittes, kersantites) with many polymetallic veins in this region. In most cases, lamprophyres are pre-ore or intra-ore in the age of emplacement. The Sn and W mineralization is associated with small granite cupolas at Bukuka-Belukha, Khapcheranga, Etyka, and Orlovka, which are also accompanied by lamprophyric dikes.

The amazonite granite stock of Etyka (Levitskii et al. 1963) is an apophyse of a hidden body of the Shakhtamin granite complex (Syritso 2002). The amazonite Ta-enriched granite postdates wolframite veins. Lamprophyres are widespread in the Etyka district, where they are the earliest rocks of the pre-granitic complex. Troshin (1978) gives the following sequence of magmatic rocks: lamprophyres, porphyritic diorites, plagiogranites, amazonite granites. Levitskii et al. (1963) described an intersection of a lamprophyric dike by a plagiogranite (porphyry) dike, all of them crosscut by a late topaz-cassiterite vein (Fig. 8).

A Ta deposit is related to the Orlovka granite stock. The albitized lepidolite-amazonite Li-F granite belongs to a hidden granite intrusion which outcrops as the Khangilai (biotite-bearing) and Spokoinoe (muscovite-bearing) granites (Syritso 2002). A flat-lying pre-granitic lamprophyre dike with a thickness of about 100–120 m Reif (2000) is intersected by a lepidolite-amazonite granite intrusion. Abushkevich (2005) and Abushkevich & Syritso (2007) distinguished between the dikes of K-rich trachydacites and trachyrhyolites, lamprophyres, diabases and dolerites. Sub-alkaline basaltic rocks crosscut amazonite granites and are the latest in magmatic sequence (Syritso 2002). Lamprophyres are pyroxene-kersantites and amphibole-spessartites. The Rb-Sr ages show identical ages for various lamprophyres at about 153 Ma while the granites were formed between 145–139 Ma as shown by zircon ages. Abushkevich (2005) postulates the effect of mantle fluids indicated by -1.7 εNd values.

The RM deposits in northeastern Mongolia are part of the Transbaikalian metallogenic province. Lamprophyres occur subordinately in the Gobian-Southern Kerulen in the Baga Khairkhan, Buren Tsogtin and Sharakadin ore districts, which are associated with Mesozoic granites. In the Baga Khairkhan granite massif of Middle to Upper Jurassic age (Kovalenko et al. 1971) and in the Ikhe Khairkhan ore district (Marinov et al. 1977) quartz-wolframite veins are associated with granodioritic, dioritic, granite porphyry, and lamprophyric dikes which crosscut Triassic effusive rocks. Granitic dikes are intersected by lamprophyre dikes (up to 3m thick) with a strike length up to 1 km (Kovalenko et al. 1971).

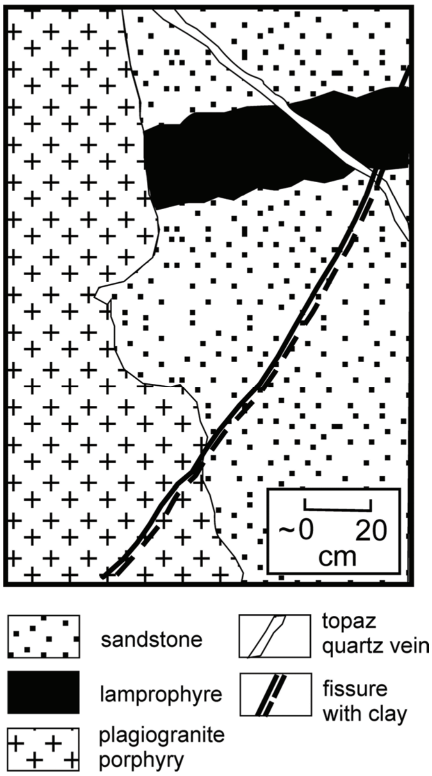

Fig. 8. Intersection of a lamprophyre dike by a plagiogranite (porphyry) dike at the Etyka deposit in Transbaikalia (from Levitskii et al. 1963) (no scale given in the original).

In the Primorie region (Russian Far East) the Voznesenka granite complex host a bimodal suite of dikes and is postdated by Sn mineralization. Govorov (1977) distinguished: (1) pre-granitic dikes of gabbrodiorite, diabase, monzonite; (2) pre-ore dikes of diabase, spessartite and kersantite emplaced after the origin of the earliest greisens and quartz veins; (3) post-ore dikes of diorites ("plagioclase porphyrites") which intersect greisen/tourmaline and sulfide ores. The dikes of the second stage control the mineralizations in the Voznesenka, Pogranichnyi, and Yaroslavskii ore fields. Krymsky and Belyatsky (2001) dated the Li-F granites between 467 to 452 Ma, diorite-monzonite intrusions at 415 - 406 Ma and intra-mineralization subalkaline basalts at 405 Ma. The above mentioned authors postulated the influence of depleted mantle besides the Precambrian crust material on the granite composition.

The *Yano-Kolyma* district in the Verkhoyansk fold belt (Russia) is located between the Siberian craton and the Kolyma-Omolonsky superterrane and show mainly Sn(-W) and Ag-Sb mineralization (cf. Pavlova, Borisenko 2009). Alkaline mafic magmatism is represented by diabase, dolerite, kersantite, minette, and camptonite dikes. Lamprophyres are associated with Sn mineralization at the Deputatskoe Sn-sulfide deposit hosted by Jurassic and Upper Triassic sedimentary rocks of the Polousny syclinorium (Fig. 9; Pavlova, Borisenko 2009). The deposit is related to a hidden Cretaceous granite intrusion known from the boreholes in a depth of 250 to 375 m below the surface (Höll et al. 2000). Four mineralization stages are distinguished: (a) cassiterite greisen, (b) cassiterite-tourmaline-sulfide-quartz, c) cassiterite-chlorite-sulfide-Sn and (d) galena-sphalerite (Smirnov et al. 1978). The dike suite consists of (a) pre-granitic diorites, (b) quartz and dacite porphyries, and (c) diorites, dolerites, and lamprophyres (also as intra-ore dikes). Many dikes of diabases, diorites, and lamprophyres enclose xenoliths of granite porphyries. Lamprophyre dikes contain clasts of rocks with pyrite and arsenopyrite and are crosscut by quartz-siderite stringers with galena and sphalerite. The sequence of magmatic and mineralization events as indicated by geological evidence and age dating is as follows (cf. Pavlova, Borisenko 2009): granite → rhyolite → Sn-W association → diabase porphyry → Sn- sulfide association → lamprophyre → Sn-Ag veins. In the southern Verkhoyansk district Triassic terrigenous sediments are intruded by 123–119 Ma granites and 92 - 99 Ma granitoids (cf. Pavlova, Borisenko 2009). Biotite pyroxene lamprophyre dikes (>120 Ma) and postgranitic diabases and amphibole/pyroxene lamprophyres also occur at the Menkechenskoe deposit. The Ag-Sb mineralization of the second stage is superimposed on later lamprophyres which crosscut Sn-W and Sn-sulfide ore bodies and are intersected by quartz-porphyry dikes. The sequence of events is as follows (cf. Pavlova, Borisenko 2009): lamprophyre → Ag-Pb-siderite veins → granite → granite porphyry → Sn-W → diorite → Sn sulfide → diabase → lamprophyre → Sn-Ag → rhyolite.

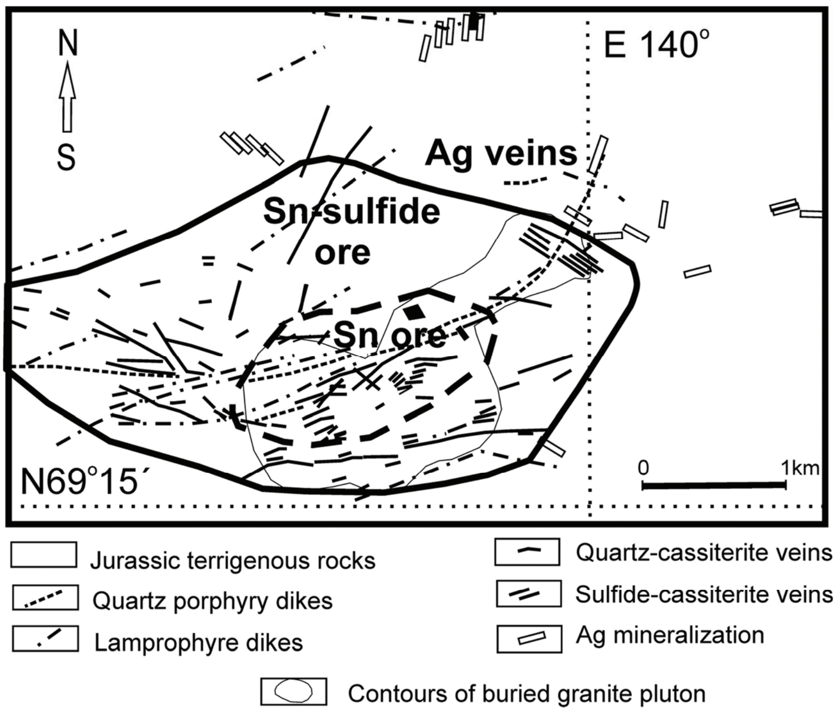

Fig. 9. Geological map of the Deputatskoe deposit (from Pavlova & Borisenko 2009). The contour of the Sn(-sulfide) mineralization is marked by a bold line.

In the northern part of the southern Verkhoyansk synclinorium the Upper Khandiga (Khandigskii) granitoid massif hosts lamprophyres (spessartites, kersantites, vogesites, minettes) enclosing abundant xenoliths (Korostelev 1977). Many lamprophyre dikes show transitions from biotite to amphibole-bearing varieties. Some lamprophyres are close in composition to camptonites or camptonite-vogesite due to an increased content of Ti-augite, barkevikite and olivine.

In *Yakutia*, Layer et al. (2001) studied the tectonic setting of plutonic belts related to Sn, W, Ag, Pb, and Zn mineralization. At Polousnyi a hidden granodiorite body at Churpunnya is associated with cassiterite-quartz veins containing abundant tourmaline accompanied by diorite, lamprophyre, and microgranite dikes. Cassiterite-sulfide mineralization with tourmaline and chlorite at the Dyakhtardakhskoe deposit is associated with granite porphyry dikes, monzonites, and lamprophyres and it is related to a hidden granite intrusion (Lugov et al. 1986). Indolev and Nevoisa (1974) studied Mesozoic and Cenozoic lamprophyres in Ag-Sb deposits of Yakutia. Indolev (1979) describes some lamprophyres in Yakutia as analcime pyroxene camptonites spatially associated with monzonites related to a volcano-plutonic complex. In the Ilintas deposit in the southern Yanskii district veins of cassiterite-silicate formation occur in the exocontact of a Mesozoic granite (Lugov et al. 1986). Indolev (1979) reported that a mica-lamprophyre dike at Ilintas crosscuts an aplite which is associated with adamellite of the Bezimyannyi massif. This aplite is intersected by a sulfide ore vein. The dike assemblage includes also granite porphyries and diorites.

Lamprophyres in association with the Mesozoic granites (Milov, Ivanov 1965) in *Chukotka* (Russia) are described by Zagruzina (1965), who distinguished (a) biotite, (b) pyroxene-biotite- and (c) hornblende-lamprophyres where biotite lampropyhres are predominant. At the Iul'tin deposit in Chukotka (Russia), a dike of monchiquite intersects a granite dike and a quartz vein (Lugov et al. 1986). The intrusion of the latest lamprophyres may not be coeval with the RM granitoid intrusions. At the Svetloe tin deposit the Early Cretaceous dikes of lamprophyres (mainly spessartites, less abundant kersantites, up to 300 m long and 0.5–5 m thick) are associated with dikes of granodiorites over a hidden granite massif (Lugov et al. 1986). Ore veins of the cassiterite-quartz formation are related to numerous dikes of lamprophyres, granite porphyries, and diorites at the Pyrkakai Sn deposit. In the Pervonachalnoe deposit transitions of pyroxene and biotite-pyroxene lamprophyres are reported by Lugov et al. (1986).

6.7. Australia

In Australia the ore district of the *Blue Tier batholith (Tasmania)* which is also characterized by the occurrence of tin-bearing alkali-feldspar granites (Sun, Higgins 1996) and the Late Paleozoic Sn(-W) greisen-type mineralization (Groves, Taylor 1973) is apparently independent of Cretaceous lamprophyre intrusions (Mc Clenaghan, Baillie 1975).

7. Results and interpretations

7.1. Temporal and geographical position, tectonic setting of lamprophyres in RM districts

Calc-alkaline and alkaline lamprophyres are a component in dike suites of some granite-related RM deposits in major orogenic belts of the northern hemisphere. The occurrences of lamprophyres (Fig. 2) in association with RM granitoids follow a major E-W-trending zone over the continents in the northern hemisphere, extending from the European Variscides to Variscan central Asiatic fold belts and over the Mesozoides in Transbaikalia to Verkhoyansk-Kolyma, Chukotka and Alaska. Lamprophyres occur also in Cenozoic Mo provinces of the North American Cordillera.

In the database on about 200 granite intrusions (cf. Štemprok 1998; cf. Seifert 2008) dealing specifically with granitoids associated with RM deposits or with RM deposits which are only marginally associated with igneous rocks, only 63 have been recorded as having lamprophyres in the mafic dike suite (Tab. 3). Many lamprophyric associations with RM deposits occur around granite stocks or cupolas representing elevations of larger, partly concealed granite bodies of the size of plutons or batholiths. The predominance of small granitoid bodies commonly of less that 1 km^2 of outcrop size accords with the observation that the contact zones of small granite cupolas are most productive in terms of the occurrence RM mineralization (Štemprok 1990; Seifert, Kempe 1994).

While the bimodal dike suite in association with granitoids is often considered to be related to the origin of magmatic bodies having the size of batholiths or plutons, some lamprophyre dikes are related according to Mikhaleva (1989) and Seifert (2008) to “small intrusions” of variable compositions which are independent of the origin of major granite bodies and are important for the origin of some types of Au, Cu, Mo, and Sn(-W) mineralization. This idea is close to the concept of Cu-Mo and Cu-Au porphyry deposits which are related to small, commonly felsic magmatic bodies of porphyritic textures (Müller, Groves 1993, 1997; Candella, Picolli 2005; Robb 2005; Sinclair 2007).

Lamprophyres which are associated with mesothermal Au deposits (Rock 1991) show ages from Archean to Cenozoic, and are confined for example to the Cordilleran orogen in North America, the Altaid orogene of Central Asia, and the Paleozoic Tasmanian orogen (Kerrich et al. 2005). The gold-lamprophyric association is uniformly distributed in various domains from Precambrian shields to Miocene provinces of subduction zones both in northern and southern hemispheres. It is significant that lamprophyric dikes with shoshonitic geochemical signature related to mesothermal Au-Sb veins in New South Wales in Australia (Ashley et al. 1994) occur in the same orogen as Paleozoic tin and tungsten deposits which lack any distinct spatial association with coeval lamprophyres (Taylor 1979; Pirajno 2009).

All the granitoid intrusions with associated lamprophyres in RM districts are of Phanerozoic age. Lamprophyres documented in the Bushveld complex in South Africa are distant from important Sn districts (Pirajno 2009). Highly altered lamprophyres intruding as dikes and isolated pockets into the Bushveld granite on Klipdrif 123 in the area of Franspoort line (RSA) were reported by Gorsky (1958), who classified the rock as alkaline lamprophyre. Cloete (1992) describes lamprophyres in the Western and Eastern lob of the Bushveld complex associated with alkaline and carbonatite complexes.

Lamprophyres in association with RM deposits occur in two geotectonic settings: (1) in subduction environment of active continental margins (continent/continent and continent/arc collision) in association with calc-alkaline granitoids and shoshonites; (2) in the regions of asthenospheric mantle upwelling in extensional tectonic regime, e.g. Transbaikalia (Syritso 2002) or Internal Variscides of Europe (Seifert 2008). Extensional tectonic setting is postulated as the most important factor for the emplacement of late stage or postorogenic granites and mafic dikes including lamprophyres (e.g. Rock 1991; Amato et al. 2003; Seifert 2008; Cheng, Mao 2010).

7.2. Contemporaneity of intrusions of lamprophyres and associated granites

Recent isotopic measurement on zircons determined the age of lamprophyric intrusions and of granites in a particular RM district such as SW England, the Erzgebirge/Krušné hory (Germany, Czech Republic), Eastern Transbaikaliain Russia and the Geiju district in China (see references in Table 2). The intervals of lamprophyre emplacement overlap with granite intrusions in RM districts of Paleozoic, Mesozoic, and Cenozoic provinces. These data show that the lamprophyre and granite intrusions are in some metallogenic provinces genetically related (e.g. in the Erzgebirge as bimodal sequences and associated late-Variscan mineralization, Seifert 2008). On the other side, some ore districts show that the intrusion of lamprophyres may not be coeval with RM granites or mineralization. For example, at the Kitsault porphyry molybdenum deposit in British Columbia lamprophyre dikes are almost 20 Ma younger than the intrusive complex that is related to the deposit (Steininger 1985).

7.3. Petrography of lamprophyres

Lamprophyres in RM districts share petrological and geochemical features of lamprophyres which occur in the broader vicinity. Thus in Cornwall and in Normandy minettes are predominant (Turpin et al. 1988), whereas in the western part of the Armorican Massif and in the western part of the French Massif Central kersantites prevail. In the Krušné hory/Erzgebirge kersantites and minettes occur in approximately equivalent amounts (Kramer 1976, 1988; Holub, Štemprok 1999; Seifert 1994, 2008). In the Krupka region of the Eastern Krušné hory kersantites, minettes, and spessartites occur jointly with granite porphyries and aplites hosted by gneisses (Pivec et al. 2002). In RM deposits of Chukotka and Alaska, spessartites and kersantites are predominant (Zagruzina 1965; Sainsbury 1969). In Transbaikalia spessartites and kersantites are dominant, while minettes are subordinate in association with Sn and W greisen-type deposits (Troshin 1978; Syritso 2002). Kersantites are reported in the Etyka district (Levitskii 1963) while in the Orlovka district Abushkevich (2005) described spessartites in predominance over kersantites. Also, the major element composition supports the classification of lamprophyres as spessartites in some Transbaikalian regions. The presence of spessartites and kersantites in Alaska may be testified on the basis of chemical analyses reported by Sainsbury et al. (1968) and Sainsbury (1969). Alkaline lamprophyres were observed in association with RM granitoids, e.g., monchiquites at the Iul'tin deposit in Chukotka (Lugov et al. 1986) and camptonites in Eastern Transbaikalia (Mikhaleva 1989). Shchukin (1974) described in the southern Gissar (Tien Shan, Kyrgyzstan), which host several RM districts, a widespread variety of lamprophyres (monchiquites, camptonites, vogesites, kersantites, spessartites) and observed transitions between monchiquites and camptonites and between kersantites and spessartites. However, many lamprophyres recorded in Table 3 are described as "lamprophyres" without distinguishing their petrographic nature.

7.4. Lamprophyre associates in the dike suites

The dikes associated with lamprophyres in RM districts show the predominance of felsic compositions with more than 60 % of occurrences (Fig. 10). These include granite porphyries, aplites, pegmatites, microgranites and rhyolites (quartz porphyries). Dioritic composition constitutes 17 % and diabase and gabbro about 14 % of recorded observations. In many districts lamprophyres are closely spatially associated with diorite and diabase dikes and are possibly connected by mutual transitions (Mikhaleva 1989). Lamprophyres are also interpreted to be a component of a separate Mesozoic lamprophyre-diabase formation in southern Siberia by Mikhaleva (1989) which accompanies many polymetallic and fluorite deposits.

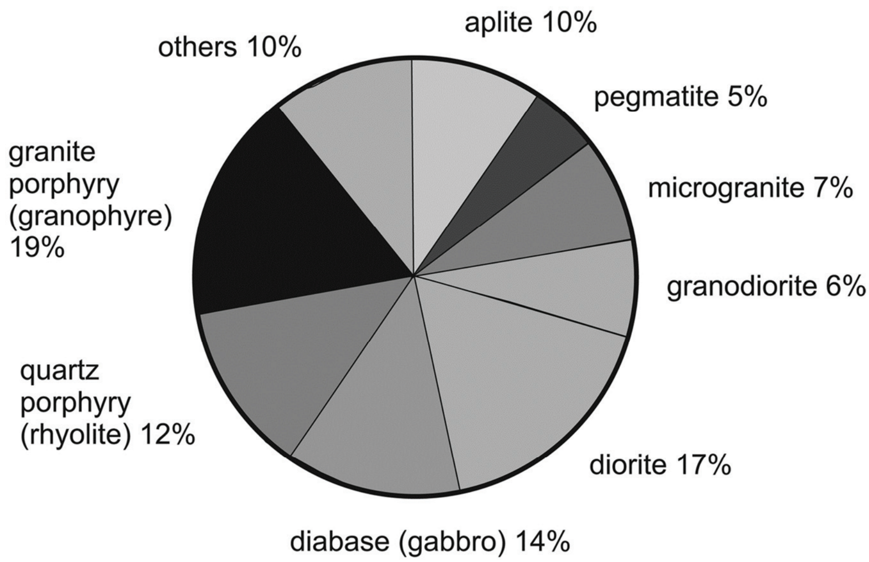

Fig. 10. Statistics of the occurrences of dike associates of lamprophyres in RM districts as based on the data in Table 3. The group "others" includes dolerites, bostonites, essexites, trachytes, and syenites.

The variable composition of felsic or intermediate members of bimodal dike suites possibly mirrors the extent of differentiation of parental intrusive bodies and their interaction with host rocks.

7.5. Postmagmatic and ore-bearing alterations of lamprophyres

The petrographic description of lamprophyres in RM districts observes a constant presence of deuteric alterations like pilitization of olivine (cf. Velde 1968) and urallitization of pyroxens (e.g. Zagruzina 1965; Rock 1991; Seifert 1994; Pivec et al. 2002; Seifert 2008). Lamprophyres also reflect postmagmatic processes in granites or alterations caused by RM mineralization. Abdullaev (1957) described skarnization of a lamprophyre dike at the Ingichke W skarn deposit in Uzbekistan. Quartz-sulfide mineralized lamprophyres were observed in the Pervonachal'nyi stockwork deposit in Chukotka (Lugov et al. 1986). Alteration of lamprophyres with epidote, actinolite, chlorite, carbonate, albite, pyrite, and quartz was observed at the Savinskoe-5 deposit (Eastern Transbaikalia) associated with granites of the Upper Jurassic Kukulbei complex (Lugov et al. 1986). Some lamprophyres in Sn-bearing districts are greisenized as indicated by their mineral composition and geochemical characteristics (e.g. high Sn, Li, and F contents in greisenized lamprophyres in the Krušné hory/Erzgebirge, Novák et al. 2001; Seifert 2008). An intensively greisenized kersantite was observed in Krupka in the Eastern Krušné hory where greisenization produced an alteration band zoned from a cassiterite-bearing quartz veinlet outwards (Novák et al. 2001). The outer glimmeritic zone consists of Mg-biotite, fluorite, quartz, and topaz and retained the original texture of kersantite. The inner zone is enriched in Li-bearing Mg-biotite and contains small amounts of quartz, topaz, and fluorite and some cassiterite, scheelite, and apatite. Greisenized lamprophyres in Sn-W deposits in the Saxonian Erzgebirge show Sn contents of up to 1200 ppm (Seifert 2008). Indolev (1979) describes at the Ilintas deposit (Yakutia) greisenization of a lamprophyre dike which is crosscut by a granitic dike. The altered lamprophyre shows a taxitic texture and consists of melanocratic actinolite-biotite portions with titanite and quartz-feldspar-tourmaline-mineralization.

7.6. Intrusions associated with rare metals and lamprophyres

The dominant magmatic intrusions in RM districts are leucogranites (Štemprok 1998). Many granitoids associated with these leucogranites have composition of diorites and show association with granodiorites and monzogranites. Granodiorites are commonly relatively homogenous plutons or stocks hosting also some RM mineralization; quartz monzonites are often spatially associated with some ore-bearing leucogranites.

According to modal composition the ore-bearing leucogranites described in the database are commonly classified as syenogranites or alkalifeldspar granites (IUGS classification) or alaskites in the earlier literature. The dominant varieties of ore-bearing leucogranites granites distinguished according to micas are: (a) biotite, (b) two mica, (c) muscovite or (d) lithium mica (zinnwaldite, protolithionite, lepidolite). Alkali-pyroxenes and alkali-amphiboles are very rarely present in some granite varieties in small granite cupolas (Štemprok 1990).

Lamprophyres occur specifically in the districts with RM granites that host albite-rich highly evolved alkali-feldspar granite varieties with Li-micas, which are typical for the Mesozoic provinces of Transbaikalia (Etyka, Orlovka) and Variscan provinces of Central Europe (Erzgebirge/Krušné hory, Slavkovský les) and of Western Europe (Massif Central) and the Blue Tier batholith in Tasmania (Tab. 3). These granites correspond to apogranites in the sense of Beus et al. (1962) which are the highly evolved granites affected by postmagmatic albitization (Syritso 2002). Granodiorite intrusions are often associated with skarn deposits (e.g. W deposit Ingichke or Vostok 2 in Russia). Diorites forming minor intrusions are typical for the districts which host Sn-sulfide deposits in the Maritime region of Russia.

RM granites are commonly peraluminous, and most of them were originally assigned with S-type granites according to Chappel and White (1974). S-type granites were supposed to be associated with Sn deposits while I-type granites are related with W deposits. This simple classification is hardly acceptable by the present data and it was supplemented several additional types of granites (see Frost et al. 2001). RM granites are characterized by high Li, Rb, and Cs, very high F and B and increased Sn, W, and Mo contents (Tischendorf 1977; Tauson 1977; Kozlov 1985; Seifert, Kempe 1994) which can also be explained partly by an overprint by RM mineralization. Most Sn-bearing granites show enrichment in K_2O which is also significant for the dike suite of associated mafic rocks (e.g. Sn province of Transbaikalia, Beskin et al. 1979; Kozlov, Efremov 1999; Erzgebirge, Seifert 2008).The intrusion of lamprophyres often separates the intrusions of granite stocks and felsic dikes and RM mineralizations.

7.7. Metals and styles of RM deposits associated with lamprophyres

The statistics of the data in Table 3 shows the predominance of RM deposits with Sn or the combination of Sn and W in deposits (Fig. 11). Tungsten and W-Mo deposits are less widespread. We noted subordinate occurrences of Sn-W-Mo mineralization in some RM deposits. In the statistics of the mineralization types we documented a characteristic predominance of greisen- and vein-type deposits (Fig. 12). Numerous Sn-sulfide deposits in northeastern Russia are associated with lamprophyric intrusions.

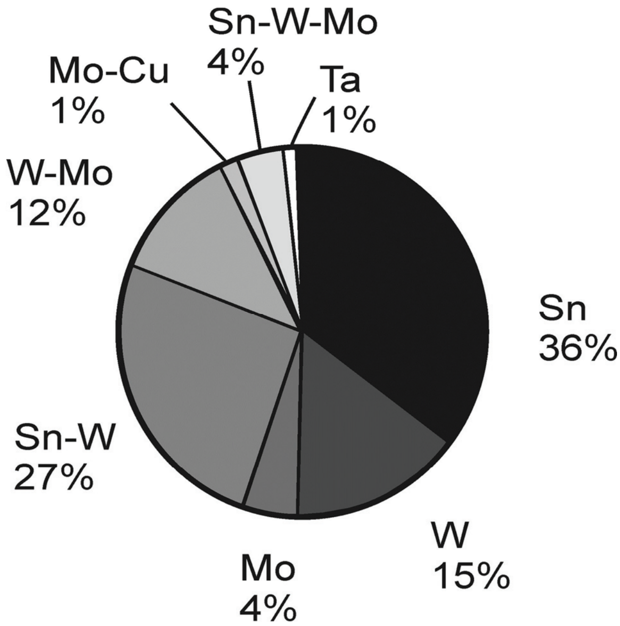

Fig. 11. Statistics of metals in RM deposits associated with lamprophyres based on data in Table 3.

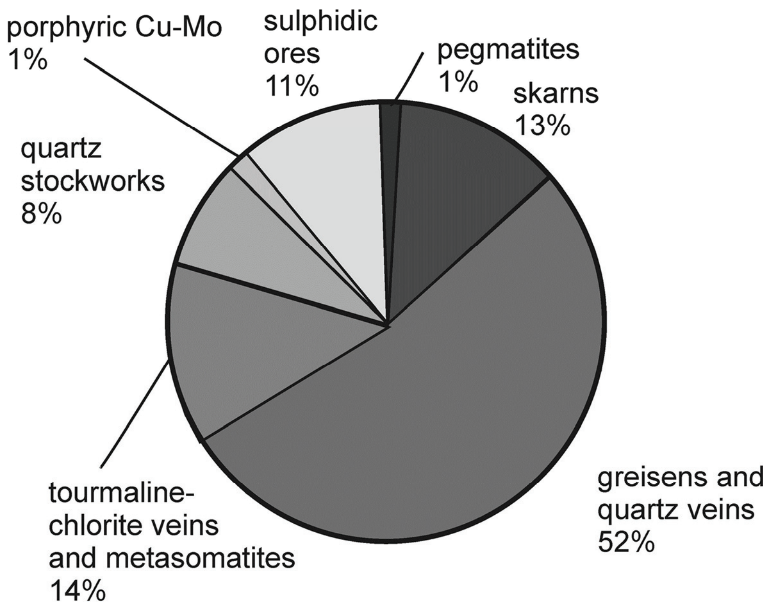

Fig. 12. Statistics of the styles of deposits in RM district based on the data in Table 3

TABLE 3

Rare metal (RM) districts and mineral deposits with the occurrences of lamprophyres coeval with granitic magmatism. Legend: qtz. diorite = quartz diorite, gr.porph = granite porphyry, alk.syenite = alkaline syenite, rhyolite = subvolcanic rhyolitic dikes (“quartz porphyry”); locations: Erzg = Erzgebirge; Pal. = Paleozoic, Mes. = Mesozoic.

Name	Country	Age of granitic magmatism	Deposit type	Petrology of felsic/intermediate rocks	Lamprophyres	Dyke assemblage	Reference
Agylkin	Russia	130 - 190 Ma	Sn tourmaline, W skarns	granite, granodiorite?	camptonite, kersantite	granodiorite, tonalite, qtz.diorite, diorite, gabbro, diabase	Indolev (1979), Lugov et al. (1986)
Atasu West	Kazakhstan	Pal.	Sn greisen	granite	lamprophyre	gr.porph, aplite, pegmatite	Zhilinskii (1959)
Baga Khairkhan	Mongolia	130 Ma	W greisen	granite, granodiorite	lamprophyre	granodiorite, granite, diorite	Marinov et al.(1977)
Bainazar	Kazakhstan	Pal.	W-Mo stockwork	granite	kersantite, vogesite	granosyenite, syenogranodiorite, granodiorite, monzonite, syenodiorite, diabase	Shcherba (1960)
Belukha	Russia	155 Ma	W-Mo greisen	granodiorite, granite	spessartite	gr.porph, rhyolite, aplite, diorite	Ontoev (1974)
Blue Tier	Australia	Pal.	Sn-W greisen	granite	lamprophyre	aplite	Groves, Taylor (1973), Mc Clenaghan, Baillie (1975)
Bogdatskoe	Russia	Mes.	Sn skarn, greisen	granodiorite	lamprophyre	diorite, granite	Lugov et al. (1986)
Bugdatin	Russia	Jurassic	Mo stockwork	granite	lamprophyre	gr.porph, rhyolite, diorite	Smirnov et al. (1978)
Bukuka	Russia	app.150 Ma	W greisen	granodiorite, granite	lamprophyre L2 or L3	granodiorite, aplite, diorite, gr.porph, rhyolite	Smirnov et al. (1978)
Buren Tsogtin	Mongolia	140 - 168 Ma	W greisen	gr.porphyry, granite	lamprophyre	gr.porph, rhyolite, aplite, diorite, pegmatite	Marinov et al. (1977)

cont. Table 3

Burgachan	Russia	Mes.	Sn tourmaline	diorite, granodiorite	lamprophyre	diorite, granodiorite	Lugov et al. (1986)
Chorukh-Dairon	Tadjikistan	Pal.	W-Mo skarn, greisen	granite, monzonite, granodiorite, diorite	lamprophyre	gr.porph, rhyolite, aplite	Smirnov et al. (1978), Mamadzhanov (2001)
Cornwall	Great Britain	Pal.	Sn greisen, tourmaline	granite	minette	aplite, gr.porph, "elvans"	Leat et al. (1987)
Covas	Portugal	Pal.	W skarn	granite	lamprophyre	?	Conde et al. (1971)
Dachang	China	107 - 97 Ma	Sn sulfide	granite	lamprophyre	diabase, gr.porph, diorite	Mao Jingwen et al. (1995)
Deputatskoe	Russia	112 - 108 Ma	Sn tourmaline, sulfide, chlorite	granite	kersantite L2	diorite, gr.porph, diabase	Pavlova et al. (2009), Pavlova, Borisenko (2009)
Dyakhtardakhskoe	Russia	125 - 96 Ma	Sn tourmaline, sulfide, chlorite	granite porphyry	camptonite	gr.porph, monzonite	Lugov et al. (1986)
Dzhida	Russia	210 Ma	W-Mo stockwork	granite	kersantite, spessartite	syenite, bostonite, diorite, granite	Povilaitis (1960), Makeev et al. (1983)
Echassière	France	Pal.	W-Sn greisen	granite	kersantite	gr.porph, aplite	Burnol et al. (1974)
Egugskoe	Russia	101 Ma	Sn greisen		lamprophyre	diorite, rhyolite	Lugov et al. (1986)
Ehrenfriedersdorf/ Erzg	Germany	320 - 290 Ma	Sn-W veins, greisen	granite	kersantite L1	aplite, granite	Bolduan, Hoffmann (1963), Kramer (1976), Seifert (2008)
Etyka	Russia	126 Ma	Sn-W (Ta) greisen	granite	lamprophyre	gr.porph, diorite	Levitskii et al (1963), Troshin (1978), Litvinovskii et al. (1995)
Gejiu	China	Mes.	Sn sulfide, Cu, Pb, Zn, Sb, Mo, Au, Bi	granite	lamprophyre	alkaline rocks, gabbro, diorite	Cheng Yanbo et al. (2008)
Gottesberg-Mühlleithen/Erzg	Germany	320 - 290	Sn-W greisen	granite	minette L2	rhyolite, aplite, gr.porph, breccia pipes	Kaemmel (1961), Seifert (2007, 2008)

Ikhe Khairkhan	Mongolia	Mes.	W greisen	granite	lamprophyre	granodiorite, diorite	Marinov et al. (1977)
Ilintas	Russia	Mes.	Sn tourmaline	granite	kersantite	gr.porph, aplite	Indolev, Nevoisa (1974), Lugov et al. (1986)
Ingichke	Uzbekistan	200 - 180 Ma	W skarn	granite, granodiorite, diorite	lamprophyre	granodiorite, gr.porph, rhyolite	Denisenko (1986)
Iul'tin	Russia	Mes.	Sn-W-Mo greisen	granite	kersantite, monchiquite	gr.porph, granite, diorite, aplite, pegmatite	Zil´bermints (1966), Lugov et al. (1986)
Kaiba	Kazakhstan	Pal.	Sn-W-Mo greisen	granite	spessarite	gr.porph, aplite, diabase, gabbro, diorite	Zhilinskii (1959)
Kalba Narym	Kazakhstan	Pal.	Sn-W greisen	granite	lamprophyres	aplite, pegmatite, diorite	Shcherba (1957)
Kandoma	Russia	Mes.	Sn-W greisen	granodiorite, granite	spessartite	gr.porph, aplite, diabase	Izokh et al. (1957)
Karmana	Kyrgyzstan	Pal.	Sn-W tourmaline	granodiorite, granite	spessartite, camptonite	dolerite, leucogranite, aplite, pegmatite	Lugov et al. (1986)
Karnab	Kyrgyzstan	Pal.	Sn-W tourmaline	granodiorite, granite	lamprophyre	leucogranite, gr.porph, aplite	Lugov et al. (1986)
Khapcheranga	Russia	Mes.	Sn-W greisen, chlorite	granite	lamprophyre L1 and L2	aplite, granite, diorite, diabase	Ontoev (1974)
Krupka/Erzg	Czech Republic	320 - 290 Ma	Sn greisen	granite	kersantite L1?, minette L2	gr.porph, rhyolite, aplite, pegmatite	Novák et al. (2001), Seifert (2008)
Kti-Teberda	Russia	280 - 250 Ma	W stockwork, sulfide	granodiorite, granite	lamprophyre	gr.porph, diabase, aplite	Makeev et al. (1983)
Kumarkh	Tadjikistan	Pal.	Sn-W tourmaline	granodiorite	lamprophyre (Mesozoic?)	diorite, aplite	Smirnov et al. (1978), Lugov et al. (1986)
Kumyshtag	Kyrgyzstan	Pal.	Sn-W greisen, skarn, pegmatite	granite	lamprophyre		Pavlova, Borisenko (2009)
Kurgan	Kyrgyzstan	Pal.	Sn sulfide	granites	lamprophyre	alk.syenite, dolerite, bostonite	Pavlova, Borisenko (2009)
Lapas	Uzbekistan	Pal.	Sn greisen	granite	lamprophyre L1	?	Lugov et al. (1986)

cont. Table 3

Lost River	USA	80 - 70 Ma	Sn greisen	granite	kersantite L2 or L3?	diabase, rhyolite	Sainsbury et al. (1968), Dobson (1982)
Marienberg/Erzg	Germany	320 - 290 Ma	Sn-W veins, greisen	granite, rhyolite	kersantite L3	rhyolite, granite, aplite	Seifert (1994, 2008)
Maikul	Kazakhstan	Pal.	Sn greisen	granite	spessartite	qtz.diorite, diabase, aplite, pegmatite	Zhilinskii (1959)
Menkechenskoe	Russia	123 - 119 Ma	Sn-W greisen, Sn-sulfide	granite	lamprophyre L1 and L2	gr.porph, diorite, diabase	Layer et al. (2001), Pavlova, Borisenko (2009)
Orekitan	Russia	165 - 169 Ma	Mo stockwork	granite	lamprophyre	felsite, diabase, diorite, gr.porph	Makeev et al. (1983)
Orlovka	Russia	142 Ma	Ta granite	granite	kersantite, spessartite	diabase, dolerite, trachydacite, trachyrhyolite	Litvinovskii et al. (1995), Abushkevich (2005), Abushkevich, Syritso (2007)
Pervonachanl´noe	Russia	60 - 105 Ma	Sn greisen	granite?	lamprophyre	gr.porph, diorite	Lugov et al. (1986)
Pöhla/Erzg	Germany	320 - 290 Ma	Sn greisen, Sn-W skarns, U veins	granite	kersantite L1	granite	Seifert (2008)
Puy-les-Vignes	France	320 Ma	W veins	granite	minette	granite	Weppe (1951)
Pyrkakay	Russia	Mes.	Sn W	granite	lamprophyre	gr.porph, granodiorite	Lugov et al. (1986)
Red Mtn. (Urad, Henderson)	USA	29.8 Ma	Mo stockwork	granite, rhyolite	kersantite	rhyolite, gr.porph	Wallace et al. (1978), Shannon et al. (2004)
Sachsenhöhe/Erzg	Germany	320 - 290 Ma	Sn-W greisen	granite	minette L2	gr.porph, microgranite	Seifert (2008)
Shara-Khadin	Mongolia	Mes.	Mo-W greisen	granite	lamprophyre	gr.porph	Marinov et al. (1977)
Sorskoe	Russia	Pal.	Mo-Cu stockwork	granite	spessartite	aplite, pegmatite, diabase	Makeev et al. (1983)

Svetloe	Russia	Mes.	Sn greisen	granite?	spessartite, kersantite	granodiorite	Lugov et al. (1986)
Trezubets	Tadjikistan	Mes.	Sn-W	granite	lamprophyre	topaz-protolithionite granite	Pavlova, Borisenko (2009), Pavlova et al.(2009)
Trudovoe	Kyrgyzstan	312 - 270 Ma	Sn-W tourmaline	granite	lamprophyre		Dzhenchuraeva et al. (2007)
Valkumei	Russia	Mes.	Sn tourmaline	granodiorite, granite	lamprophyre	granite, gr.porph, granodiorite, diorite	Lugov et al. (1986)
Vostok 2	Russia	Mes.	W skarn	granodiorite, plagiogranite	spessartite	gr.porph, diorite, diabase, granodiorite	Makeev et al. (1983)
Yamutin	Russia	Pal., Mes.	Sn-W-Mo greisen	granodiorite, granite	spessartite	rhyolite, gr.porph, granodiorite, diabase	Izokh et al.(1957)
Yaogangxian	China	169 - 178 Ma	W-Mo skarn, Sn-W greisen	granite	lamprophyre	granite, aplite, rhyolite, gr.porph, diabase	Kaneda, Takeuchi (1988)
Yustid	Russia	Pal.	Sn-W greisen, W-Mo greisen	granite	lamprophyre	diabase, gabbro-diabase	Pavlova, Borisenko (2009)
Zabytoe	Russia	88 Ma	W-Sn greisen	granite	lamprophyre	gr.porph	Ivanov et al. (1980)

8. Discussion

8.1. Relationships of lamprophyres, granites, and RM mineralization

Rock (1991) pointed out that enrichment of lamprophyres in F, Cl, S, H_2O, and CO_2 relative to most igneous rocks, together with their high temperatures and explosive emplacement by violent drilling mechanisms probably confer on them an enhanced ability to dissolve and transport elements which form soluble complexes with one or more ligands. In his opinion, volatiles enhance the dissolution of certain elements from country rocks which include transition metals (e.g. Zr, Th, U) and the (primary?) enrichment in Mo, Sn, W, PGE, and Au. A number of recent papers proposed an importance of mixing mafic and felsic magmas in genesis of porphyry (Cu-Mo-Au) deposits (e.g. Maughan et al. 2002; Candella, Picolli 2005). Dietrich et al. (1999) suggested that magma mixing was responsible for the formation of the Bolivian Sn porphyry deposits associated with small subvolcanic rhyodacite bodies.

Various schemes were suggested in the literature to explain the association between lamprophyres and ore-bearing granites. Troshin (1978) postulated a mafic magma chamber in the Khapcheranga ore district in Eastern Transbaikalia which is responsible for the origin of lamprophyre and diorite dikes. The thermal effect of this chamber and of its fluids caused the melting of overlying crustal rocks and formation of granitic melts. Leat et al. (1987) suggested a similar model for granitic intrusions in SW England, assuming that these granites are the product of a mafic melt trapped in the mid-crust to form a minette/gabbro body. Kramer (1988) considered lamprophyric (shoshonitic) melts as a product of melting of metasomatic mantle in the Fichtelgebirge-Erzgebirge anticlinorium. He postulated the relationships between lamprophyres and mineralization without a detailed investigation. Seifert (1994, 1999, 2008) presented an abundant evidence that the late-Variscan Sn, W, Mo, Ag, Pb, Zn, Cu, In, and U mineralization in the Erzgebirge are connected with post-collisional lamprophyric and “granitic small intrusions”/rhyolitic (bimodal) magmatism rather than with the large granitic intrusions of the main late Variscan (late-collisional) Erzgebirge pluton (e.g. “Western and Central Erzgebirge Pluton”).

Turpin et al. (1988) concluded that geochemical features of mafic lamprophyres in Western Europe cannot be explained by simple melting of a depleted mantle but are due to some kind of contamination, either during ascent through the crust or as consequence of mantle enrichment prior to its melting. A relative petrographic similarity of trace elements in lamprophyres in relatively distant areas suggests processes independent of the composition of the crust. The subducted material can be the source of this enrichment, e.g. altered oceanic crust, its sedimentary cover and/or fluids and melts resulting from partial melting of subducted crustal segments (cf. Turpin et al. 1988).

Mantle fluids/melts responsible for the mantle metasomatism are capable to dissolve large amount of silicate material (Scambelluri, Phillippot 2001) and could exist as high alkali-rich silicic melts which may account for the enriched trace element patterns and presence of phlogopite in the mantle (Petersen et al. 1996).

Beskin et al. (1979) reported relatively high potassium contents in most RM granites in Transbaikalia. It is important to note that late-Mesozoic alkali basalts are described to occur around the RM granites (e.g. Orlovka deposit, Syritso 2002) and latites which follow the intrusion of RM granitoids in Transbaikalia (Tauson et al. 1984). The above mentioned latites show realively high B, F, Rb, Cs, Sr, Ba, Pb, and Zr contents. A K-enrichment was also documented in the granites which are associated with RM deposits in Chukotka (Zagruzina 1965). Kozlov and Efremov (1999) concluded that there is a general correlation of increased potassium contents and rare-metals in basaltic rocks and metallogenetic specialization of related ore-bearing intrusions in Chukotka, Transbaikalia, and Bohemian Massif, explaining this association by coeval magmatic chambers of deep-seated subalkaline basalt and crustal granitoids. Both were influenced by a prolonged supply of potassium and granitophile elements with fluids from the mantle. The association of K-rich intrusions and Au±Cu deposits was observed worldwide in many epithermal to mesothermal and porphyry-style deposits (Müller, Groves 1993). The enrichment in K, rare alkalies (Rb, Cs, Li), and volatiles appears as a feature specific both for RM granites and calc-alkaline lamprophyres associated with RM mineralization.

8.2. Origin of RM deposits as evidenced by lamprophyres

Despite a predominant spatial association of Sn, W, and Mo deposits with felsic rocks, some authors have doubted a narrow genetic relationship of outcropping granites and Sn deposits. Sainsbury and Hamilton (1967) noted a widespread occurrence of major faulting, post-dating the intrusion and consolidation of granites and supposed that the main phase of tin deposit formation is well after the formation of granites. Štemprok (1967) supposed that the solutions which gave rise to the deposits of tin and tungsten in the Western Pluton in the Krušné hory/Erzgebirge are not derived from the same granites, which enclose the deposits, but come from a deeper source in the crust. This concept is newly supported by the measured interval of about 20 Ma between the granite intrusion and greisenization in the Western pluton of the Krušné hory/Erzgebirge granite batholith by modern age dating of zircons by Kempe et al. (2004) and by numerous new geological, age, and geochemical data from Seifert (1994, 2008). Verschure and Bon (1972) supposed that high concentration of Sn and other trace elements (e.g. W, Mo, Ta, Li, Be, F) in plutono-volcanic complexes such as those in Rondonia and Nigeria is primarily due to an enrichment in volatiles from alkali basalt. Such volatiles could have been "inherited" by the granitic magmas. Sillitoe (1974) also postulated mantle origin of Sn deposits in anorogenic settings (e.g. Nigeria). Osipova (1974) suggested a possible mantle origin for some rare metals at the Kavalerovo deposit (Maritime Region, Russia) pointing out to the interval between the origin of alaskite granites, diabases, and Sn-polymetallic mineralization (Radkevich et al. 1974). Baskina (1980) considered a subcrustal source for both “diabase dikes” and ore deposits in many regions of the Far East of Russia where Sn deposits are spatially associated with mafic dikes or “small intrusions” of dioritic composition.

8.3. Models RM mineralization compared with those of mesothermal gold deposits

Rock et al. (1989) proposed a model explaining the relationship between gold deposits, and lamprophyric and felsic (porphyry-granitoid) magmatism (Fig. 13a). In case of the RM-lamprophyre association the enrichment of the earth’s mantle in LILE and F was decisive for the metallogenic specialization of RM-granites (cf. Rock 1991; Seifert 2008). The melting in the lower crust was affected by addition of volatiles to the source of granitoid magmas from an underplated lamprophyric magma similarly as it is proposed for the gold deposits by Rock et al. (1989; Fig. 13a) and for Sn-W-Mo, Ag-base metal and U deposits by Seifert (2008). These volatiles possibly extracted some rare metals from the mantle. The enrichment of rare metals in hydrothermal systems was caused by differentiation of granitic magmas in deep seated chamber(s) in the lower crust and/or by mantle-derived fluids (Seifert 2008; Fig. 13b).

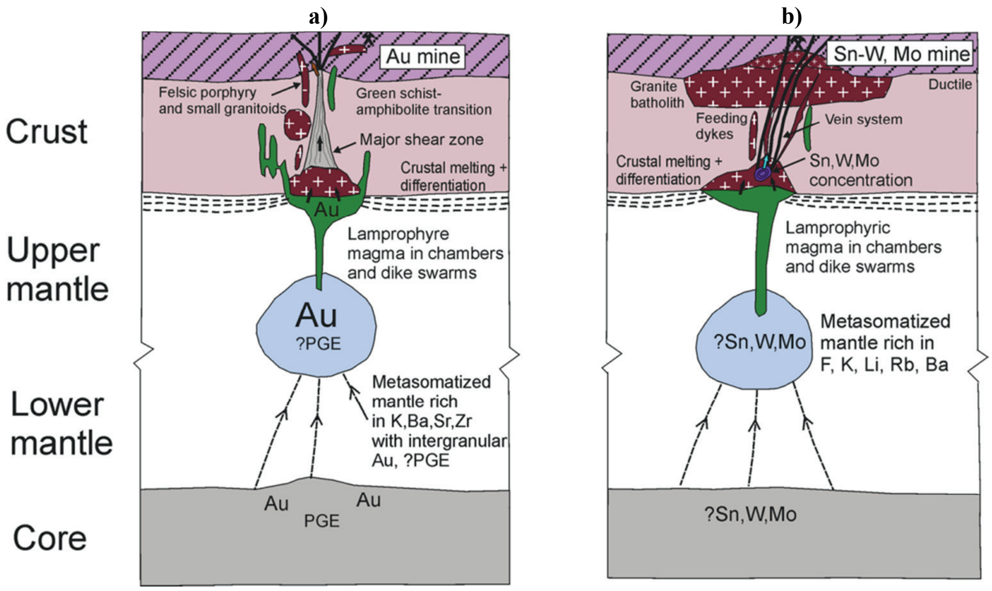

Fig. 13. Genetic models of the origin of Au (Rock et al. 1989) and Sn-W-Mo deposits associated with lamprophyres (based on Seifert 2008 on the example of the Erzgebirge, modified in Štemprok & Seifert 2010). Mantle component from underlying lamprophyric melts is transported by fluids near or at the crust/mantle boundary to a chamber of granitic melts. Lamprophyres may affect the granitic melts throughout all the time of their differentiation (see the concept of L1 to L3-type lamprophyres, Seifert 2008).

9. Conclusions

Kersantites, minettes, and spessartites as well as camptonites and monchiquites occur in RM districts of Phanerozoic age almost exclusively in the northern hemisphere. They share some geochemical characteristics of granitoids spatially associated with RM mineralization. We propose a model of granite differentiation in a deep seated magmatic chamber close to the mantle/crust boundary influenced by an underplated lamprophyric magma or volatiles from the mantle. The granitic chamber(s) produced first barren granites and later on granites enriched in RMs as consequence of prolonged differentiation under the effect of mantle derived volatiles.

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