Ore Geology Reviews 89 (2017) 324–349

Contents lists available at ScienceDirect

Ore Geology Reviews

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

Transvaporite model of ore genesis and an exploration strategy for new giant ore deposits

Boris A. Lebedev[a], Eduard M. Pinsky[b,*]

[a] Earth Science Institute, St. Petersburg University, Universitetskaya Embankment 9, 199034 St. Petersburg, Russia
[b] All-Russian Geological Research Institute (VSEGEI), 199106 Sredny pr. 74, St. Petersburg, Russia

ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form 6 April 2017
Accepted 9 April 2017
Available online 15 May 2017

Keywords:
Transvaporization
Large Igneous Provinces (LIPs)
Giant ore deposits
Hydrocarbon deposits
World-wide

ABSTRACT

In the current work we stand for the revival of the transvaporite ore genesis model, which was introduced by Hungarian academician E. Szadeczky-Kardoss more than half a century ago, but has now fallen out of favor and superseded by the orthomagmatic model. Our arguments in support of the transvaporite model are based on the contemporary overpressure theory developed for Mesozoic–Cenozoic petroleum basins. We propose a new variant of the transvaporization model whereby the formation of giant ore deposits occurs in the areas where former petroleum-rich basins are intersected by Large Igneous Provinces (LIPs). At such sites, structural–magmatic activity leads to hydrocarbon deposits being destroyed and many new ore deposits being created beneath a new regional volcanic fluid seal built by rapidly accumulating (up to 3–4 km in 1 Ma) lava flows. In such conditions, a zone of significant overpressure that is 1.4–1.8 times higher than hydrostatic pressure develops. Subsequently, under the influence of compressive mechanism of mass transfer, gas-saturated brines of sedimentary rocks migrate toward intruding melts, and then mix with them. As a result, unusual rocks (transvaporites) are formed and giant ore deposits created.

Here, we review six supergiant ore deposits of various types and ages with different associations of metals and host rocks, including the Norilsk district in Russia (Cu–Ni–Co–Pt–Pd), El Teniente–Los Bronces district in Chile (Cu–Mo), Almaden deposit in Spain (Hg), Ermakovskoe deposit in Russia (Be), Pebble Copper deposit in southern Alaska (Cu–Mo–Au), and Olympic Dam deposit in southern Australia (U–Cu–Au–REE), noting that all listed metals in each and every deposit do reach giant reserves. In all these deposits transvaporization appears to play the key role in ore genesis given the: (1) short duration of the main ore genesis stage (<0.2 Ma); (2) high original porosity and permeability of the sedimentary host rocks; (3) marked fluctuations in isotopic compositions indicative of mixing between mantle and crustal components; (4) non-stoichiometric relationships between oxides in "magmatic" transvaporites as revealed by chemical analysis; (5) clear evidence of explosive activity during or immediately after the final stage of ore genesis, as expressed by the presence of abundant breccias, pyroclastics, and lapilli; (6) presence of unusual original rock types that include pseudo-breccias, pseudo-skarns, and hybrid metasomatic rocks with rare mineral associations such as, for example, simultaneous crystallization of biotite and anhydrite in the El Teniente and Pebble Copper deposits. Moreover, a compilation and analysis of a database of 416 of the world's largest ore deposits shows that transvaporization with the aforementioned features is evident in 167 of these deposits (i.e., 40%). Furthermore, within 52 polymetallic giant ore deposits in which two to five metals reach giant reserve levels, evidence of transvaporization is present in 33 deposits (i.e., 63%).

A significant practical implication of the transvaporite model is that it should modify future strategies for ore deposits exploration. Instead of pursuing just any deposit, exploration efforts should focus specifically on giant ore deposits, concentrating search efforts at the sites where former petroleum basins have been intersected by LIPs. Basin analysis of enriched oil and gas provinces is already being conducted in detail by seismic transects, involving two-dimensional cross-sections and areal surveys, followed by three-dimensional mapping of productive reservoirs. The same strategy should be applied to ore-bearing regions, but at better precision and accuracy given the smaller velocity contrast in seismic wave propagation in ore rocks compared with oil- and gas-bearing sedimentary rocks. Important advances in the ore geology of LIPs such as geological mapping and gravity and magnetic surveys have already produced significant new data. These studies can be divided into two types, which first involve a general

---

* Corresponding author.
E-mail addresses: lebedevtethys@yandex.ru (B.A. Lebedev), pinsky273@gmail.com (E.M. Pinsky).

http://dx.doi.org/10.1016/j.oregeorev.2017.04.025

description of the LIP, and are then followed by an investigation of major intrusions likely to be directly linked to ore genesis. A combination of these investigations into hydrocarbon basins and LIPs will lay the foundation for transvaporite exploration, which will be the key criterion for the successful search for new giant ore deposits.

1. Introduction (terminology and goals)

The term *transvaporization* was introduced by the Hungarian academic Szadeczky-Kardoss (1958, 1961) more than half a century ago to describe the processes occurring when fluids of sedimentary basins mix with silicate melts that ascend into these basins. In the 1978 edition of the Russian Geological Dictionary (Paffengoltz, 1978), the term was explained as "*the process of volatile components exchange in between two bodies, where the direction and intensity of such process is determined by the gradient of partial pressure decrease of these components*". However, this term is not present in the latest edition of this dictionary or in the Explanatory Dictionary of English Geological Terms (Judson and Richardson, 1995).

According to Szadeczky-Kardoss (1961), the necessary prerequisite for silicate melts and sedimentary fluids to mix is that, during certain stages of a sedimentary basin's development, the fluid pressure in the sedimentary rocks becomes higher than in the magmas. Consequently, the fluids migrate by a *compressive mechanism*, vaporize next to the melts, and are then absorbed by the magma. However, this hypothesis was short-lived and was quickly abandoned by the majority of geologists, given the apparent dominance of magmatic temperatures and pressures compared with those in sedimentary rocks. As such, the orthomagmatic model became the preferred mechanism for (most) ore deposit formation, and postulates that melt–fluid separation enriches the fluid in volatile components and, therefore, only partial assimilation of the host rock by the magma takes place (Barnes et al., 2010; Eales and Costin, 2012). For example, Ni-rich sulfides with high platinum group element (PGE) contents formed in the early stage "...when interacting with the enclosing sedimentary Transvaal rocks" (Hutchinson et al., 2015).

The main obstacle in distinguishing between orthomagmatic and transvaporite models of ore genesis is the fact that direct measurements of ore-bearing solutions' pressures have only been performed for hydrothermal mid-ocean ridge systems (Macdonald, 1982; Krasnov et al., 1992) and in continental volcanic regions (Naboko, 1980; White et al., 1988). However, in both these environments, mass transfer is dominantly *convective* (determined by temperature differences) and not *compressive*. This phenomenon characterizes the global ocean system, hydrothermal systems at mid-ocean ridges, and oceanic basaltic magmas. Accordingly, the compressive mechanism of mass transfer and subsequent transvaporization are not possible in such settings. As such, we disagree with the reasoning of Korzhinsky (1982) who rejected the transvaporization hypothesis in principle, just because it does not take place in the oceans.

Similarly, indirect pressure evaluations performed by homogenization of gas–liquid inclusions in rocks and ores do not yield conclusive means for discriminating between convective and compressive mass transfer. Given that homogenization of inclusions can be caused by both increased temperature and pressure, it is almost impossible to determine which of these factors drives migration. Nevertheless, data from gas–liquid inclusions are crucial for developing a rigorous understanding of ore genesis in any deposit. Such data are particularly important for transvaporite-generated deposits, given that solution chemistry, as well as the chemical and isotopic compositions of gas and liquid phases, derived from inclusion studies directly characterize ore genesis. Such data are now commonly obtained in most ore studies, but here we limit our analysis to data for transvaporites that have recently been published.

For the purposes of this study, we chose to examine two groups of deposits, which are the Late Cenozoic copper–molybdenum ores of Chile and Peru (Maksaev et al., 2004; Frikken et al., 2005; Maksaev et al., 2006; Astudillo et al., 2010; Barra et al., 2013; Deckart et al., 2013, 2014; Riveros et al., 2014; Spencer et al., 2015) and tungsten and tin ores of different ages from the eastern part of southern China (Pašava et al., 2003; Peng and Frei, 2004; Wu et al., 2006; Cheng et al., 2012; Hu et al., 2012; Wei et al., 2012). We consider that the majority of the ore deposits in these provinces were formed by the transvaporite model and, therefore, we summarize the general features of inclusions in these deposits and their isotopic compositions.

We focus on three specific types of data, which we consider to be the most interesting: inputs of crustal and mantle materials; mineralization of solutions and their ionic composition; and radiometric ages. Numerous isotopic data are clearly paradoxical and complex to interpret. On the one hand, mantle material is always strongly evident, but, on the other hand, the authors of almost every work refer to contamination (assimilation) of sedimentary material by magmatic melts. In addition, the term "mixing" is used in the majority of the aforementioned studies in a variety of contexts. In our view, this represents evidence for transvaporization, which is implied by the authors of these studies, although not explicitly. The same conclusions can be reached from the mineralization data, with greater mineralization being associated with an increasing role for sedimentary brines. The geochronology data for these deposits determine the relative timing of these processes.

In many (but not all) of the reviewed deposits, crustal granitic magmatism controls the mantle–crust interactions; this is particularly true for the Chinese ore deposits. In these deposits, overprinting by the granite intrusions requires meticulous study of all three of the features of transvaporites in order to identify this process. Crustal magmatism in Chile and Peru is also very intensive, but in these regions magmatic rocks (stocks, dikes, and sills) do retain some obvious features of transvaporites.

The confirmation that compression-driven mass transfer during transvaporization takes place, however, can devised using concepts from petroleum geology. In any oil well, measurements of formation pressure are not only performed at each test interval, but also continuously with depth, using, for example, drilling data (Lebedev, 1992). In petroleum basins, pressure is expressed in megapascals (1 Atm = 0.1 MPa). However, for the analysis of the mass transfer mechanism it is more convenient to use the dimensionless coefficient of overpressure (C_o) calculated by dividing the formation pressure (P_f) by the hydrostatic pressure (P_h) (i.e., $C_o = P_f/P_h$). Through numerous studies, the ramified overpressure theory has been established for global oil and gas basins (Hunt, 1991; Fertl et al., 1994; Magoon and Dow, 1994; Osborne and Swarbrick, 1997; Lee and Williams, 2000; Aplonov and Lebedev, 2010). The main features of this theory relevant to our problem are:

1. The migration of fluids between two formations *via* the compressive mechanism is driven by the difference of overpressure coefficients, and not by the difference in absolute pressures.
2. Studies of overpressures and assessment of their coefficients can be carried out predominantly for Mesozoic–Cenozoic oil and gas basins where, even at the latest stages of their development, continued regional subsidence generates a major gas reservoir, which is the main factor in facilitating compressive mass transfer.
3. The maximum overpressure coefficients are not characteristics of the lowest part of the sedimentary cover or the basement roof, but reach a maximum for the highest reservoirs of the lower oil and gas complex, directly isolated by its regional fluid seal. For example, Figs. 1 and 2 show that in the northern part of the western Siberian Basin C_o decreases from a maximal value of 1.9 to ~1.3–1.4 down section, whereas the absolute pressure rises with increasing depth.
4. Whether gas formation is sufficient to induce the movement of liquids and gases by the compressive mechanism depends on the value of C_o reached in a particular part of the basin, which in turn is dominantly controlled by the capping properties of the regional fluid seal – this is the critically important postulate!
5. Within a given petroleum basin, movement by the compressive mechanism is limited to the region with maximum C_o, and results in fluids breaking through the lower regional fluid seal. Figs. 1 and 2 depict how such movement occurred during formation of giant gas deposits in Cenomanian sandstones of the northern part of the western Siberian Basin (Lebedev, 1992). From a maximum C_o of ~2.0, hydrocarbons migrate upward toward the hydrostatic pressure zone (Fig. 2), from where they "rise and float up" (relatively to the "fixed" waters) through voids into high-capacity reservoirs beneath the upper regional fluid seal. Similar floating can also be observed within the whole lower oil and gas complex, as at greater depths and consequently higher temperatures gas generation sharply increases, gradually leading to the formation of an overpressured zone beneath the lower regional fluid seal.
6. Hydrocarbon gases or gas-saturated oils migrate rapidly through this fluid seal *via* a network of fractures in weakened areas, which are mostly wedge-like bodies with higher permeability. Gas deposits with high condensate factors often accumulate in the dead-end parts of such bodies, forming the largest condensate deposits in the world. For example, Achimov wedge-like bodies to the east and northeast of the giant Urengoy gas deposit (Fig. 1) contain almost one billion tonnes of condensate (reserves and resources) at C_o = 1.4–1.7. These unique accumulations are hosted within specific interstitial fracture–pore reservoirs where the permeabilities of pores and fractures are broadly comparable (Lebedev, 1992).

In a previous study (Aplonov and Lebedev, 2010), we demonstrated that any ore-rich sedimentary basin younger than 2 Ga is a former petroleum-rich basin, which was subjected to structural–magmatic activation. During such activation the regional fluid seals are opened, and hydrocarbon migration is eventually replaced by the migration of aqueous solutions, including ore-bearing fluids. The migrating melts and solutions may follow the hydrocarbon migration pathways and, as such, residual decomposed oil and gas material can play a role in ore genesis.

It is self-evident that the principles of compressive mass transfer applicable to hydrocarbons are also relevant for the ore-forming stage. However, disturbance of the regional fluid seal by faults and zones of extensive fissuring during the igneous activation leads to a general decline in formation pressures to the levels of hydrostatic pressures within the whole basin. The compressive mechanism of mass transfer (driven by the increase in C_o) is then replaced by a convective mass transfer regime (directed by temperature differences), primarily due to the massive injection of silicate melts and the subsequent increase in the geothermal gradient (Lebedev and Pinsky, 2000).

However, this change in the migration mechanism is not irreversible. Although the former oil and gas basin retains some of its fluid seals, these are no longer regional in nature. More importantly, the role of a regional fluid seal shifts from the sedimentary rocks (typically clay- or salt-bearing) to the volcanic rocks. Volcanic rock fluid seals can even be found in several petroleum basins (Wu et al., 2006; Giambiagi et al., 2009; Lampe et al., 2012). However, in the activated ore-bearing basins, young volcanic–sedimentary formations are quite common with large areal extents. Such formations temporarily assume the role of regional fluid seals,

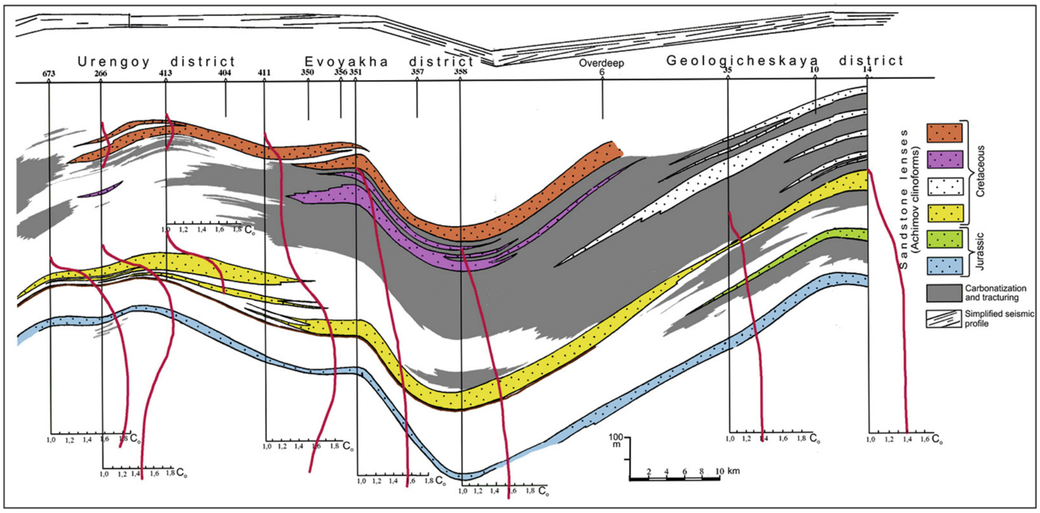


Fig. 1. The distribution of overpressure coefficients (C_o = red curves) relative to the properties of the Upper Jurassic to Lower Cretaceous shale regional fluid seal within the northern part of the western Siberian Basin (compiler = I.B. Chervyakov) (Aplonov and Lebedev, 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

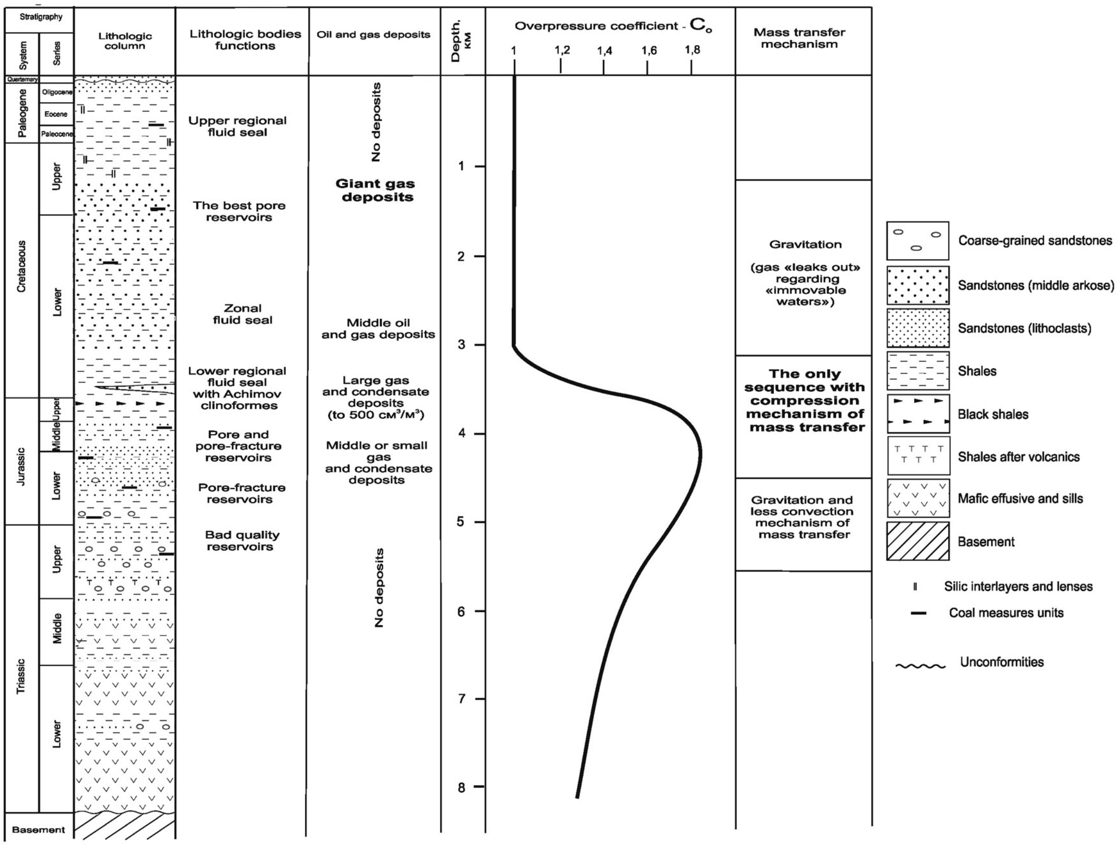


Fig. 2. The compressive mechanism of hydrocarbon migration as the main factor for giant gas deposits distributed in the northern part of the western Siberian Basin (Large Urengoy district).

and their presence leads to the "revitalization" of the isolating properties of underlying former petroleum fluid seals, which are an important factor in the formation of stratiform ore bodies.

It is important to note that formation pressures are widely thought to increase during the course of structural and igneous activity. However, this assumption is incorrect. Given that the compressive transfer mechanism is totally dependent on the properties of regional fluid seals, more intense structural and igneous activity, in fact, lowers the barrier properties of fluid seals. Accordingly, the influence of compression on migration is minimal until a new, mostly volcanic, fluid seal is established.

All of the above-elaborated statements directly relate to the transvaporization phenomenon. Indeed, in order to mix melts with migrating fluids from sedimentary rocks, it is necessary for these melts to inflow from the asthenospheric mantle or lower crust into the upper sedimentary cover that has a large amount of water-saturated pores. The possibility of such inflow is directly determined by the intensive draft-like migration guided by the convective mass transfer mechanism. However, without the compressive mechanism, sedimentary fluids are unable to mix into the moving melt until volcanic rocks accumulate on the surface and create a new regional fluid seal. The volume of the gas phase is always in excess, given that an extensive influx of melts significantly increases the geothermal gradient, which facilitates gas generation by carbonization of organic materials, or even hydrolysis of carbonate minerals (Lebedev, 1992). These rather simple considerations allow us to state that the sequence of events described above is not anomalous: *if the former petroleum basin is exposed to structural and magmatic activity, then all subsequent processes including transvaporization are interdependent.*

In general, the fundamentals of liquid and gas migration in petroleum basins that have been formulated in accordance with direct measurements of formation pressures and temperatures are the foundation for our proposed theory of fluid migration in ore-bearing basins. This analogy is applicable to many geological processes. For example, ore stockworks are the equivalent of fracture–pore oil and gas reservoirs, where the permeabilities of pores and fractures are similar. The well-known petroleum geology concept of more intensive fracturing being characteristic for massive rocks, as compared with ductile ones, is applicable to skarn mineral systems, and explains why ore vein systems are often associated with skarns. For a long time, we have argued that important analogies exist between the transformation of oil reservoirs and wall-rock alterations in ore deposits, which may have practical implications (Lebedev et al., 1976; Lebedev, 1992).

2. Giant ore deposits associated with transvaporization

In this section, we examine specific examples of giant ore deposits. One of the main postulates of the ore genesis concept we have proposed (Aplonov and Lebedev, 2010) is that the genesis of ore giant deposits is mostly predetermined by global factors, whereas formation of smaller deposits is influenced by individual regional factors, in other words, by the stochastic local events.

We have compiled a database that incorporates ~500 of the world's largest ore deposits, including 416 ore deposits and 84 hydrocarbon deposits. We selected these deposits using major monographs on ore giant deposits (Laznicka, 2006; Rundquist et al., 2006), and used the http://earth.jscc.ru/super_deposits/search.php?lang=en database to quantify their reserves.

It is apparent from this database that sedimentary basins have a role in ore geology. For example, major contemporary oil and gas basins (western Siberia and Persian Gulf) have an earlier history of more ancient oil and gas basins, which are now ore-bearing. Moreover, in the Jurassic almost all of North America was an extensive oil and gas basin, and in the Early Devonian eastern Siberia had similar characteristics. We now also know that the ore-bearing areas of the Yangtze Block were once large oil and gas basins, and the present-day Sichuan Basin is an example of the development of such a system (Aplonov and Lebedev, 2010).

Adopting such logic, we selected a number of oil and gas basins (Vysotsky et al., 1995) to illustrate our ore genesis theory. From the Cenozoic, we selected the basins of the South China Sea and its neighboring seas (Hodgetts et al., 2001; Areshev, 2003; Gartrell et al., 2006; Gong et al., 2013), and the Maracaibo (Escalona and Mann, 2006; Mann et al., 2006) and Orinoco (Alayeto et al., 1974) basins in Venezuela. From the Mesozoic–Cenozoic, we selected the Persian Gulf (Alsharhan and Nairn, 1997), western Siberian (Aplonov and Lebedev, 2010; Khafizov, 2012), North Sea (McLeod et al., 2002), eastern Brazilian (Cobbold et al., 2001), Gulf of Mexico (McDonnell et al., 2008; Pilcher et al., 2011), and west African basins (Kolla et al., 2001).

2.1. Norilsk ore region (Russia)

The Norilsk region is a truly unique case of transvaporization-driven ore genesis, and perhaps the best global example of mixing of sedimentary brines with basaltic melts to form extremely rich ores. Firstly, five metals reach giant reserve status in the Norilsk region, which are nickel, copper, cobalt, platinum, and palladium. Few other deposits worldwide are known to host such extensive metal reserves of multiple elements. Secondly, in three layered intrusions (Talnakh, Kharaelakh, and Norilsk I) the proportion of ore volume to intrusion volume reaches unprecedented values of ∼15% (Naldrett, 2004; Likhachev, 2006; Spiridonov, 2010). The remaining ∼40 intrusions either have no ore or the amount of ore is several orders of magnitude lower than in the three main intrusions. Finally, Norilsk appears to be the only ore region in the world where it is possible to demonstrate from the 11 suites of the Lower Triassic traps (Fig. 3) that the metals of the richest ores were completely extracted from melts within a narrow stratigraphic interval, which is the Nadezhdinskaya suite (Distler, 1994; Li et al., 2003; Naldrett, 2004).

Naldrett (2004) calculated that the volume of lava that has passed through the Talnakh deposit and was erupted onto the surface exceeds the volume of the intrusion by a factor of 200. In our opinion, this result is the most important evidence for transvaporization, because there are no other sources for the vast mass of sulfur in the ore sulfides apart from the gas-saturated brines in the sedimentary rocks. Assimilation of sulfates in the sedimentary rocks was clearly not possible, because the temperature of the Norilsk melts was too low (<1100 °C) to melt such amounts of sulfate.

We propose that the main cause of the unique Norilsk sulfide ores (Fig. 4) was the exceptionally high rate of lava accumulation within the large area of the Putorana plateau in the earliest Triassic. In less than 0.5 Ma, the erupted lava thickness exceeded 1 km, and formed a regional fluid seal with very low permeability. Melts that passed along faults in Paleozoic sedimentary sequences caused intensive contact metamorphism and powerful vaporization and gas generation in brown coals of the Tunguss suite (Middle Carboniferous to Upper Permian). H_2O, H_2S, CH_4, and CO_2 were produced from the coals, and lower and middle Paleozoic carbonate and evaporate rocks released H_2O, CO_2, and SO_3.

The Norilsk region has been subjected to intensive study by both Russian and international researchers (Genkin et al., 1981; Czamanske et al., 1992, 1995; Lightfoot et al., 1994; Dodin, 2002; Li et al., 2003; Naldrett, 2004; Distler et al., 2006; Pinsky, 2012; Ripley and Li, 2013). For example, more than ten isotopic systems have been used to determine the relative input of mantle and crustal materials to the igneous rocks (Petrov et al., 2011). Herein, we focus solely on the results directly relevant to the role of transvaporization in ore genesis.

The first important feature is the unusual composition and structure of the Norilsk rocks and ores, which contain abundant inclusions of sedimentary rocks and, in particular, gas-saturated brines trapped in rock voids. Notably, these rocks contain abundant alkalis and chlorine, and even chlorates (Pletnev et al., 2001; Likhachev, 2006). The intrusions and their exocontact zones contain several unique rocks termed "pseudo-breccias", "pseudo-skarnoides", "pseudo-tachylites", "hybrid-metasomatic rocks", and other unusual rocks. Another series of terms commonly used to describe the types of Norilsk wall-rocks are "taxitic gabbro–dolerites", "talnakhites", "anhydrite–pyroxene hornstones", "microcline metasomatites", "vesuvian–prehnite–albite rocks", and "anhydrite–garnetiferous–serpentine rocks with magnetite". Therefore, many models of ore genesis in this region deviate from the orthodox layered intrusion model (Aplonov, 2001; Pokrovskii et al., 2005). The presence of these types of rocks in our view is the key evidence of mixing between fluids from sedimentary rocks and melts.

There are also many original features preserved in the ores, which vary in structure from massive to densely interspersed to disseminated. Some of the ore-forming fluids migrated into the host terrigenous–carbonate rocks, forming ore bodies with typically stratiform characteristics. These properties are also evident for the low sulfide ores, and typical of many of the world's layered intrusions (Distler, 1994). In the Norilsk district, these ores are distinguished by particularly high alkali and chlorine contents, as well as uniquely high palladium reserves –one small Kharayelakh intrusion contains 75% of the global supplies of this metal.

Fig. 4 shows a model of the formation of ore-bearing intrusions in the Norilsk district. This model is based on the compressive

Age	Suites	Thikness, m	Functions
Lower Triassic	Samoed	> 600	Do not take part in ore generation
	Coomgin	160-210	
	Kharaelakh	380-620	
	Moculaev	400-690	
	Morongov	240-700	
	Nadezhdin	150-530	Source melt
	Tooclon	< 220	Regional fluid seal
	Khacanchan	< 260	
	Goodchikhin	< 250	
	Sivermin	< 195	
Upper Permian	Ivakin	80-140	

Fig. 3. Upper Permian to Lower Triassic volcanic sequences (trap formations) and their role in ore generation, Norilsk district.

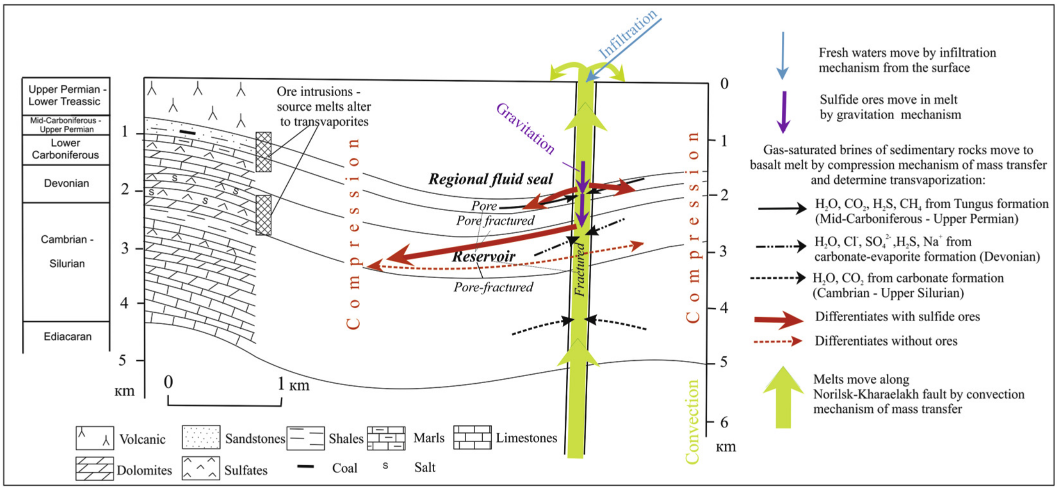


Fig. 4. Norilsk district, Talnakh, and Kharaelakh giant ore deposits (Cu–Ni–Co–Pt–Pd). The schematic cross-sections illustrate the directions of fluid migration during transvaporization and sulfide ore generation.

mass transfer mechanism (Fig. 2). However, the complexity of Norilsk ore genesis requires three other mechanisms (convective, gravitational, and infiltrative) in addition to the main compressive mechanism at different stages of ore generation and in different parts of the ore-bearing intrusions. It is important to stress that these mechanisms do not occur at the same time and place (Lebedev and Pinsky, 2000). Accordingly, the schematic shows how these four mechanisms occur separately, and in different sectors of the Norilsk intrusions.

A regional profile (Fig. 5) shows the timing and direction of hydrocarbons, melts, solutions, brines, and salt diapirs migration during the Proterozoic and Phanerozoic history of the Siberian Platform. In this schematic we aim to depict the main determinants of oil and ore genesis in this region. Salt diapirism provided an important control on the timing of hydrocarbon accumulation and on the role of brines in the genesis of the Norilsk district ore deposits. The profile passes through three igneous provinces, including those erupted in the Early Triassic (traps), Late Devonian to Early Carboniferous (diamond-bearing kimberlites), and Late Ediacaran (ultramafic alkaline magmatism including carbonatites).

As a direct result of our unified concept of hydrocarbon and ore accumulation (Aplonov and Lebedev, 2010), comes the notion that in order to correctly interpret Norilsk ore genesis, it is necessary to consider the entire history of the Siberian Platform, and account for all deposits formed at different times. It is important to note that the greatest basement depth of the platform (16 km) is reached in the Norilsk–Khatanga region (Gubina and Berilko, 2012).

The first eastern Siberia oil and gas basins had already formed by the end of the Paleoproterozoic, and this process continued into the Mesoproterozoic–Neoproterozoic, Ediacaran, and Early Paleozoic. Maximal oil and gas accumulation occurred in the Early Devonian, resulting in the eastern Siberia province becoming the richest hydrocarbon reserve in the world (Aplonov and Lebedev, 2010). This extensive reserve was mainly determined by a vast Lower Cambrian regional fluid seal of salt (1.5 million km^2; Zabaluev, 1980). Subsequently, the oil- and gas-bearing capacity has been falling constantly. However, even today there are significant resources beneath the salt, although certainly much less than in the Early Devonian.

There are no distinctive Lower Cambrian salt formations in the Norilsk–Khatanga region, but salt diapirs have extensively penetrated the Leno–Tunguska province, thereby forming an Upper Devonian salt-bearing regional fluid seal (Matukhin, 1991). Due to this seal, the oil- and gas-bearing capacity was still relatively high in the Late Paleozoic until the massive Early Triassic trap magmatism. The tectonic activity related to these traps led to a disturbance of all fluid seals by fault and fracture systems, and to the dissolution of salts and infilling of reservoirs by brines throughout

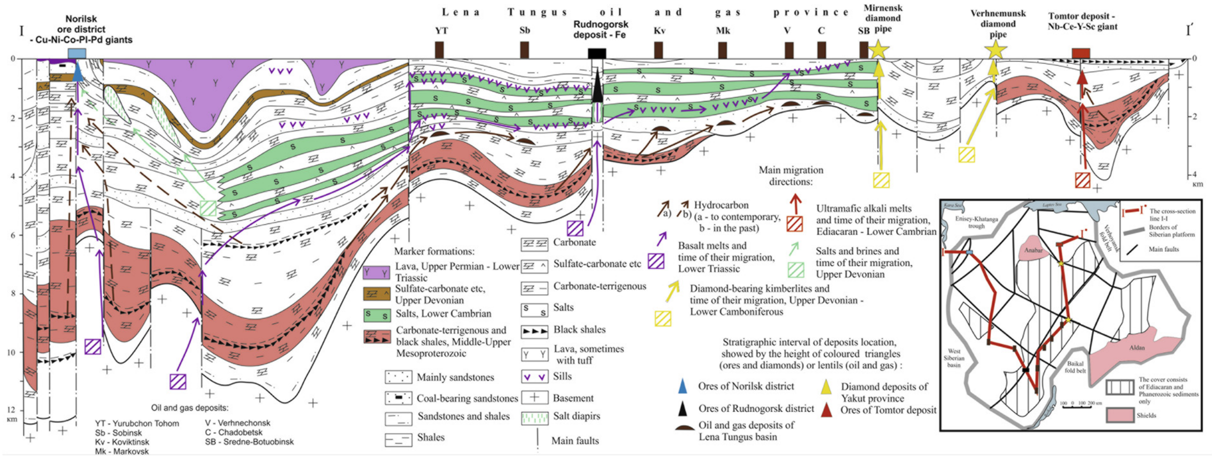


Fig. 5. A regional cross-section showing the generation and distribution of hydrocarbon, ore, and diamond deposits throughout the Siberian platform.

the section, including the friable coal-bearing sandstones of the Tunguss suite (middle Carboniferous to upper Permian).

The contact metamorphism of the sedimentary rocks, particularly thick coal beds, led to intensive volatilization (e.g., CO_2, H_2S, and CH_4) (Godlevsky et al., 1962; Dodin, 2002; Turovtzev, 2002). The thick Lower Triassic lavas formed a volcanic fluid seal, and caused C_o to increase, according to our estimates, up to 1.4–1.8 (Fig. 2). The thickness of lava required to achieve this state was reached by the time of the Nadezhdinskaya suite eruption, and thus gas-saturated brines from sedimentary rocks penetrated and mixed specifically with Nadezhdinskaya melts. This caused basalt alteration and unprecedented levels of accumulation of metallic sulfide phases and wall-rock alteration.

The transvaporization was a rapid process by geological standards (only Nadezhdinskaya time), mainly due to the high porosity and permeability of the Tunguss sandstones. The sandstone properties facilitated fast and extensive migration of gas-saturated brines toward the ascending melt. Subsequent mixing of the brines and melts and transvaporization produced explosive activity that is evident from the many tuff layers in the Nadezhdinskaya suite. Cracking of the fluid seal and reduction of the pressure to hydrostatic levels followed the explosion, and transvaporization was terminated.

However, the formation of unequilibrated melt resulted in continued (beyond the transvaporization) process of ore genesis. At these later stages, the gravitational mechanism in layered intrusions was likely a dominant process, and led to the formation of low-sulfide platinum–palladium ores (Distler, 1994). An infiltrative mechanism involving the mixing of surface waters with melts also likely took place.

A further important ore genesis factor was the confinement of ore-generating processes to the broad contact zone between a contrasting carbonate–evaporate formation (Upper Devonian to lower Carboniferous) and a terrigenous coal-bearing formation (middle Carboniferous to upper Permian). The first of these formations likely supplied alkalis and chlorine, the second provided excessive volumes of gas, and both formations provided the excess of sulfur necessary for the precipitation of metals from the melts. According to geological and isotopic data (Petrov et al., 2011), nickel and most platinum are of mantle origin, whereas sulfur, copper, perhaps cobalt, and most palladium are of crustal origin.

Importantly, Norilsk ore genesis was a shallow process ($\leq$3–4 km), and occurred in rocks with a high porosity (i.e., sandstones of the Tunguss suite). The isotopic data robustly confirm the dominance of inputs of crustal material (Fig. 6), as well as the mantle contributions. In detail, the lowest inputs of crustal material are observed in rocks and ores from the Norilsk I intrusion located in the Triassic traps. More crustal inputs are found in ores from the Talnakh intrusion due to the Tunguss suite sandstones, and the highest crustal inputs are evident in ores of the Kharaelakh intrusion that is located in Upper Devonian evaporate and carbonate rocks.

In general, ore-bearing intrusions of the Norilsk district are characterized by low values of mantle helium (1%–22%; $^3He/^4He = 0.05–2.5 \times 10^{-6}$) and high values of crustal argon (65%–100%; Prasolov et al., 2008). Moreover, intrusions hosting giant deposits and high reserves contain extreme values of mantle helium and crustal argon (1%–4% and 100%–85%, respectively), whereas those with average reserves are 1%–4% and 87%–60%, respectively, and those with small reserves and mineral occurrences are 5%–22% and 95%–66%, respectively (Fig. 7). Finally, Aplonov (2001) used gas–liquid inclusions in Norilsk ores and host rocks to constrain the abundance of crustal material as, for example, shown by the considerable increase of K and Na concentrations in pore solutions as compared with Ca and Mg.

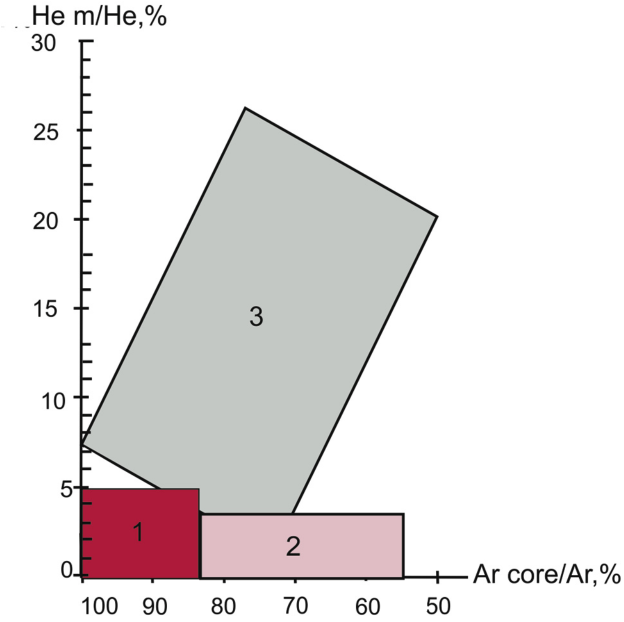


Fig. 7. Relationship between the proportion (in%) of mantle He and crustal Ar in the Norilsk mafic intrusions with different ore reserves: 1 = giant and high; 2 = middle; 3 = small and mineral occurrences.

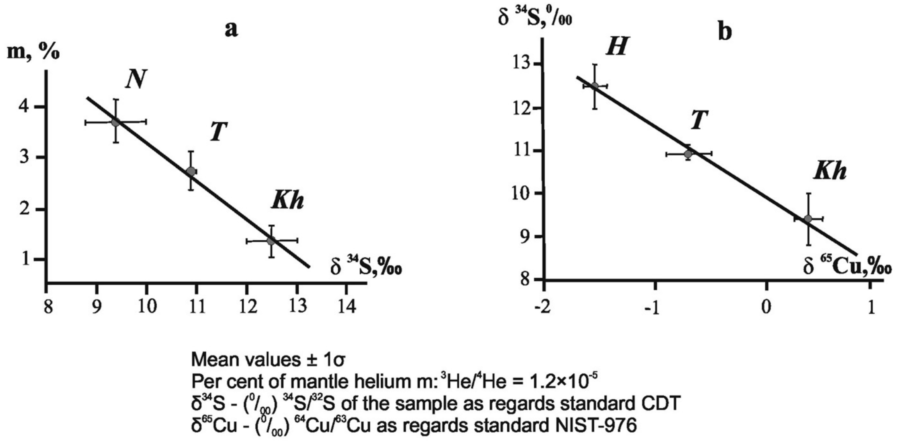


Fig. 6. Isotopic relationships in the Norilsk district's main ore intrusions: N = Norilsk I; T = Talnakh; H = Kharaelakh (Petrov et al., 2011).

2.2. El Teniente–Los Bronces ore region (Chile)

This region contains the world's richest copper (>150 Mt) and molybdenum (~3.8 Mt) reserves (Cooke et al., 2005). The overwhelming majority of its ores were formed 8–4 Ma, and the duration of individual ore deposits' formation did not exceed 0.2 Ma (Maksaev et al., 2004; Cannell et al., 2005; Frikken et al., 2005; Stern et al., 2007; Deckart et al., 2013, 2014), which is similar to the duration of sulfide ores formation in the Norilsk region.

During the Mesozoic and Cenozoic, many sedimentary platform basins with extensive oil and gas accumulations were formed not only in the El Teniente–Los Bronces region (Fig. 8), but also to the north and south of this region. However, after the Cenozoic structural deformation and magmatism, only limited relics of these basins remain in the form of relatively petroleum-poor basins such as those of Neuquen and Mendoza (Mitchum and Uliana, 1985; Giambiagi et al., 2009). Interestingly, these relic basins contain oil deposits not only in sedimentary, but also magmatic rocks, including sill intrusions (Witte et al., 2012). This, on one hand, serves as evidence of the former basins' extensive reserves; while, on the other hand, implies the likelihood of the volcanic sills being significant additional fluid seals for the hydrocarbon deposits. It is

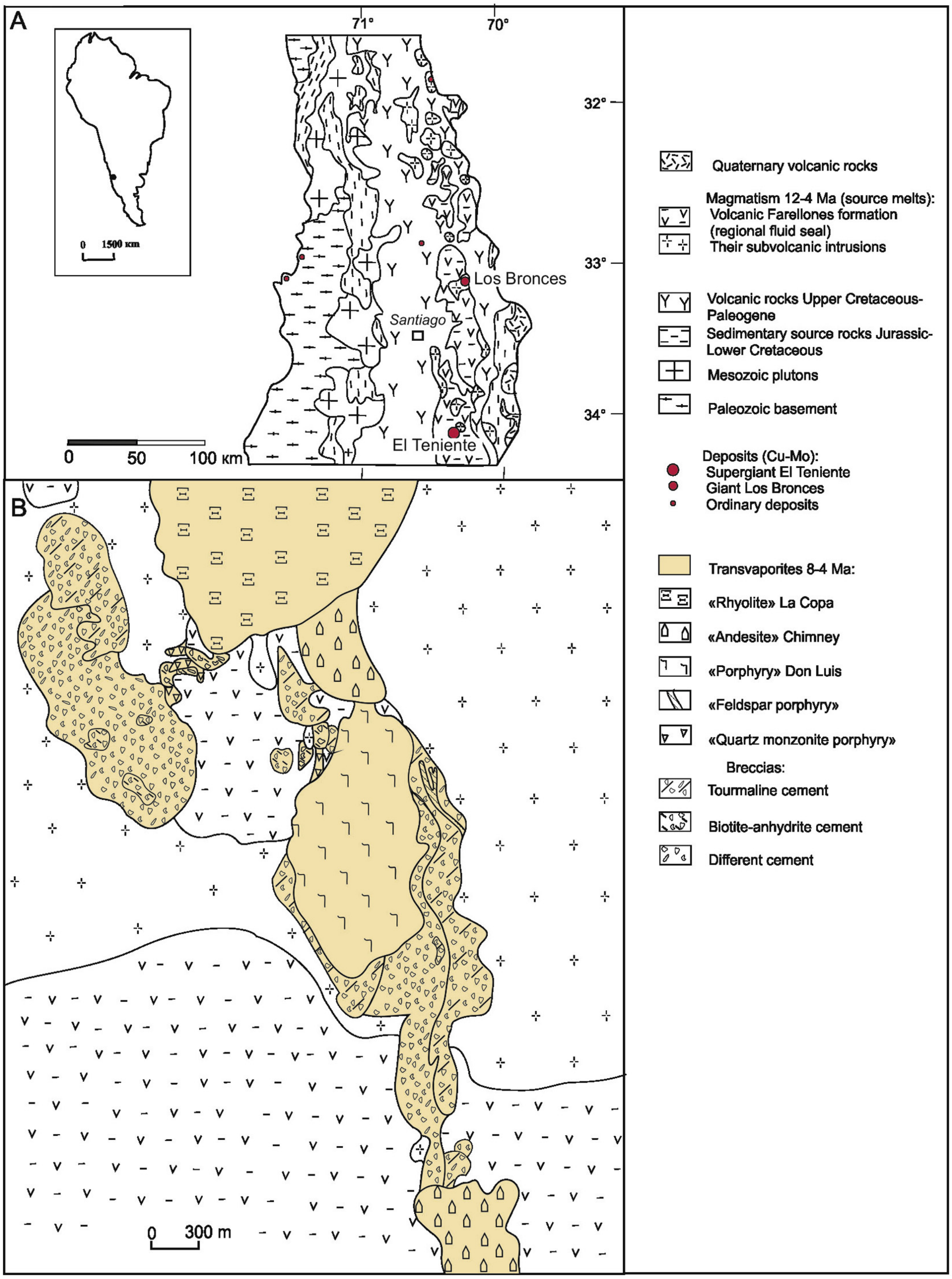


Fig. 8. The El Teniente–Los Bronces Cu–Mo ore district. A. Regional geology of central Chile and location of the Rio Blanko–Los Bronces deposit. B. Local geology of the Los Bronces giant ore deposit (modified after Frikken et al., 2005).

important to note that in all basins, including those that are ore-rich, Upper Jurassic carbonates and evaporites were later subjected to transvaporization (Mitchum and Uliana, 1985; Ossandon et al., 2001; Frikken et al., 2005; Stern et al., 2007; Vry et al., 2010; Piquer et al., 2015).

Even in comparison with the Norilsk region, the ores and zones of wall-rock alteration within the El Teniente–Los Bronces province contain a vast range of unusual types of rocks and mineral associations (Klemm et al., 2007; Deckart et al., 2014). Particularly striking is the existence of five different types of ore-bearing breccias with different cements (i.e., igneous, potassium feldspar, biotite, anhydrite, and tourmaline). The documented association of simultaneously formed biotite and anhydrite (Vry et al., 2010) is highly unusual, and even seems hardly possible for the old-school petrographers; while the origin of such rare composite is attributed to the lower crust or even mantle. The veins have been divided into 13 types based on mineral compositions, and are related to pre-ore, ore-forming, and post-ore transformations (Davidson et al., 2005; Stern et al., 2007; Deckart et al., 2014).

Fig. 8B shows the main varieties of rocks within the Los Bronces deposit, which are synchronous or almost synchronous with ore formation. The mineralization is most closely associated with breccias (Warnaars et al., 1985; Skewes et al., 2002) where the composition of the cement usually changes in the following sequence: tourmaline → biotite–anhydrite–sulfides → K-feldspar. Upon completion of ore genesis, some hydrothermal features are produced resulting in the formation of quartz, sericite, pyrite, and occasionally tourmaline and other minerals.

In our opinion, the formation of ores and syn-ore rocks can only be comprehensively explained by transvaporization and the compressive mass transfer mechanism. The regional fluid seal required for this comprises volcanic rocks of the Farellones Formation or their intrusive equivalents (i.e., sills or porphyries), and the final stage of its development promotes ore genesis (Davidson et al., 2005; Frikken et al., 2005). The abundance of gases responsible for transvaporization and the formation of numerous breccias resulted from intrusions and dikes, which increased the geothermal gradient, levels of contact metamorphism, and ultimately the mineralogical diversity of veins and metasomatic associations.

With a strong variability in intrusions' morphology (mainly stocks and dikes, occasionally sills); chemical composition (mafic rocks, tonalites, diorites, quartz diorites, and syenites); degree of crystallinity; extension; and phenocryst size, it is characteristic that almost none of these intrusions possess stoichiometric composition. Although ratios between alkali and alkaline earth metals (Ca) vary, sulfur and chlorine contents and gas saturation are abnormally high. As a result, in several published studies commonly used rock names are written in quotation marks such as "microdiorite", "dacite", "porphyry", and "feldspar porphyry". A feature of these rocks is the presence of up to 10%–20% of anhydrite, as well as considerable mixtures of biotite, magnetite, and/or quartz. It is typical for these unusual "intrusive" rocks to contain abundant gas–liquid inclusions where the liquid phase is hypersaline with up to 70% $NaCl_{equiv}$ (Klemm et al., 2007). Taken together, the presence of unusual mineral associations, abundance of breccias, high gas-saturation of rocks, and other features are all indicative of intensive mixing between melts and large volumes of liquids and gases from the host sedimentary rocks. Therefore, this analysis of the El Teniente–Los Bronces region provides reliable evidence of transvaporization.

2.3. Almaden ore region (Spain)

In comparison with the other ore giant deposits discussed here, the Almaden region possesses outstanding contrasting features, as it contains almost half of the world's reserves of mercury (250,000 t) within an area of just 450 × 600 × 50 m (Saupe, 1990). We are convinced that such a phenomenon is generally conceivable only due to the transvaporization, and only within the platform quartz sandstones – the only type of sedimentary rocks that at the depth of 2 km are able to conserve the uniform open porosity of >30%, and a permeability of >0.01 m km^2 (Lebedev, 1992).

The Almaden syncline is located in the far south of the Central Iberian zone, adjacent to the border with the Ossa Morena latitudinal zone. It is one of the numerous Lower Paleozoic rift depressions in this region (Fig. 9) (Pardo and Garcia-Alcalde, 1984; Dallmeyer and Martinez Garcia, 1990). The syncline includes a full cross-section of Ordovician and Silurian sediments with a thickness of almost 4 km (Higueras et al., 2013). This section includes two black shale formations of Lower Ordovician and Lower Silurian age, as well as five main layers of quartz sandstones in alternation with shales (Fig. 10). After 100 Ma of continuous subsidence, this sedimentary section naturally converted into an oil-bearing unit. The most productive interval is the third sandstone layer Craidero (Lower Silurian), which is characterized by the largest thickness, peak effective porosity during ore genesis, and a reliable clay fluid seal. This unit can be further subdivided into four sandstone interlayers, which all have high effective porosity (Fig. 11).

Intensive eruption of basalts from asthenosphere began at the end of the Silurian, and the opening of magmatically related faults destroyed the existing fluid seal, removed the oil and gas, and caused the filling of sand reservoirs with brines. However, these high brine concentrations can be attributed to the fact that the Early Silurian was characterized by high evaporation levels throughout the European–American continent (Kozary et al., 1968; Dellwig and Evans, 1969; Ianshin and Zharcov, 1977). The progressive accumulation of the Upper Silurian to Devonian sedimentary–volcanic sequences dominated by lavas, as well as intrusion of numerous sills with thicknesses of up to 5 m, resulted in the formation of a new regional fluid seal (Fig. 11). At the same time, an extensive gas generation caused by contact metamorphism increased the formation pressure to levels substantially exceeding hydrostatic pressures ($C_o = 1.5–1.7$).

The overpressuring facilitated mixing of melts and brines and, consequently, the non-equilibrium precipitation of mercury from both: mixed melts, and mostly Lower Ordovician black shales. The presence of two mercury sources is supported by isotopic data that demonstrate a wide range of ratios between mantle and crustal values. Isotopic data for sulfur (always crustal), carbon, and oxygen are particularly informative in identifying these sources (Eichmann et al., 1977; Saupé and Arnold, 1992; Higueras et al., 2013).

Previous studies advocating a dominant role for a mantle source with an insignificant sedimentary influence (Hernández et al., 1999; Villaseca et al., 2011; Higueras et al., 2013) have invoked the natural evolution of magmatism from basalts, to alkaline varieties, and then to more evolved rocks (i.e., quartz diabases, trachybasalts, trachytes, and less commonly rhyolites). All three of these evolutionary stages are distinctive, but in our opinion the formation of the alkaline varieties is interpreted incorrectly, as it is not purely a magmatic process.

An important phenomenon in this regard is Fraileska: a number of diatremes with highly variable clusters of magmatic and sedimentary rocks, as well as lapilli tuffs. These are commonly called basanites or nephelinites, but their actual chemical composition is quite different to these rocks. The total amount of alkali oxides is usually only 2 wt%, and the silica content is less than 40 wt%. However, these rocks contain an average of 10 wt% of volatiles, with CO_2 being 4–10 wt% (occasionally up to 20–30 wt%). CaO and MgO contents (together) are ~23 wt%, and TiO_2 contents are ~3 wt% (Higueras et al., 2013). The surprising feature is the

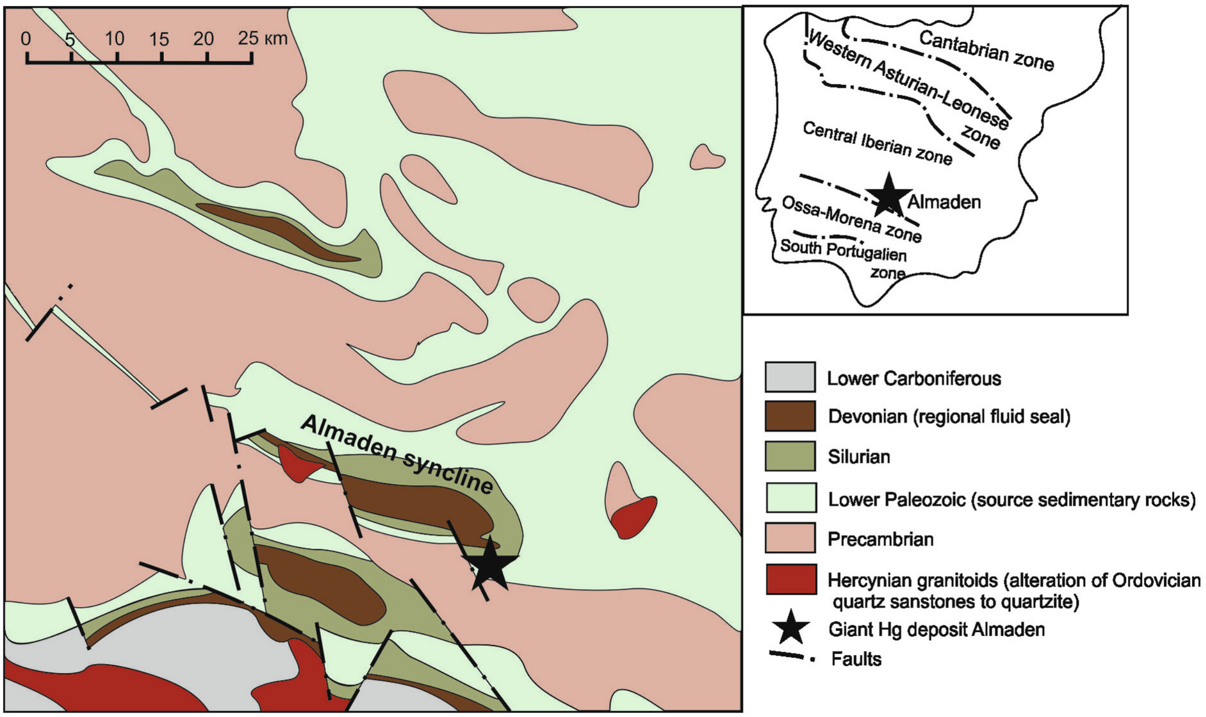


Fig. 9. Geological map of the Almaden Syncline (Central Iberian Zone) without Cenozoic cover (Palero-Fernández et al., 2015).

abundance of explosive breccia structures, as well as phenocrysts of different compositions and sizes. Many previous studies (e.g., Saupe, 1990; Higueras et al., 2013) have noted the possibility of fluid overpressuring during Fraileska formation.

As such, at the end of the Silurian and the beginning of the Devonian, a gradual magmatic change was followed by a sudden event, caused by the increased thickness of the regional fluid seal (a sedimentary–volcanogenic formation). This event was characterized by a significantly elevated (greater than hydrostatic) formation pressure, mixing of melts with gas-saturated brines, geologically instantaneous precipitation of cinnabar, and finally explosive formation of numerous tuffs and breccias. The ore genesis under such conditions was extremely fast and likely to have taken place in <0.2 Ma, which is consistent with the age of the ores, determined to be ~380 Ma (mid-Middle Devonian) (Hall et al., 1997; Higueras et al., 2005).

Moreover, the transvaporization-driven mechanism of ore genesis in the Almaden region is consistent with a specific feature, which underlies the abundance of its ores. Specifically, the presence of gigantic volumes of effective pores and voids in the quartz sandstones allowed large volumes of fluids to be mixed. This, in our opinion, facilitated maximal accumulation of precipitating mercury relative to its source in basaltic melts and mercury-rich Lower Ordovician and lower Silurian black shales. In this respect, the Almaden region is similar to the Norilsk region where the Tunguss suite sandstones have reservoir properties comparable to the Craidero sandstones and, therefore, were able to facilitate almost complete extraction of nickel, platinum, and other metals from the basaltic melts of the Nadezhdinskaya suite (Li et al., 2003; Naldrett, 2004).

During the formation of the Almaden deposit and for some time thereafter, the remobilization of mercury led to the development of numerous small deposits and ore occurrences, including veins and stockworks. Such ores were typically accompanied by hydrothermal (usually 100 °C–300 °C) changes to wall-rocks (i.e., formation of Ca–Mg–Fe carbonates, sericite, chlorite, quartz, prehnite, epidote, and other minerals (Higueras et al., 2013). Significantly, after the major ore genesis stage, Hercynian metamorphism (335 Ma) resulted in the complete transformation of quartz sandstones into quartzites. The entire history of the Almaden syncline development has lasted approximately 150 Ma.

2.4. Ermakovskoe giant beryllium deposit (west Transbaikalia, Russia)

This beryllium deposit exhibits clear features of transvaporization, but is located within more ancient (Mesoproterozoic) rocks than the previously discussed deposits. The approximate stratigraphic age of the carbonate and terrigenous Zoon–Moorin suite host rocks varies from 1330 to 1020 Ma (Kupriyanova et al., 2009; Lykhin et al., 2010; Kupriyanova and Shpanov, 2011). According to our previous palinspastic reconstructions (Aplonov and Lebedev, 2010), the peak of oil and gas accumulation in western Transbaikalia was at the end of the Proterozoic. Subsequently, the sedimentary basins were subjected to numerous structural and magmatic events, particularly in the Phanerozoic, when amphibolite-facies metamorphism occurred.

In the Ermakovskoe deposit (Fig. 12) and throughout the surrounding area, we can classify the magmatism into five main stages: pre-ore minor granitoid dikes (330 Ma); massive gabbros (320 Ma); contact and regional metamorphism (270 Ma); syn-ore stocks and minor intrusions of variable composition (227–224 Ma); post-ore intrusions (up to the end-Jurassic and later) (Lykhin et al., 2010). The peak of ore genesis was at 224 Ma, and took place in a relatively short interval.

The evolution of scientific concepts regarding Ermakovskoe ore genesis is quite remarkable. In early studies of the magmatic rocks and ores and, in particular, the “stock Syenite”, Ginzburg et al. (1977) convincingly substantiated its metasomatic and not magmatic nature. Analogous to the southern Chilean ore deposits, we consider it highly appropriate to use quotation marks when

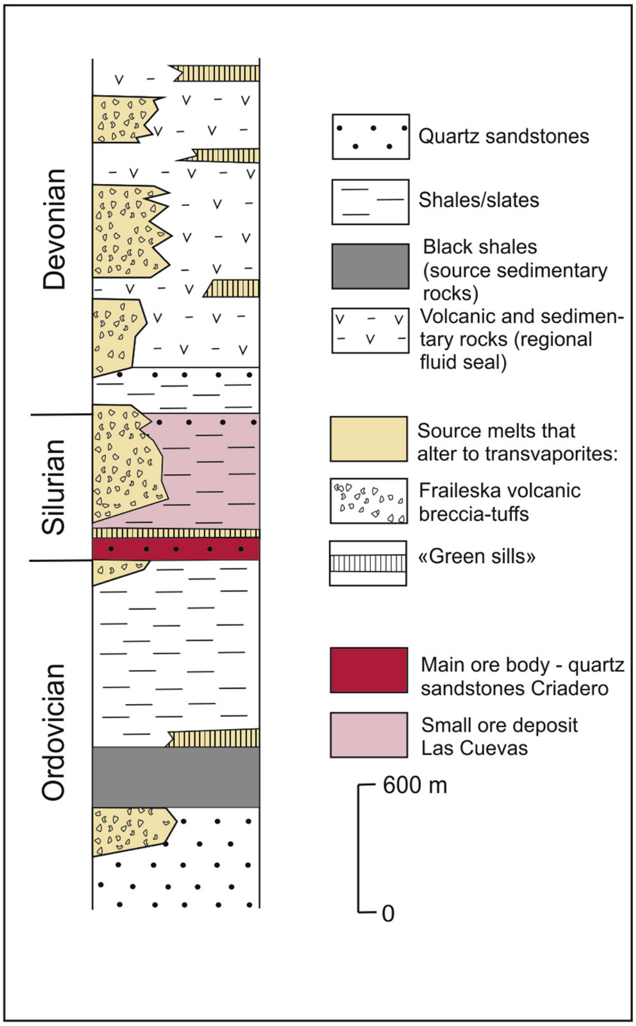


Fig. 10. Lithostratigraphic column of the Almaden giant ore deposit (modified after Higueras et al., 2013).

describing these rocks, such as “fine-grained aegirine granites”, “phlogopite rocks with fluorite–melinophan–leicophan–eudidymite cement”, “vesuvian skarns”, “fluorite syenites”, “carbonatite-like rocks”, and other mineralogical and petrographic varieties. Ginzburg et al. (1977) insisted that it would be scientifically incorrect to denote these rocks as syenites, given the marked predominance of potassium feldspar (microcline) over albite. Based on Ginzburg et al. (1977), we categorize the majority of the Ermakovskoe syn-ore rocks, such as “syenite-porphyry”, “diorite-porphyry”, and “alkaline granites”, as metasomatic rocks of transvaporitic origin (Fig. 12).

However, in the majority of publications within the last decade, the quotation marks for these petrographic terms tend to be omitted, and the unique rocks “magically transform” into the common granitoids, diorites, and syenites. As such, the process of transvaporization has been neglected. But experimental data on these rocks has continued to be acquired and, in particular, studies characterizing gas–liquid inclusions have identified a group of brine inclusions that are likely related to evaporates within the Zoon–Moorin suite remobilized during Triassic ore genesis.

Therefore, the unique phenakite–bertrandite ores of the Ermakovskoe deposit, which also include an unprecedented variety of other beryllium-bearing minerals, were also formed during mixing of sedimentary fluids with basaltic melts. Both the ores and the wall-rock minerals, such as fluorite, apatite (up to 5%), zircon, baddeleyite, and thorite have the same origin as the non-conventional silicates and aluminosilicates.

Although the presence of breccias (i.e., typical transvaporite rocks) is less profound in the Ermakovskoe deposit than in the El Teniente–Los Bronces region, in several ores such as the XVIII ore zone, breccias with fragments of “aegirine granites”, “skarns”, and “sluidites” have exerted a significant role in ore genesis.

Many previous studies (e.g., Lykhin et al., 2001, 2010) have linked the formation of the Ermakovskoe deposit, as well as many other beryllium deposits, with a Triassic intercontinental rift zone (230–215 Ma) that extends for >1000 km and includes volcanic rocks of the Sagan–Hunteyskaya suite that exceed 2 km in thickness. By analogy with other global basins, we propose that it is the main component of the regional fluid seal responsible for the basin overpressure, consequent transvaporization by the compressive mass transfer, and resultant ore genesis. The Triassic volcanic sequences above the Ermakovskoe deposit are now generally eroded away due to uplift, and only preserved in a depression to its east (Fig. 12) beneath Cretaceous volcanic rocks. However, to the north, Triassic volcanic rocks are widely exposed and characterized by a significant thickness (Lunina, 2009).

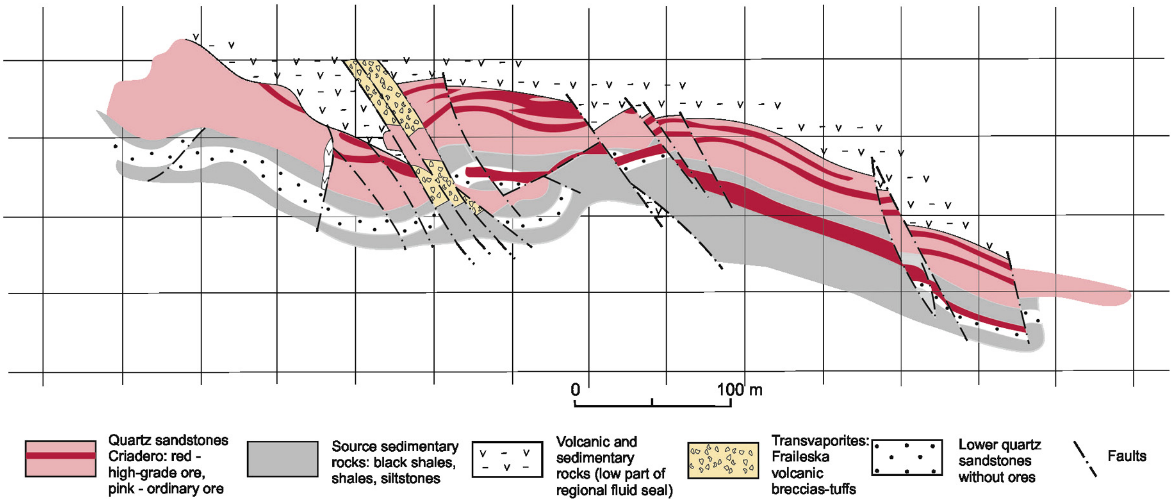


Fig. 11. Cross-section of the Almaden giant ore deposit (Palero-Fernández et al., 2015).

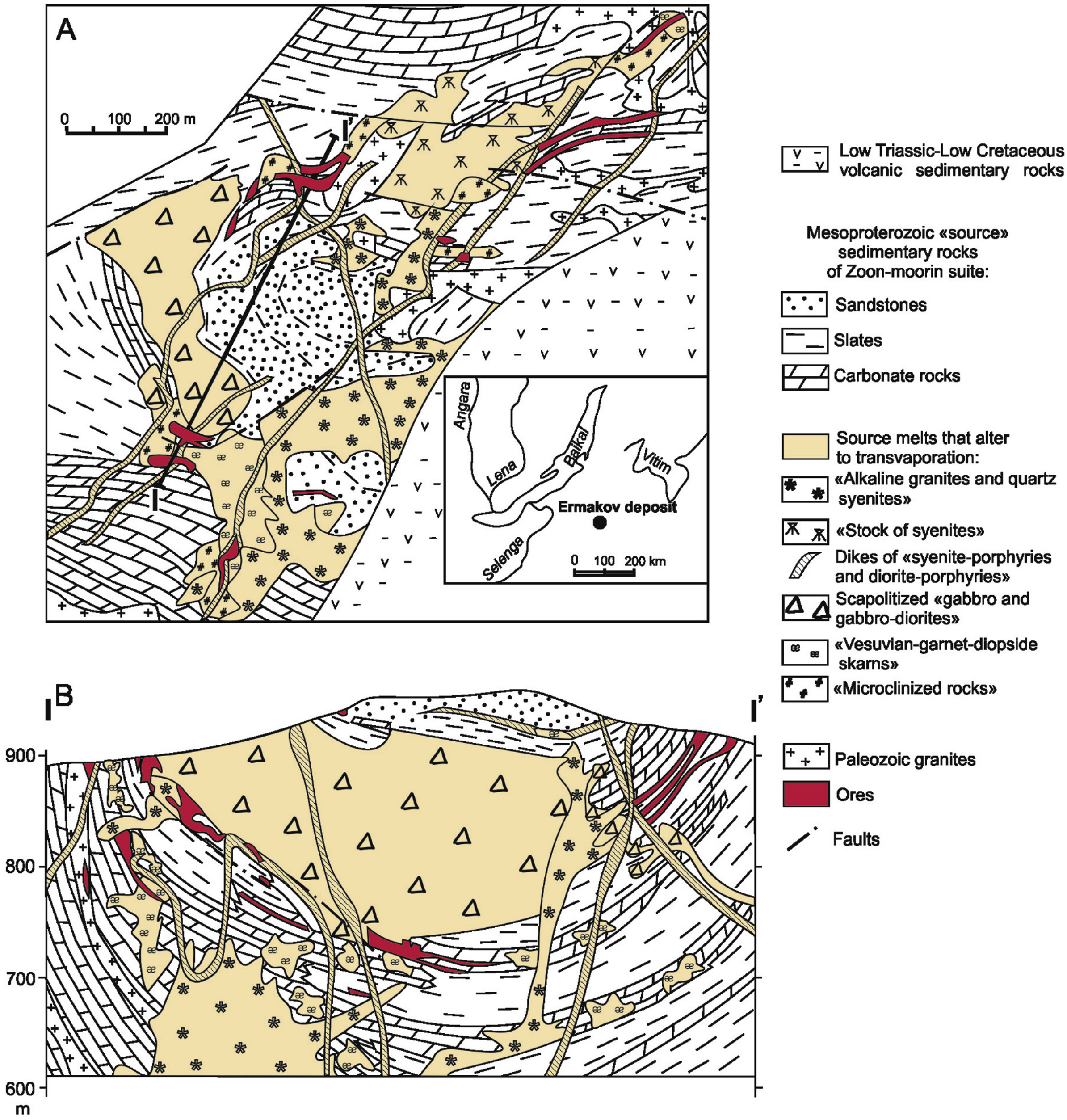


Fig. 12. Geological map (A) and cross-section (B) of the Ermakovskoe giant (Be) ore deposit (by V.I. Galchenko). The surface geology is shown prior to quarrying (modified after Kupriyanova et al., 2009).

2.5. Pebble Copper giant deposit (southern Alaska, USA)

This deposit contains the world's fourth and second largest copper and molybdenum reserves, respectively (Kelley et al., 2013), and is similar to the El Teniente–Los Bronces deposit, as well as numerous other Cenozoic ore deposits in subduction zones in the USA, Chile, southern Peru, Mexico, and Canada (Cooke et al., 2005; Kelley et al., 2013). However, there are some considerable differences between these deposits. Firstly, in addition to copper and molybdenum, the Pebble Copper deposit hosts supergiant gold reserves (the third biggest globally after Witwatersrand and Muruntau). Secondly, it is older than the Cenozoic giant ore deposits, as its ores are 90–89 Ma in age (Lang et al., 2013). Thirdly, the Jurassic and Lower Cretaceous source sediments (Kahiltna Formation) were deposited in a zone with cold climate (higher paleo-latitudes), and thereby are represented almost exclusively by terrigenous rocks that did not contain strong brines (Kalbas et al., 2007; Goldfarb et al., 2013).

Here, a comparison with oil and gas basins suggests itself. In the Persian Gulf basin, evaporates have large thicknesses in the Mesozoic carbonate sequences, and very strong brines are almost universally present. However, in the western Siberian basin the Mesozoic section is purely terrigenous and, therefore, in zones with compressive mass transfer the salinity of the formation waters never exceeds 20–50 g/L (Lebedev, 1992). Accordingly, in southern Alaska, in contrast to all the other deposits reviewed here, the likelihood of brines participating in transvaporization is small.

This last point is of great importance, as the low salinity of the reservoir waters reduces the contrast in composition with the wall-rock minerals. Nevertheless, the thickness of the Mesozoic sedimentary basin prior to the beginning of magmatism at the end of the Early Cretaceous had likely reached 4–5 km (Goldfarb et al., 2013) and, therefore, this basin was oil- and gas-bearing, even if only for a short period of time.

The Pebble Copper region is characterized by an atypical sequence of magmatic events, involving alkaline (100–96 Ma) and then subalkaline (96–89 Ma) magmatism. In our opinion, this is due to transvaporization, which defined the unusual composition of ore-forming melts, and occurred in the low salinity conditions of the Kahiltna Formation reservoir waters. During both magmatic stages, magmas were not only erupted, but also formed numerous intrusive bodies, including the main Kaskanak ‘‘batholith" that produced significant contact metamorphism of the sedimentary rocks as evidenced by the abundant hornfels (Tosdal and Richards, 2001; Trop and Ridgway, 2007). The effusive lava flows, as well as three vast diorite sills with thickness of up to 300 m, created an excellent regional fluid seal that ensured occurrence of intensive transvaporization.

Despite the fact that transvaporization within the Pebble Copper deposit is not highly evident, the same processes that were detected in the El Teniente–Los Bronces deposit are also found in here. For example, the intrusive rocks contain 10%–15% biotite, 10% magnetite, 5% K-feldspar, and occasionally some anhydrite. Amongst other obvious features of transvaporization, are an abundance of phenocrysts in the magmatic rocks, and frequent presence of pegmatoid rocks and breccias. Moreover, some ‘‘stocks" have unusual compositions, and may contain megacrysts of potassium feldspar up to 1.5 cm in size, as well as abundant phenocrysts of plagioclase and hornblende. In other cases, some ‘‘stocks" contain large amounts of magnetite, apatite, and zircon in the cements. Importantly, the age of all these minerals coincides with ore genesis time at 90–89 Ma (Plafker et al., 1994; Tosdal and Richards, 2001; Pavlis and Roeske, 2007; Trop and Ridgway, 2007; Lang et al., 2013).

As such, we conclude that while the presence of strong brines is extremely important for transvaporization, their absence does not prevent the formation of giant ore deposits during transvaporization. In the case of the Pebble Copper deposit, massive formation of biotite, magnetite, and K-feldspar appears to be sufficient. Moreover, the total magnetite content in the ore-bearing wall-rocks is notable for this deposit and, as a result, geomagnetic exploration is widely used there (Anderson, 2005; Goldfarb et al., 2013).

The special character of the ore genesis, as well as the role of the magmatic rocks, in the Pebble Copper deposit are shown in Fig. 13 and elaborated on in the legend to this figure, which we have slightly modified to reflect our transvaporite model. Although the absence of brines has a negative impact on the potential for ore genesis, the high initial organic content, particularly in the Jurassic sediments (Goldfarb et al., 2013; Lang et al., 2013), appears to compensate for this.

Clearly, the most important requirement for the compressive mass transfer mechanism is a robust regional fluid seal. In the Pebble Copper deposit, the considerable thickness and extent of the Upper Cretaceous volcanic rocks, along with the three sills, combined to create a consistent fluid seal. It is also notable that whereas post-ore volcanic sequences do not participate in ore genesis, they do facilitate preservation of ores from erosion in the most enriched eastern zone of this deposit. The cross-section in Fig. 13B also demonstrates the significant role of the syn-ore pluton as a potent provider of intense gas generation in the Jurassic sediments.

2.6. Olympic Dam deposit (South Australia, northeastern Gawler Craton)

This deposit holds the world's richest uranium reserves (1.2 Mt), as well as giant reserves of copper, gold, and rare earth elements (Hitzman et al., 1992; Skirrow et al., 2007; Wade et al., 2012). Despite the status of this deposit as an absolute record-holder in number of scientific publications, its ore genesis remained enigmatic for a long time until publication of a special issue of *Economic Geology* (№ 3, v.102, 2007) devoted to the deposit and the Gawler Craton. This issue summarized all previous studies, and reported multiple new isotopic data clarifying not only the ages of these rocks and ores, but also the metal sources. As a result, greater clarity developed with regards to the ore deposit genesis, which makes it possible to evaluate the applicability of the transvaporite model of ore genesis to the Olympic Dam deposit. This is important as no reliable evidence of transvaporization in such ancient ores (1590 Ma) had been previously documented.

Perhaps the most significant observation is the substantiation that certain rocks of the Wallaroo Group (1765–1740 Ma), such as carbonate–evaporate rocks, black shales, and volcanic rocks, played an active role in ore genesis providing sulfur, carbon, alkalis, and some other components (Oreskes and Einaudi, 1992; Haynes et al., 1995; Johnson and Cross, 1995; Bastrakov et al., 2007; Skirrow et al., 2007). As we have previously demonstrated (Aplonov and Lebedev, 2010), the extended sub-meridional zone in central Australia (from the uranium deposits in the Northern Territories to at least the giant Broken Hill zinc–lead–silver deposit) was subjected to global sedimentary cyclicity during an entire global cycle (ca. 1.8–1.6 Ga), which governed the genesis of the numerous giant deposits. Amongst such deposits we have mentioned the Olympic Dam, and considered that the narrow stratigraphic interval of the Wallaroo group represents only a small part of the bigger sequences involved in the formation of Olympic Dam giant (Aplonov and Lebedev, 2010).

In general, most studies have emphasized the predominance of crustal sources for all the metals within the deposit (Creaser and Cooper, 1993; Budd and Skirrow, 2007; Davidson et al., 2007; Fraser et al., 2007; Hand et al., 2007; Skirrow et al., 2007). However, importantly for our transvaporite model, the participation of primitive, mantle-derived magmas in ore genesis is always required, and has been confirmed by several isotopic studies (Johnson and Cross, 1995; Davidson et al., 2007; Skirrow et al., 2007). In addition, other petrological, mineralogical, and geochemical data also indicate that crustal and mantle sources were involved in ore genesis (Skirrow et al., 2007).

A complex and multifaceted role in ore genesis was performed by iron-bearing minerals (magnetite and hematite), which although not being profitable with respect to iron, certainly contributed to the concentration of other metals, including mainly copper and uranium. Several types of associations of iron-bearing minerals with other different minerals exist (Williams and Barton, 2005; Bastrakov et al., 2007). Although their relationship to ore genesis is not always clear, the control of uranium ores by hematite breccias, for example, is obvious.

It is important to note the clear presence of a volcanic fluid seal, shown on the map of the Olympic Dam region (Fig. 14). The seal is the Gawler Range volcanic formation comprising co-magmatic sub-volcanic intrusive rocks with ages of ≤1600–1575 Ma (Skirrow et al., 2007). Similarly to the other discussed deposits, the volcanic and intrusive rocks have often been partially or almost completely eroded by later uplift events.

The intrusive rocks display varying degrees of transvaporization and, therefore, as we argued earlier, their names should be used with quotation marks. This specifically pertains to the complex Hiltaba suite, which consists of ‘‘granites", ‘‘granodiorites", ‘‘quartz monzonites", ‘‘quartz monzodiorites", ‘‘granosyenites", and other similar lithologies that include felsites and mafic dikes.

Multiple other transvaporization features are observed within the Olympic Dam ore deposit, such as high alkali contents, hypersaline brines in gas–liquid inclusions, and high biotite and magnetite contents in the wall-rocks. Moreover, many rocks exhibit evidence of metasomatism, which was mostly potassic in nature

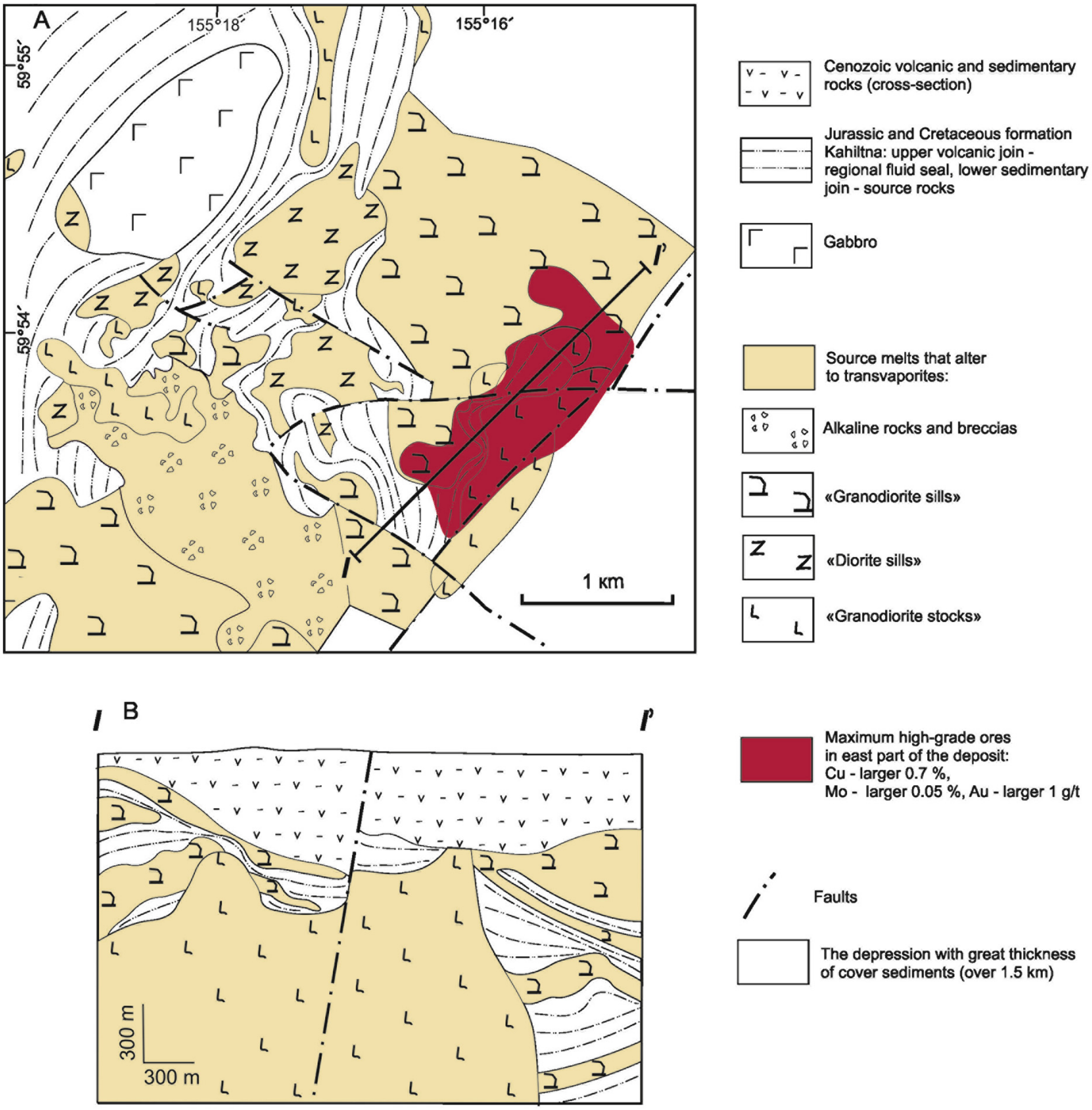


Fig. 13. Geological map (A) and cross-section (B) of the giant Pebble Copper Mo–Au–Cu deposit (modified after Lang et al., 2013).

(Hitzman et al., 1992; Skirrow et al., 2007). Yet, perhaps the most significant transvaporization feature is the abundance of hematite and granite breccias, which have been noted from the onset of exploration of this deposit. All these breccias apparently originated from the "explosive effects" accompanying the compressive mechanism of mass transfer during ore genesis.

Finally, rocks from poor and barren mineralized zones have average maximum εNd values of +5, whereas for the giant Olympic Dam deposit maximum εNd values are +3, which clearly indicates a major contribution from mantle material (Fig. 15).

2.7. Summary overview of the giant ore deposits associated with transvaporization

Table 1 compares six giant ore deposits according to their individual features. We now provide an overview of these deposits, focusing on the features specific to the transvaporite model of ore genesis. This analysis is designed to improve our exploration for new giant ore deposits.

Two main conclusions can be derived from the analysis in Table 2, which relate to the distribution of giant deposits according to the age of the sedimentary basins and location (i.e., continental setting).

The main age peak of the analyzed ore giant deposits is 0.8–0.5 Ga (45% of deposits). This is the age that Chinese geologists refer to as the Sinian, and our analysis is likely to provide an additional appeal for its stratigraphic significance. In Aplonov and Lebedev (2010), we presented paleo-profiles that reconstructed the geological history of southeast China from the Early Devonian to the Mesozoic – a time when massive, petroleum-rich basins were transformed into ore-rich basins. These profiles highlight the hydrocarbon history of the contemporary Sinian–Silurian oil and gas system of the Sichuan Basin (Zou et al., 2015).

The second age peak of the analyzed ore giant deposits (25% of deposits) accounts for the previously petroleum-rich Mesozoic–

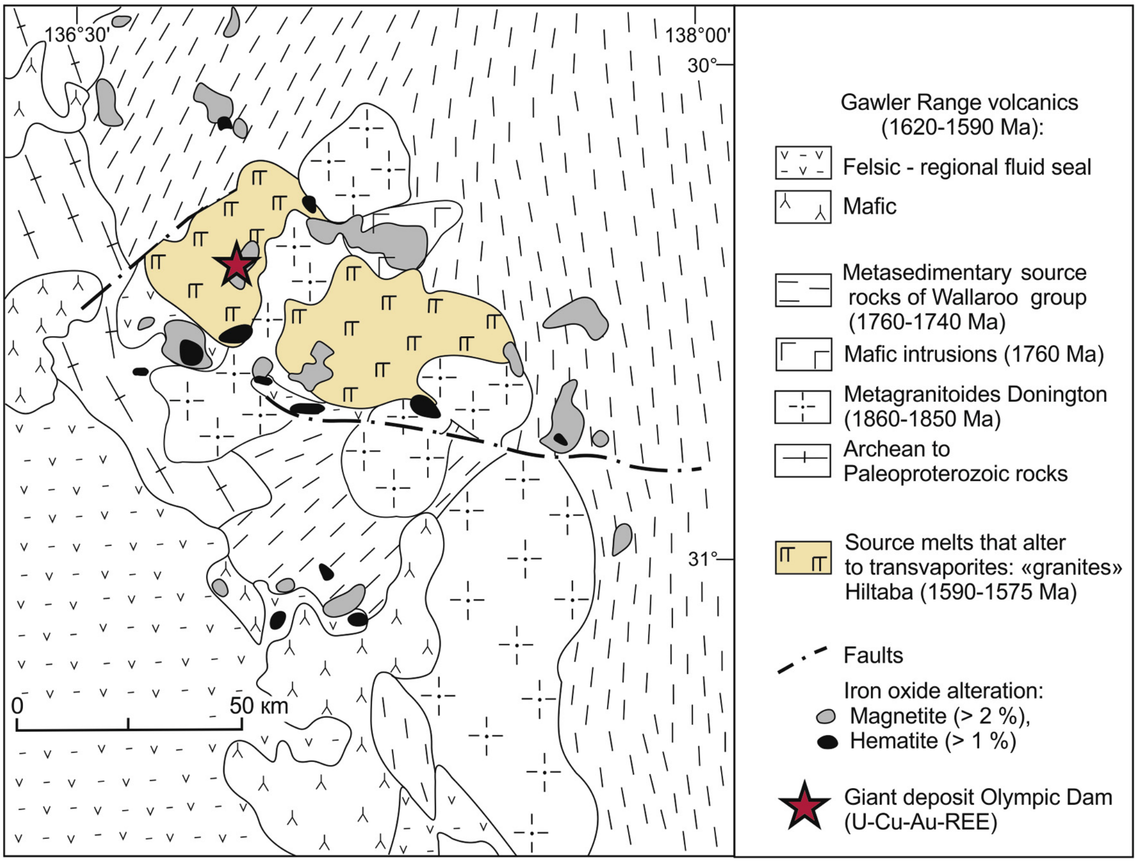


Fig. 14. Geological map of the Olympic Dam district (pre-Pandurra Formation) (modified after Skirrow et al., 2007).

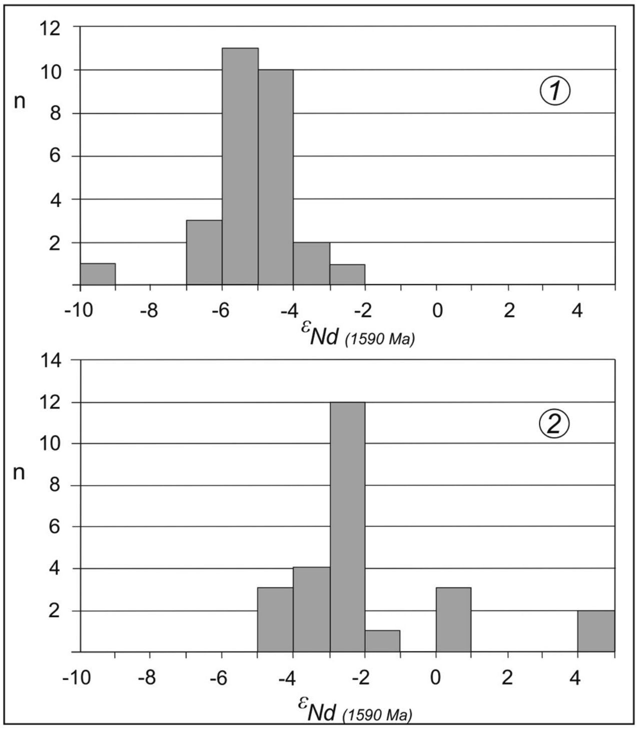


Fig. 15. Frequency histograms of Nd isotopic compositions (n = number of samples) calculated at 1590 Ma for barren or weakly mineralized prospects (1), compared with the Olympic Dam giant ore deposit (2) (modified after Skirrow et al., 2007).

Cenozoic basins in the western part of North and South America, which have been destroyed by the subduction associated with the formation of Andes and Rocky Mountains Large Igneous Provinces. The age of magmatism decreases from north (90 Ma in southern Alaska) to south (6–4 Ma in Chile), and the ores were generated at these times (Maksaev et al., 2004; Cooke et al., 2005; Lang et al., 2013). Mesozoic oil and gas basins remain only in the depressions of the Rocky Mountains, and in South America (i.e., mainly Argentina).

The remaining transvaporite ore giant deposits are associated with sedimentary basins that accumulated from 1.6–0.8 Ga (Table 2). These basins contained petroleum deposits that are 0.5 Ga in age and older. There are no transvaporization-related ore giants in basins with ages of 0.50–0.25 Ga.

The oldest transvaporite ore giant deposit (1.59 Ga) is the Olympic Dam deposit. The timing of its formation coincides with the completion of a major turning point in the history of the Earth at 1.9–1.6 Ga (Salop, 1982; Aplonov and Lebedev, 2010). However, this does not mean that oil and gas giant deposits were not generated prior to this time. For example, it is known that the natural fission reactors of Oklo were active at 1.87 Ga (Gauthier-Lafaye and Weber, 1989), which was only possible within a degrading, older, massive petroleum basin (Aplonov and Lebedev, 2010). Fuchs et al. (2016) also showed that gold deposits in the Black River Formation at the base of the Transvaal Supergroup (above the richest gold reefs in the Witwatersrand Supergroup) were formed within a degrading petroleum basin.

The location of ore giant deposits on different continents is almost certainly defined by the age of former large petroleum basins. Transvaporite giants are very rare in Africa and Australia where ancient basins are widespread. In Asia, where Sinian basins

Table 1
Features of giant ore deposits, originated *via* transvaporization.

Country, Region	Chile	USA, Southwest Alaska	Russia, West trans-baikalia	Russia, East Siberia	Spain	Australia, Gawler Craton
District	Central Chile	Kahiltna basin	Khudan range	Norilsk	Central Iberian zone	Olympic Dam district
Deposits	El Teniente, Los Bronces	Pebble Copper	Ermakovskoe	Talnakh, Norilsk I, Kharaelakh	Almaden	Olympic Dam
Metals	Cu–Mo	Cu–Mo–Au	Be	Cu–Ni–Co–Pt–Pd	Hg	U–Cu–Au–REE
Source sedimentary rocks	Jurassic-lower Cretaceous terrigenous-carbonate-evaporate	Jurassic-lower Cretaceous terrigenous rocks	Mesopro-terozoic terrigenous-carbonate-evaporate	Neoprotero-zoic-Paleozoic terrigenous-carbonate-evaporate	Lower Ordovisian terrigenous-carbonate-evaporate	Paleopro-terozoic terrigenous-carbonate-evaporate
Ore age	8–4 Ma	90–89 Ma	224 Ma	250 Ma	380 Ma	1590 Ma
Composition, age of regional fluid seal	Volcanic rocks, from acidic to mafic, 12–4 Ma	Volcanic rocks, from acidic to mafic, 95–88 Ma	Volcanic rocks, from acidic to mafic, 230–215 Ma	Basalt, 251–250 Ma	Basalt, alkali basalt, 420–380 Ma	Volcanic rocks, from acidic to mafic, 1620–1590 Ma
"Magmatic" transvaporites	Andesites, microdiorites rhyolites	Diorites, granodiorites	Alkali basites	Alkali basalts	Basanites, green sills	Alkali granites, granosyenites
Breccias		Cements: tourmaline, biotite, igneous	Cements: lapilli, tuffs	Clastes: syenites, granites	Cements: biotite, microcline, magnetite	Clastes: granite, hematite
Metasomatic transvaporites	Skarnoids, chlorates	Biotite–mag-netite–anhy-drite rocks	Fraileska	Skarnes, Microclini-zation	Microclini-zation	Microclini-zation
Figures	3–7	8	9–11	11	12	13–14

Table 2
Temporal and spatial analysis of the distribution of giant ore deposits and their metal associations.

Age (Ga)	Continents (or their parts)							Number of giants
	North America	South America	Europe	Africa	Asia		Australia	
					Middle Asia, Kazakhstan	East Siberia, China		
≤0.25	25 Mo, Cu	14 Cu, Mo	2 Mo	–	–	–	–	41
0.5–0.25	–	–	–	–	–	–	–	0
0.8–0.5	11 Ag, W	12 Sn, Ag	6 Hg, Sn (U)	–	12 W, Sb, Hg, Mo (Ag, U)	34 W, Mo, Sn, Sb, Hg (Ni, Pt, Pd, Co, Cu)	–	75
1.2–0.8	5 Be, Ta, Li	2 Ta, Zr, Be(Sn)	1 Zr, Ta (Nb)	6 Ta, Li, Be	6 Ta, Zr, Li	12 Be, Ta, Zr	–	32
1.6–1.2	3 TR, Nb, Zr	4 Nb, TR, (Ti, U)	–	4 Nb, TR (U)	–	7 TR, Nb, Y	–	18
1.8–1.6	–	–	–	–	–	–	1 U, Cu, Au, TR	1
≥1.8	–	–	–	–	–	–	–	–
Total	44	32	9	10	18	53	1	167

are widely developed (China, eastern Siberia, Kazakhstan, and central Asia), tens of giant ore deposits have already been discovered, and perspectives for a new ones are the greatest.

In conclusion, we note that the metal associations in transvaporite ores are almost universally determined by the age of the source sedimentary basins, rather than the age of the ores. This result is interesting, because generally the age of the ores is close to the age of the magmatism.

3. Transvaporite formation by interaction of Large Igneous Provinces with older, large petroleum basins

Transvaporization is a unique process that results from the mixing of two radically different fluids: (1) primitive, mantle-derived, basaltic melts low in volatiles; (2) extremely gas-saturated brines that migrate out of sedimentary rocks that have a high porosity and permeability. Both types of fluids have almost infinite volumes. In one case, deep faulting transfers basaltic magmas to the upper part of the crust and the surface. In the second case, reservoirs with a high effective porosity accumulate large amounts of brines prior to magmatism. Examples of such reservoirs occupying vast areas have been already discussed, including the polymict sandstones of the Tunguss suite in the Norilsk district and quartz sandstones in the Almaden district.

Thus, if a former oil and gas basin, typically with an area in excess of 1 million km^2, is intersected by a LIP (Coffin and Eldholm, 1992; Ernst and Buchan, 2001; Anderson, 2005; Wignall, 2005; Ernst, 2007; Davies et al., 2012; Heaman, 2014; Shellnutt, 2014), then transvaporization takes place. The specifics of this process in different regions are distinguished by many features, but the mixing of two contrasting fluids – gas-saturated brines and basaltic melts – is the main condition required for ore genesis in the transvaporite model.

This conclusion justifies the choice of giant ore deposits used for our current study (Aplonov and Lebedev, 2010). The giant deposits discussed show widely different metal associations (Table 1), but are all characterized by transvaporization features. The other common characteristic of such deposits is that, in most cases, several metals reach great reserves in each deposit: five in the Norilsk region; four in the Olympic Dam deposit; three in the Pebble Copper deposit; two in the El Teniente–Los Bronces region.

The variety of ore types is unique. The Norilsk region includes copper–nickel–cobalt along with PGE deposits in layered intrusions associated with the traps. The El Teniente–Los Bronces and Pebble Copper regions are copper–molybdenum–(gold) porphyry deposits located in a large Cenozoic belt of subduction magmatism. The Ermakovskoe beryllium deposit is linked to a Mesoproterozoic platform sedimentary basin, which was activated by Mesozoic rifting and alkaline magmatism. The Almaden mercury deposit was formed in a vast Lower Paleozoic platform sedimentary basin as a result of intense Upper Silurian to Devonian magmatism. Finally, the Paleoproterozoic sedimentary basin of the Gawler Craton (location of the Olympic Dam giant deposit) was affected by different magmatic events and, although mostly silicic in nature, included intrusion of mantle-derived basalt during the key stage of ore genesis.

Deposits with such diverse and very different metal associations are rarely considered and compared with each other. However, they possess an important common feature – a clearly pronounced transvaporization, which determines the uniqueness of each deposit's composition and structure, due to the mixing of two very different fluid systems. Magmas that move by convective mass transfer mix with brines from sedimentary rocks that move by the compressive mechanism. The compression can be explained by the formation of a reliable volcanic fluid seal, and by extremely intense vaporization as a result of a range of interrelated factors, such as an increase in the regional geothermal gradient and contact metamorphism. Both of these factors are created by the intrusion of melts in the LIPs.

We specifically emphasize the importance of the regional fluid seals in this process. After structural and magmatic activity, conventional fluid seals in the former petroleum basins tend to lose their sealing properties. The clay sequences become fluid permeable as a result of their disruption by fault and fracture zones; and the salt-bearing sequences lose their sealing ability due to diapirism, and salt dispersion and dissolution (Hudec and Jackson, 2006; Pilcher and Blumstein, 2007). Therefore, the eruption of lavas onto the surface is important, as they form short-lived but very effective regional fluid seals, under which ore giant deposits can be formed.

In all of the ore giant deposits discussed, we can define with certainty the ages of the igneous provinces, as well as those of the former oil and gas basins activated by these LIPs. The igneous rocks of the Norilsk ore district are part of the eastern Siberian trap province (Dodin, 2002; Ryabov et al., 2005). It includes, for example, the Angaro–Ilimsk iron ore diatremes (Von-der-Flaass, 1997), giant Gulin intrusion (Kogarko et al., 1994; Malich and Kostoyanov, 1999), and a series of sills in Neoproterozoic–Ediacaran–Lower Cambrian pre-salt sediments, which during the Lower Devonian were enriched with oil and gas throughout the Lena–Tunguss basin (>1.5 million km^2). Part of this unique former hydrocarbon deposit is still preserved today (Zabaluev, 1980).

The El Teniente–Los Bronces region in Chile, as well as the Pebble Copper region in southwestern Alaska, are small fragments of Cenozoic volcanic belts that extend along the west coasts of North and South America, and include several dozen ore giant deposits (copper–molybdenum, and also tin, silver, gold, and tungsten). This volcanic belt traverses more than a dozen of massive, formerly oil- and gas-rich basins of different ages (Aplonov and Lebedev, 2010), which are now only evident as Athabaska bitumens (Canada) and Orinoco Basin (Venezuela).

The western Transbaikalian igneous province, in addition toErmakovskoe and other beryllium deposits, includes gold, uranium, niobium, and zinc deposits. Some of these are giant deposits (Mironov and Plusnin, 2002). In this province, lower Paleozoic–Mesozoic rift magmatism mainly controlled ore genesis in former Mesoproterozoic sedimentary basins containing petroleum.

The Almaden mercury deposit is contained within one of several Lower Paleozoic oil- and gas-bearing rift depressions, which were intruded by Lower Silurian to Devonian basaltic magmatism. The large reserves of mercury are not accompanied by significant accumulations of other metals, and the transvaporites of Fraileska represent one of the most original examples of an explosive event immediately after ore formation.

Finally, the Mesoproterozoic LIP of the Gawler Craton (Agangi et al., 2012) intersected an Upper Paleoproterozoic former oil and gas basin (Wallaroo Group) and generated the unique polymetallic, Olympic Dam giant deposit. It is the oldest giant ore deposit exhibiting obvious features of transvaporization.

We now attempt to summarize all the geological events from the subsidence of the sedimentary basins through to the formation of the giant ore deposits (Fig. 16). During the formation of each supercontinent, the diastrophism phase is characterized by a peak in isotopic ages, and is then followed by continental rifting. In general, at the same time spreading occurred in large marginal basins and formed oceanic crust. However, intense destruction of new and large orogens produces large amounts of sedimentation, which reduces the thermal flux and causes spreading to cease. Horizontal movements generate vertical tectonism, and sedimentation is subjected to global cycling. The sedimentary basins then develop and reach 6–7 km or more in thickness. As a result of basin formation,

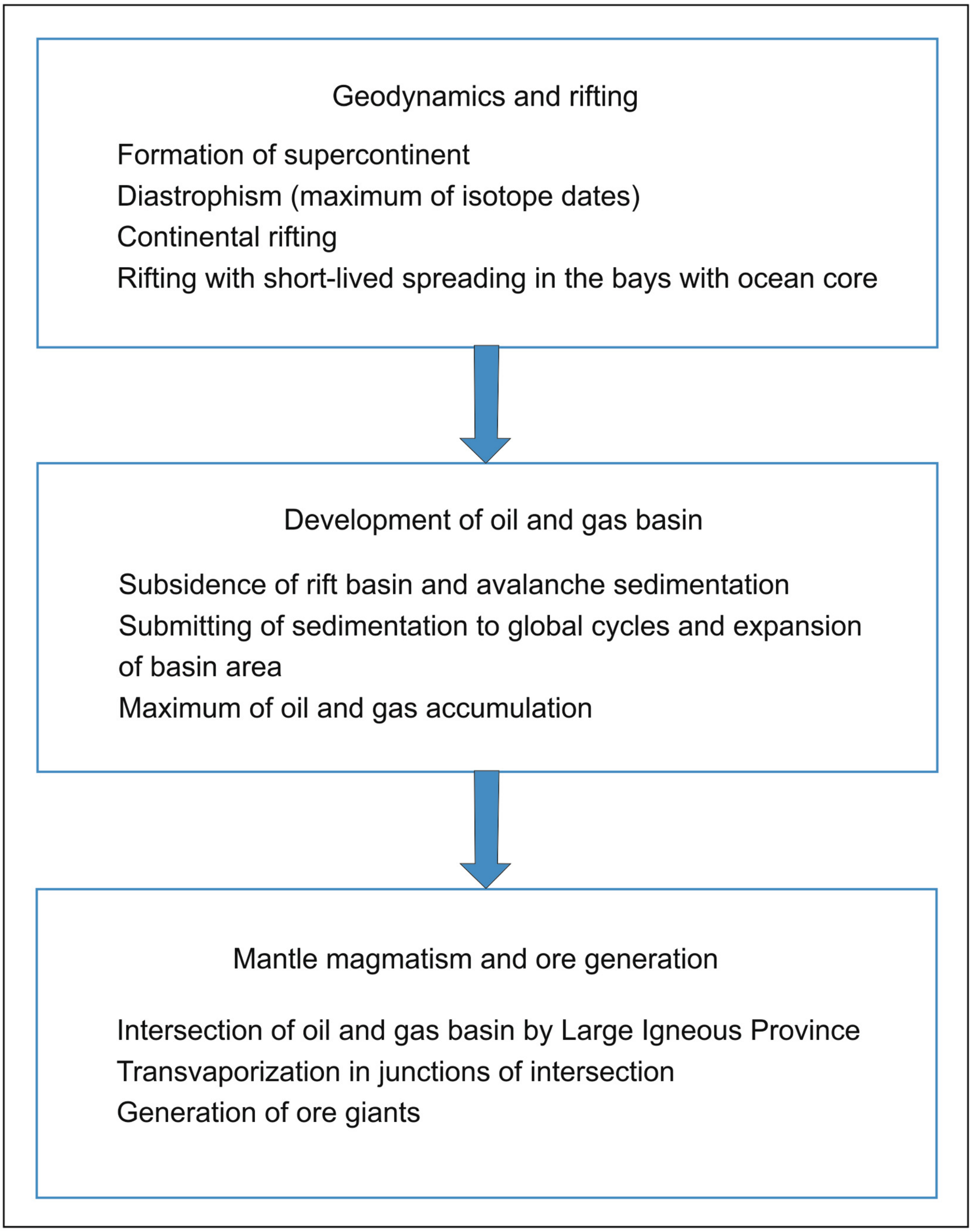


Fig. 16. The succession of geological events from rifting and subsidence of a sedimentary basin to the generation of giant ore deposits by the transvaporite model.

oil and gas accumulate. Subsequently, the sedimentary basin can undergo tectonic activation with the intrusion of mantle-derived melts, and mixing of basaltic melts with gas-saturated brines generates transvaporites and giant ore deposits.

It is useful to compare our model with the results obtained during the characterization of individual ore deposits in LIPs. The number of such studies is rapidly increasing and, amongst these, we note the review by Pirajno and Hoatson (2012), which links numerous, mostly giant ore deposits to specific igneous provinces. However, this and other studies (e.g., Davies and Heaman, 2014; Shellnutt, 2014) lack any data on the sedimentary basins, contained within reviewed LIPs. Therefore, such studies, unfortunately, fell short of comprehensive understanding of ore genesis mechanisms; and, consequently, are incapable of suggesting an algorithm to search for new giant ore deposits.

4. General features of transvaporites

We now summarize the features typical for any giant ore deposit that formed as a result of transvaporization:

(1) All deposits are characterized by giant reserves, high metal concentrations in ores, and unusual associations of metals. The original character of metal associations can be manifested in different ways, and even marked by the opposing tendencies. For example, in the Norilsk region, five metals reach giant reserve status, whereas in the Almaden region only mercury reaches giant reserve status, although this one deposit contains almost half of the world's mercury reserves.

(2) The main cause of transvaporization is the superposition of a LIP onto former oil- and gas-rich sedimentary basins.
(3) Transvaporization occurs under conditions of overpressure in sedimentary sequences when the layer pressure/hydrostatic pressure (an analogy with Mesozoic–Cenozoic oil and gas basins) or C_o is in the range of 1.4–1.8.
(4) A necessary condition for transvaporization-driven ore genesis is the successive presence of two different types of regional fluid seals. Firstly, an argillaceous or salt seal in the former oil and gas basin and, secondly, a volcanic seal developed during magmatic activity and accumulation of basaltic lava flows.
(5) The main ore genesis stage takes place over a short period of time, which is usually less than 0.2 Ma.
(6) The ores are formed in sedimentary rocks, typically sandstones or carbonates, which are characterized by high initial porosity and permeability.
(7) The melts, mainly basalts that intrude into the sedimentary basins and are exposed to transvaporization, develop non-stoichiometric compositions, typically with higher concentrations of alkalis, calcium, and volatiles.
(8) Transvaporization is normally accompanied by explosive activity, which occurs near the end (or immediately after the end) of the main stage of ore genesis, as evidenced by tuffs and breccias.
(9) The rocks formed during transvaporization display marked oscillations in isotopic compositions, most likely due to mixing of mantle and crustal components.
(10) Transvaporization processes typically generate numerous unusual types of rocks, whose names are often used (or should be used) within quotation marks such as, for example, "pseudo-breccias", "pseudo-skarnoids", and "hybrid-metasomatic rocks". These processes also produce unusual mineral associations, such as coexisting biotite and anhydrite. In general, wall-rock alteration is also variable and forms unusual lithologies.

From this list of observations, we define the term transvaporite as "Transvaporites are rocks formed as the result of mixing between gas-saturated brines from sedimentary rocks and subsurface (mantle or lower crustal) melts that intrude into these sedimentary rocks". Given that the rocks that result from this process are assigned complicated names, we suggest that this group of rocks with very different compositions and linked by a single process – transvaporization, be termed transvaporites.

The simplest way to compare transvaporites with standard rocks is by chemical analysis. Daly (1933) laid a solid foundation for all former and current geochemical rock classifications. Using different triangular diagrams, we compared the composition of transvaporites from giant ore deposits reviewed here with the chemical analyses of Daly (1933) (Fig. 17). All of the diagrams highlight the major differences between transvaporites and Daly's analyses that are consistent with the different origins of transvaporites.

As such, we attempted to identify those ore deposits in which transvaporization played a clear role in ore genesis. In general, if a LIP intersects a former large oil and gas basin of any age and giant ore deposits are present, then we can state that transvaporization took place.

For example, within the Andes and Rocky Mountains we have only considered the giant ore deposits of the El Teniente–Los Bronces region and Pebble Copper. However, it is clear that transvaporization is also responsible for the genesis of >30 copper–molybdenum giant deposits in Chile, Peru, Mexico, USA, and Canada. A similar inference can be made for the tin–silver giant deposits of Bolivia and Peru (Cerro Rico de Potosi and San Rafael), silver deposits of Mexico (Guanajuato and Pachuca), molybdenum and tungsten deposits of Canada (Quartz Hill and Maktung), and other deposits in the USA (Brobst and Pratt, 1973; Randall et al., 1994; Bartos, 2000; Dictrich et al., 2000; Emsbo et al., 2003; Heitt et al., 2003; Wilkinson and Kesler, 2009). It is also likely that the formation of stratiform gold ores of Carlin type (Emsbo et al., 2003; Heitt et al., 2003) was accompanied by intense transvaporization that affected the concentration of gold in Paleozoic sequences.

The Ermakovskoe beryllium deposit has many distant and close analogues amongst rare metal deposits. These include actual beryllium deposits (Keketuohai in China and Spur Mountain in USA), and also tantalum–zirconium (Ghurayyah in Saudi Arabia and Berthze in Mongolia) and lithium deposits (Kings Mountain in USA). Transvaporization does not require that these deposits contain pegmatites, although "pegmatoids" can be often found along with transvaporites (Brobst and Pratt, 1973).

We also suggest that transvaporization influenced the formation of rare metal carbonatites within alkaline ultramafic intrusions, as well as diamondiferous kimberlites. This is evidenced by the high gas saturation levels of melts, traces of explosive activity, and abundant alkalis and chlorine within the magmatic bodies and accompanying dike swarms (Kamitani and Hirano, 1990; Le Bas et al., 1992; White et al., 1995; Castorinal et al., 1997; Kiselev et al., 2009).

However, transvaporization is not the only ore-forming process. Obviously, transvaporization cannot take place in areas without LIPs and where magmatism is minor. In addition, it is likely that mantle-derived magmatism is necessary for transvaporization. Due to the lack of regional fluid seals, it is doubtful that transvaporization took place in the Archean, as well as most of the Paleoproterozoic (>1.8 Ga) (Aplonov and Lebedev, 2010).

Finally, we should note that there was no apparent transvaporization in numerous ore provinces where giant ore deposits are very rare or absent. These are mostly complicated fold belts with small terrains (platform fragments) where former large oil and gas basins never existed. Exploration within such regions is mostly uneconomic and environmentally unsound.

As a conclusion, in Table 2 we present some statistical data from an analysis of 500 giant hydrocarbon and ore deposits. The inclusion criteria, which we broadly defined as "The decisive role of transvaporization in ore genesis" is relatively uncertain, therefore the enclosure of some singular giants into the general sample is discussable. Nevertheless, two key conclusions can be drawn from this data. Firstly, the clear role of transvaporization is evident in 167 of the 414 largest ore deposits (i.e., 40% of the deposits). Secondly, transvaporization features are found in 33 out of 52 polymetallic giant deposits (where 2–5 metals reach giant reserves), or in 63% of the studied cases. These high proportion of giant ore deposits related to transvaporization substantiates our view that this is the dominant process in the formation of these ore giants with a unique accumulation of several metals, and with often very different geochemical characteristics.

However, several exceptional polymetallic giant deposits, such as Bushveld in South Africa (Cr–Ti–V–Pt–Pd), Lubin in Poland (Ag–Cu), Mount Isa in Australia (Ag–Zn–Pb), and Kolwezi in Equatorial Africa (Co–Cu) appear to have formed without any transvaporization. Notwithstanding the presence of such supergiant deposits, approximately two-thirds of the largest global polymetallic deposits formed *via* mixing of basaltic melts with gas-saturated brines from sedimentary basins.

5. Conclusions (strategies to search for new giant ore deposits)

The connection between transvaporization and the formation of multiple giant ore deposits has implications for their exploration.

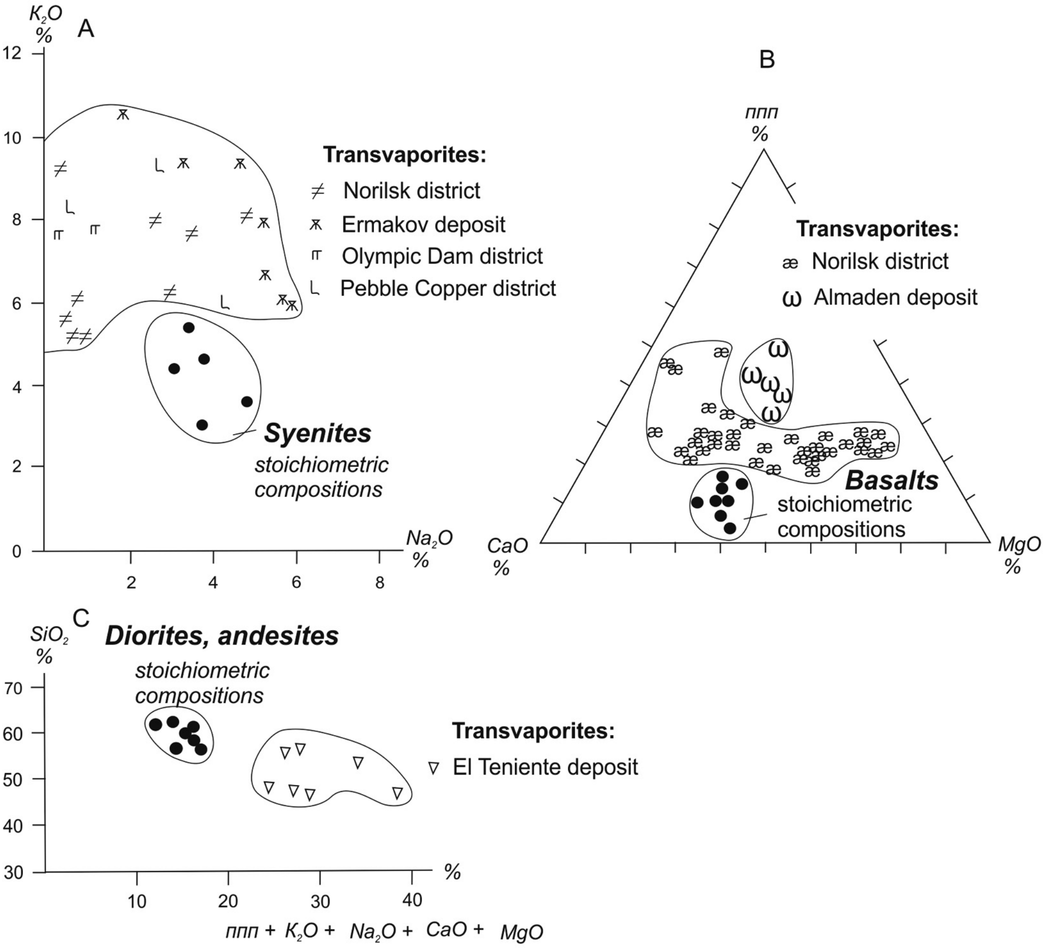


Fig. 17. The chemical compositions of different magmatic transvaporites compared with the stoichiometric compositions of the same or similar magmatic rocks. Silicate analyses were taken from the following publications: Daly (1933), Aplonov (2001), Dodin (2002), Turovtzev (2002), Bastrakov et al. (2007), Stern et al. (2007), Kupriyanova and Shpanov (2011), Goldfarb et al. (2013), Higueras et al. (2013).

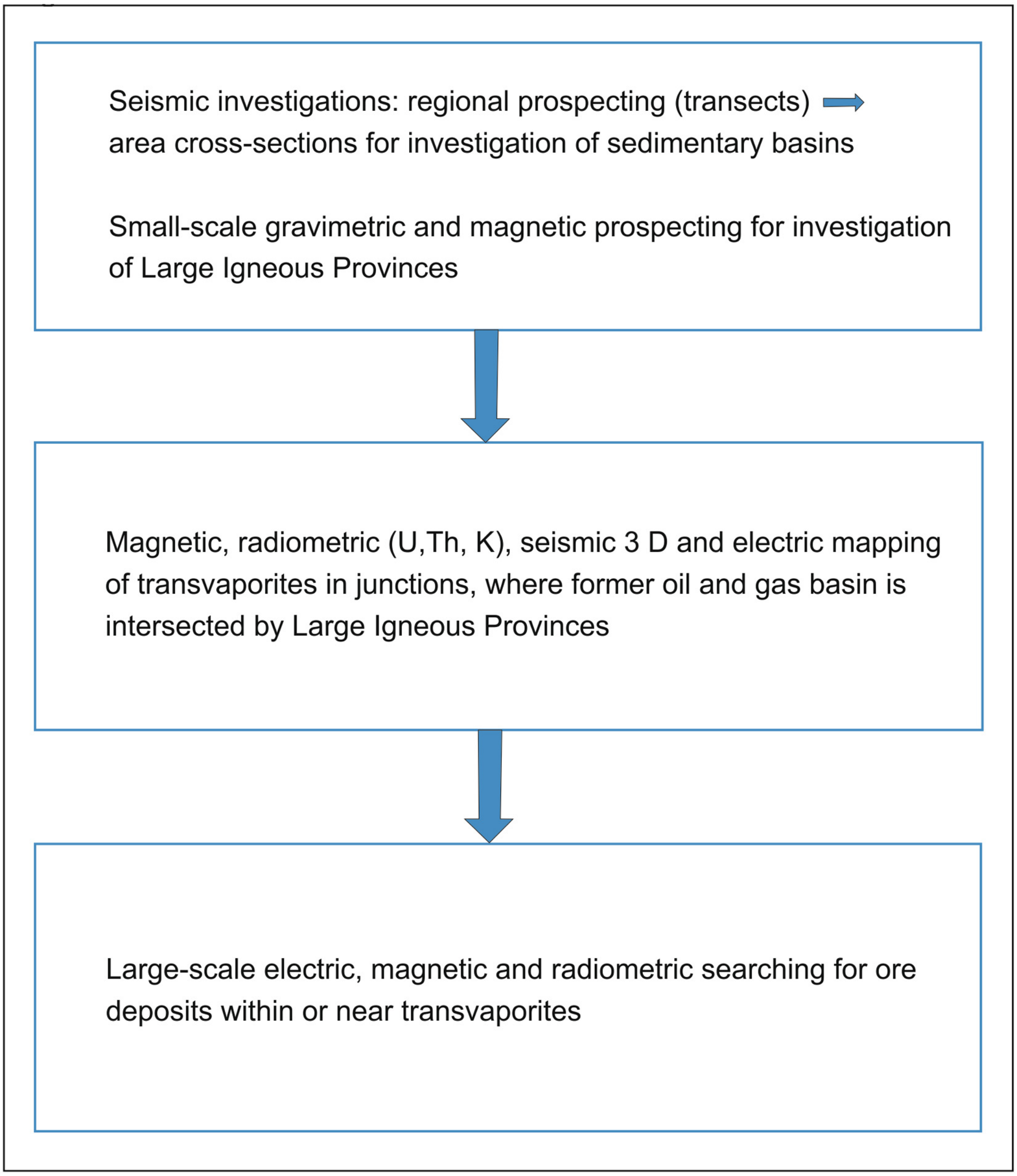
However, direct mapping of transvaporites would not be more informative than simple mapping of wall-rock alteration zones. A more suitable strategy would be to study the causes of transvaporization (i.e., the superposition of LIPs on large former oil and gas basins) (Fig. 16).

Allen and Allen (1990) and Aplonov and Lebedev (2010) have elaborated in detail on basin analysis specific for oil- and gas-rich provinces and based on seismic prospecting. Firstly, a series of regional 2D profiles (transects) are constructed, followed by a 2D grid (Fig. 18; upper rectangle), and then finally the mapping of productive reservoirs in 3D (Fig. 18; middle rectangle). These procedures for the exploration and development of hydrocarbon deposits are based on seismic stratigraphy. The method of seismic stratigraphy guides seismic prospecting using the history of each sedimentary basin, which may have experienced sedimentation cyclicity (Payton, 1976; Vail et al., 1977; Sheriff, 1980; Aplonov and Lebedev, 2010).

The same sequence of exploration procedures is required for studies of ore provinces. However, greater precision is required here, due to the substantially lower range of contrasts in the physical properties of key rock types, than would be normally conducted in seismic studies. To substantiate this, we briefly review the main exploration process used in petroleum geology, seeing it as a rehearsal of what ought to be done to guide ore exploration. Two examples of well-studied oil provinces can be used for this purpose. The first is the North Sea oil fields that are characterized by giant hydrocarbon deposits folded into large anticline structures (Dawers and John, 2000; Isaksen and Ledje, 2001; Rüpke et al., 2008; Rossland et al., 2013). The second example is the Rocky Mountains province in the USA and Canada. In the Rocky Mountains, some structurally complex regions with numerous, but usually relatively small, petroleum deposits alternate with simple (by ore deposit standards) sedimentary basins (Wood, 1994; Corbeanu et al., 2001) where superposition of intense magmatism has then led to the formation of several giant ore deposits.

The importance for future ore geology applications of the studies conducted for more than a half century in the North Sea is highlighted by numerous publications, linking the distribution of oil and gas deposits with faults (Kattenhorn and Pollard, 2001). In particular, in contrast to ore geology where faults are superimposed onto sedimentary basins by deep tectonism, studies in the North Sea have clearly demonstrated that block faulting has controlled sedimentary basin development. In the Jurassic oil- and gas-bearing sediments of the North Sea (Knott, 1993), as well as the western Siberian basin (Aplonov and Lebedev, 2010), the confinement of faults to formation boundaries has been demonstrated by many seismic and stratigraphic studies.

On a larger scale, mapping of oil and gas zones has revealed the sub-parallel spatial orientation of elongated fluvial sandstone bodies, containing oil and gas, and the grids of faults that surround the block margins (Ryseth et al., 1998; McLeod et al., 2002; Rüpke et al., 2008; Nguyen et al., 2013). Therefore, plotting faults that



Seismic investigations: regional prospecting (transects) → area cross-sections for investigation of sedimentary basins

Small-scale gravimetric and magnetic prospecting for investigation of Large Igneous Provinces

Magnetic, radiometric (U,Th, K), seismic 3 D and electric mapping of transvaporites in junctions, where former oil and gas basin is intersected by Large Igneous Provinces

Large-scale electric, magnetic and radiometric searching for ore deposits within or near transvaporites

Fig. 18. Geophysical exploration strategy to search for new giant ore deposits.

appear to control the reservoirs and isolate the hydrocarbon deposits is an efficient way to map the best oil and gas reservoirs. In general, different blocks in regions with overpressures are distinguished by diverse overpressure coefficients (Wilkinson et al., 2006; Vejbek, 2008). The former syn-sedimentary faults take part in all stages of oil and gas accumulation, and then in later destruction of the hydrocarbon deposits and formation of ore deposits.

In the Rocky Mountains, hydrocarbon accumulations are often found close to ore deposits of various ages and metal associations. In some cases, these are located in the same sedimentary sequences, and even within the same individual rocks such as, for example, carbonate. In this region, it is clear how oil and gas accumulation zones have been replaced by ore zones, as demonstrated by drilling data.

Many 3D seismic studies have been conducted in western North America due to the complicated configuration of oil reservoirs. Accordingly, many previous publications have discussed the relative roles of sedimentary factors, fracturing, and secondary alteration of rocks, in relation to the controls on porosity and permeability (Wood, 1994; Bates et al., 1999; Montgomery et al., 1999; Hennings et al., 2000; Lee and Williams, 2000; Wills, 2005; Pranter et al., 2007).

Another research direction being actively pursued in the Rocky Mountains is investigation of carbon dioxide deposits (Becker and Lynds, 2012). It is well known that such deposits are unstable in oil and gas basins, as CO_2 is rapidly (in a geological sense) consumed by reaction with aluminosilicates. Therefore, a constant CO_2 supply (usually from the basement) is required. At the same time, during accumulation of ores, carbon dioxide serves as a dominant factor in fluid mass transfer, and its deposits in (activated) oil and gas regions can serve as evidence of our model for syn-ore wall-rock alteration (Lebedev, 1992).

In such regions, or adjacent to them, overpressures are frequently observed (Lee and Williams, 2000; Wills, 2005). This increases the probability of the transvaporite process taking place. Furthermore, in the Rocky Mountains, brecciation of various sedimentary rocks due to the compressive mechanism of fluid migration can be observed (Katz et al., 2006). Combining these factors, we can reconstruct the geological history of the region, which is important for understanding transvaporization in relation with the decisive role of overpressuring. Given the widely used 3D seismic explorations (Fig. 18; middle rectangle), we can also develop a reliable strategy for using seismic data in giant ore deposit exploration (Aplonov and Lebedev, 2010).

Considerable progress has already been achieved in ore geology research in relation to the exploration of LIPs (Fig. 18; upper rectangle). In addition to geological surveys, gravity and magnetic geophysical methods are also important research tools (Schmidt et al., 1997; Clark, 1999; Anderson et al., 2013). This work can be divided into two stages, which firstly involve the general description of the LIP, and then identification of the major intrusions that have had an influence on ore genesis. We note that in two deposits reviewed in this work (Olympic Dam and Pebble Copper) magnetic surveys have already changed the methodology of ore exploration (Williams and Barton, 2005; Bastrakov et al., 2007; Skirrow et al., 2007; Anderson et al., 2013; Goldfarb et al., 2013).

Magnetite is one of the main mineral indicators of transvaporization, present in almost every deposit we have reviewed here, and typically manifests itself as a contact metasomatic phase. Metasomatism is also one of the general features of transvaporites. It is important to emphasize that magnetic studies in geophysical and petrophysical investigations of LIPs for ore exploration have been carried out for a long time (Clark, 1999), particularly for porphyry copper–molybdenum–gold ores (Schmidt et al., 1997; Sillitoe, 1997; Pollard, 2006; Astudillo et al., 2010; Goldfarb et al., 2013; Clark, 2014).

A joint analysis of all geophysical parameters combining seismic data with gravity and magnetic data will allow discovery of those nodal field zones where transvaporites are most likely to be found. The anomalous characteristics of these rocks make it possible to specify the geophysical investigations aimed directly at ore exploration (Fig. 18; lower rectangle). We emphasize that our proposal is not to search for any deposit in the hope that some will turn out to be giant deposits, but to directly target giant deposits related to transvaporization.

In summary, it is interesting to contemplate how many giant deposits remain undiscovered in the world. Aplonov and Lebedev (2010) concluded that while new oil and gas giants can possibly only be discovered in the Arctic, there are almost as many undiscovered ore deposits as there are discovered ones. Promising targets include the poorly studied Proterozoic and Early Paleozoic large former oil and gas basins, which have experienced global cyclicity, such as in eastern Siberia, Brazil, northern Canada, western Africa, China, and Middle East.

In conclusion, we have substantiated the existence of the transvaporization-driven ore genesis, confirmed the frequency of its occurrence, and underlined its importance for the generation of multiple giant ore deposits. These have led us to propose a strategy for future exploration, although much seismic prospecting needs to be carried out (along with other geophysical surveys), before a successful search for giant ore deposits can be implemented.

Acknowledgements

We wish to thank Drs. G. Lebedeva, PhD, and N. Timoshenkova, PhD for their support during the bibliographic work, and for designing the figures. Alexander Lebedev kindly assisted with editing the manuscript. We express our thanks to the geologists of Alaska, Australia, Chile, Russia, and Spain for the many publications on the ore deposits of their countries. N.G. Soudovikov is greatly acknowledged for his passionate explanation of the transvaporite model of ore genesis to us 50 years ago.

The authors do not have any financial or intellectual property related conflicts of interests. All the work has been performed by the authors in their own time, without financial support from any governmental or private charitable sources.

References

Agangi, A., Kamenetsky, V.S., McPhie, J., 2012. Evolution and emplacement of high fluorine rhyolites in the Mesoproterozoic Gawler silicic large igneous province, South Australia. Precambr. Res. 208–211, 124–144. http://dx.doi.org/10.1016/j.precamres.2012.03.011.

Alayeto, E., Louder, M.B., Louder, L., 1974. The geology and exploration potential of the heavy oil sands of Venezuela (the Orinoco petroleum belt). Can. Soc. Pet. Geol. Mem. 3, 1–18.

Allen, P.A., Allen, J.R., 1990. Basin Analysis: Principles and Application to Petroleum Play Assessment. Blackwell Scientific Publications, Oxford, p. 452.

Alsharhan, A.S., Nairn, A.E.M., 1997. Sedimentary Basins and Petroleum Geology of the Middle East. 934p. http://dx.doi.org/10.1016/B978-044482465-3/50005-X.

Anderson, D.L., 2005. Large Igneous Provinces, delamination, and Fertile Mantle. Elements 1, 271–275. http://dx.doi.org/10.2113/gselements.1.5.271.

Anderson, E.D., Hitzman, M.W., Monecke, T., Bedrosian, P.A., Shah, A.K., Kelley, K.D., 2013. Geological analysis of aeromagnetic data from southwestern Alaska: implications for exploration in the area of the Pebble porphyry Cu-Au-Mo deposit. Econ. Geol. 108, 421–436. http://dx.doi.org/10.2113/econgeo.108.3.421.

Aplonov, V.S., 2001. Termobarogeochemical model of Talnakh Pt-Cu-Ni deposit. VNIIOkeangeologiya, Saint-Petersburg, Russia. 234p (in Russian).

Aplonov, S.V., Lebedev, B.A., 2010. Ore and Hydrocarbon Accumulation: Spatial and Temporal Relation of Giant Deposits. Nauchnyi Mir Publishing House, Moscow, Russia. 224p (in Russian).

Areshev, E.G., 2003. Oil-and-Gas Potential of the Far East and Southeast Asian Marginal Seas. Avanti Publishing, House, Moscow, Russia. 288p (in Russian).

Astudillo, N., Roperch, P., Townley, B., Arriagada, C., Chauvin, A., 2010. Magnetic polarity zonation within the El Teniente copper–molybdenum porphyry deposit, central Chile. Miner. Depos. 45, 23–41. http://dx.doi.org/10.1007/s00126-009-0256-0.

Barnes, S.J., Maier, W.D., Curl, E.A., 2010. Composition of the marginal rocks and sills of the rustenburg layered suite, Bushveld Complex, South Africa: implications for the formation of the platinum-group element deposits. Econ. Geol. 105, 1491–1511. http://dx.doi.org/10.2113/econgeo.105.8.1491.

Barra, F., Alcota, H., Rivera, S., Valencia, V., Munizaga, F., Maksaev, V., 2013. Timing and formation of porphyry Cu–Mo mineralization in the Chuquicamata district, northern Chile: new constraints from the Toki cluster. Miner. Depos. 48, 629–651. http://dx.doi.org/10.1007/s00126-012-0452-1.

Bartos, P.J., 2000. The Pallacos of Cerro Rico de Potosi, Bolivia: a new deposit type. Econ. Geol. 95, 645–654. http://dx.doi.org/10.2113/gsecongeo.95.3.645.

Bastrakov, E.N., Skirrow, R.G., Davidson, G.J., 2007. Fluid evolution and origins of iron oxide Cu-Au prospects in the Olympic Dam district, Gawler Craton, South Australia. Econ. Geol. 102, 1415–1440. http://dx.doi.org/10.2113/gsecongeo.102.8.1415.

Bates, C.R., Lynn, H.B., Simo, M., 1999. The study of a naturally fractured gas reservoir using seismic techniques. Am. Assoc. Pet. Geol. Bull. 83, 1392–1407. http://dx.doi.org/10.1306/E4FD41C5-1732-11D7-8645000102C1865D.

Becker, T.P., Lynds, R., 2012. A geologic deconstruction of one of the world's largest natural accumulations of CO_2, Moxa arch, southwestern Wyoming. Am. Assoc. Pet. Geol. Bull. 96, 1643–1664. http://dx.doi.org/10.1306/01251211089.

Brobst, D.A., Pratt, W.P., 1973. United States Mineral Resources. U.S. Geological Survey Professional Paper 820. 722p.

Budd, A.R., Skirrow, R.G., 2007. The nature and origin of gold deposits of the tarcoola goldfield and implications for the Central Gawler Gold Province, South Australia. Econ. Geol. 102, 1541–1563. http://dx.doi.org/10.2113/gsecongeo.102.8.1541.

Cannell, J., Cooke, D.R., Walshe, J.L., Stein, H., 2005. Geology, mineralization, alteration, and structural evolution of the El Teniente Porphyry Cu-Mo Deposit. Econ. Geol. 100, 979–1003. http://dx.doi.org/10.2113/gsecongeo.100.5.979.

Castorina, F., Censi, P., Comin-Chiaramonti, P., Piccirillo, E.M., Neto, A.A., Gomes, C. B., de Almeida, T.I.R., Speziale, S., Toledo, M.C.M., 1997. Carbonatites from Eastern Paraguay and genetic relationships with potassic magmatism: C, O, Sr and Nd isotopes. Mineral. Petrol. 61, 237–260.

Cheng, Y., Mao, J., Yang, Z., 2012. Geology and vein tin mineralization in the Dadoushan deposit, Gejiu district, SW China. Miner. Depos. 47, 701–712. http://dx.doi.org/10.1007/s00126-012-0409-4.

Clark, D.A., 1999. Magnetic petrology of igneous intrusions: implications for exploration and magnetic interpretation. Explor. Geophys. 30, 5–26. http://dx.doi.org/10.1071/EG999005.

Clark, D.A., 2014. Magnetic effects of hydrothermal alteration in porphyry copper and iron-oxide copper-gold systems: a review. Tectonophysics 624–625, 46–65. http://dx.doi.org/10.1016/j.tecto.2013.12.011.

Cobbold, P.R., Meisling, K.E., Mount, V.S., 2001. Reactivation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil. Am. Assoc. Pet. Geol. Bull. 85, 1925–1944. http://dx.doi.org/10.1306/8626D0B3-173B-11D7-8645000102C1865D.

Coffin, M.F., Eldholm, O., 1992. Volcanism and continental break-up: a global compilation of large igneous provinces. Geol. Soc. London Spec. Publ. 68, 17–30. http://dx.doi.org/10.1144/GSL.SP.1992.068.01.02.

Cooke, D.R., Hollings, P., Walshe, J.L., 2005. Giant porphyry deposits: characteristics, distribution, and tectonic controls. Econ. Geol. 100, 801–818. http://dx.doi.org/10.2113/gsecongeo.100.5.801.

Corbeanu, R.M., Soegaard, K., Szerbiak, R.B., Thurmond, J.B., McMechan, G.A., Wang, D., Snelgrove, S., Forster, C.B., Menitove, A., 2001. Detailed internal architecture of a fluvial channel sandstone determined from outcrop, cores, and 3-D ground-penetrating radar: example from the middle Cretaceous Ferron sandstone, East-Central Utah. Am. Assoc. Pet. Geol. Bull. 85, 1583–1608. http://dx.doi.org/10.1306/8626CCCB-173B-11D7-8645000102C1865D.

Creaser, R.A., Cooper, J.A., 1993. U-Pb geochronology of middle Proterozoic felsic magmatism surrounding the Olympic Dam Cu-U-Au-Ag and Moonta Cu-Au-Ag deposits, South Australia. Econ. Geol. 88, 186–197. http://dx.doi.org/10.2113/gsecongeo.88.1.186.

Czamanske, G.K., Kunilov, V.E., Zientek, M.L., Cabri, L.J., Likhachev, A.P., Calk, L.C., Oscarson, R.L., 1992. A proton-microprobe study of magmatic sulfide ores from the Noril'sk-Talnakh district, Siberia. Can. Mineral. 30, 249–287.

Czamanske, G.K., Zen'ko, T.E., Fedorenko, V.A., King, B.W., Siems, D.F., Fries, T.L., Budahn, J.R., Calk, L.C., 1995. Petrographic and geochemical characterization of ore-bearing intrusions of the Noril'sk type, Siberia: with discussion of their origin, including additional datasets and core logs. Resour. Geol. Spec. Issue 18, 1–48.

Dallmeyer, R.D., Martinez Garcia, E., 1990. Pre-Mesozoic Geology of Iberia. Springer, Berlin, Heidelberg. http://dx.doi.org/10.1007/978-3-642-83980-1. 427p.

Daly, R.A., 1933. Igneous Rocks and the Depths of the Earth. McGraw Hill, New York, p. 598.

Davidson, P., Kamenetsky, V., Cooke, D.R., Frikken, P., Hollings, P., Ryan, C., Van Achterbergh, E., Mernagh, T., Skarmeta, J., Serrano, L., Vargas, R., 2005. Magmatic precursors of hydrothermal fluids at the rio blanco Cu-Mo deposit, Chile: links to silicate magmas and metal transport. Econ. Geol. 100, 963–978. http://dx.doi.org/10.2113/gsecongeo.100.5.963.

Davidson, G.J., Paterson, H., Meffre, S., Berry, R.F., 2007. Characteristics and origin of the oak dam East Breccia-Hosted, iron oxide Cu-U-(Au) Deposit: olympic Dam region, Gawler Craton, South Australia. Econ. Geol. 102, 1471–1498. http://dx.doi.org/10.2113/gsecongeo.102.8.1471.

Davies, J., Heaman, L.M., 2014. New U-Pb baddeleyite and zircon ages for the Scourie dyke swarm: a long-lived large igneous province with implications for the Paleoproterozoic evolution of NW Scotland. Precambr. Res. 249, 180–198. http://dx.doi.org/10.1016/j.precamres.2014.05.007.

Dawers, N.H., Underhill, G.R., 2000. The Role of Fault Interaction and Linkage in Controlling Synrift Stratigraphic Sequences: late Jurassic, Statfjord East Area, Northern North Sea1. Am. Assoc. Pet. Geol. Bull. 84, 45–54. http://dx.doi.org/10.1306/C9EBCD5B-1735-11D7-8645000102C1865D.

Deckart, K., Clark, A.H., Cuadra, P., Fanning, M., 2013. Refinement of the time-space evolution of the giant Mio-Pliocene Río Blanco-Los Bronces porphyry Cu–Mo cluster, Central Chile: new U-Pb (SHRIMP II) and Re–Os geochronology and 40Ar/39Ar thermochronology data. Miner. Depos. 48, 57–79. http://dx.doi.org/10.1007/s00126-012-0412-9.

Deckart, K., Silva, W., Spröhnle, C., Vela, I., 2014. Timing and duration of hydrothermal activity at the Los Bronces porphyry cluster: an update. Miner. Depos. 49, 535–546. http://dx.doi.org/10.1007/s00126-014-0512-9.

Dellwig, L.F., Evans, R., 1969. Depositional processes in Salina Salt of Michigan, Ohio, and New York. Am. Assoc. Pet. Geol. Bull. 53, 949–956.

Dictrich, A., Lehmann, B., Wallianos, A., 2000. Bulk Rock and Melt Inclusion Geochemistry of Bolivian Tin Porphyry Systems. Econ. Geol. 95, 313–326. http://dx.doi.org/10.2113/gsecongeo.95.2.313.

Distler, V.V., 1994. Geology and Genesis of Platinum Metals Deposits. Nauka Publishing House, Moscow. Russia. 341p (in Russian).

Distler, V.V., Lishnevsky, E.N., Sluzhenikin, S.F., Turovtzev, D.M., 2006. Geology and ore deposits of the Noril'sk district. In: 12th Quadrennial IAGOD Symposium 2006. Understanding the Genesis of Ore Deposits to Meet the Demands of the 21st Century. Moscow. Russia, pp. 91–126.

Dodin, D.A., 2002. Metallogeny of Taimyr-Norilsk Region. Nauka Publishing House, Saint-Petersburg, Russia. 822p (in Russian).

Eales, H.V., Costin, G., 2012. Crustally Contaminated Komatiite: Primary Source of the chromitites and Marginal, Lower, and Critical Zone Magmas in a Staging Chamber Beneath the Bushveld Complex. Econ. Geol. 107, 645–665. http://dx.doi.org/10.2113/econgeo.107.4.645.

Eichmann, R., Saupe, F., Schidlowski, M., 1977. Carbon and oxygen isotope studies in rocks of the vicinity of the Almaden mercury deposit (Province of Ciudad Real, Spain). In: Klemm, D.D., Schneider, H.-J. (Eds.), Time- and Strata-Bound Ore Deposits. Springer, Berlin Heidelberg, Berlin, Heidelberg, New York, pp. 396–405.

Emsbo, P., Hofstra, A.H., Lauha, E.A., Griffin, G.L., Hutchinson, R.W., 2003. Origin of high-grade gold ore, source of ore fluid components, and genesis of the meikle and neighboring carlin-type deposits, Northern Carlin Trend, Nevada. Econ. Geol. 98, 1069–1105. http://dx.doi.org/10.2113/gsecongeo.98.6.1069.

Ernst, R.E., 2007. Mafic-ultramafic Large Igneous Provinces (LIPs): importance of the pre-mesozoic record. Episodes 30, 108–114.

Ernst, R.E., Buchan, K.L., 2001. Large mafic magmatic events through time and links to mantle plume heads. Mantle Plumes Their Identification through Time - GSA Special Paper 352, 483–575. http://dx.doi.org/10.1130/0-8137-2352-3.483.

Escalona, A., Mann, P., 2006. An overview of the petroleum system of Maracaibo Basin. Am. Assoc. Pet. Geol. Bull. 90, 657–678. http://dx.doi.org/10.1306/10140505038.

Fertl, W.H., Chapman, R.E., Hotz, R.F., 1994. Studies in abnormal pressures. Develop. Petrol. Sci. 38, 454. Elsevier.

Fraser, G.L., Skirrow, R.G., Schmidt-Mumm, A., Holm, O., 2007. Mesoproterozoic gold in the central Gawler craton, South Australia: Geology, alteration, fluids, and timing. Econ. Geol. 102, 1511–1539. http://dx.doi.org/10.2113/gsecongeo.102.8.1511.

Frikken, P.H., Cooke, D.R., Walshe, J.L., Archibald, D., Skarmeta, J., Serrano, L., Vargas, R., 2005. Mineralogical and isotopic zonation in the Sur-Sur tourmaline breccia, Rio Blanco-Los Bronces Cu-Mo Deposit, Chile: implications for Ore Genesis. Econ. Geol. 100, 935–961. http://dx.doi.org/10.2113/gsecongeo.100.5.935.

Fuchs, S., Williams-Jones, A.E., Przybylowicz, W.J., 2016. The origin of the gold and uranium ores of the Black Reef Formation, Transvaal Supergroup, South Africa. Ore Geol. Rev. 72, 149–164. http://dx.doi.org/10.1016/j.oregeorev.2015.07.010.

Gartrell, A., Bailey, W.R., Brincat, M., 2006. A new model for assessing trap integrity and oil preservation risks associated with postrift fault reactivation in the Timor Sea. Am. Assoc. Pet. Geol. Bull. 90, 1921–1944. http://dx.doi.org/10.1306/06200605195.

Gauthier-Lafaye, F., Weber, F., 1989. The Francevillian (Lower Proterozoic) uranium ore deposits of Gabon. Econ. Geol. 84, 2267–2285. http://dx.doi.org/10.2113/gsecongeo.84.8.2267.

Genkin, A.D., Distler, V.V., Filimonova, A.A., 1981. Sulfide Cu-Ni ores of Norilsk deposits. Nauka Publishing House, Moscow, Russia. 234p (in Russian).

Giambiagi, L., Ghiglione, M., Cristallini, E., Bottesi, G., 2009. Kinematic models of basement/cover interaction: Insights from the Malargüe fold and thrust belt, Mendoza, Argentina. J. Struct. Geol. 31, 1443–1457. http://dx.doi.org/10.1016/j.jsg.2009.10.006.

Ginzburg, A.I., Zabolotnaya, N.P., Kupriyanova, I.I., 1977. Generation of hydrothermal deposits of beryllium. Nedra Publishing House, Moscow, Russia. 231p (in Russian).

Godlevsky, M.N., Kravtsov, G.S., Slivko, V.M., 1962. Heat transfer between intrusion and host rocks and contact thermometamorphism of coals near trap intrusions. Russ. Geol. Geophys. 2, 6–24.

Goldfarb, R.J., Anderson, E.D., Hart, C.J.R., 2013. Tectonic setting of the pebble and other copper-gold-molybdenum porphyry deposits within the evolving middle cretaceous continental margin of Northwestern North America. Econ. Geol. 108, 405–419. http://dx.doi.org/10.2113/econgeo.108.3.405.

Gong, C., Wang, Y., Zhu, W., Li, W., Xu, Q., 2013. Upper Miocene to Quaternary unidirectionally migrating deep-water channels in the Pearl River Mouth Basin, northern South China Sea. Am. Assoc. Pet. Geol. Bull. 97, 285–308. http://dx.doi.org/10.1306/07121211159.

Gubina, N.K., Berilko, G.A., 2012. The features of Mesoproterozoic deposits in Yenisei regional trough by seismic data. In: Russ. J. Geology and Mineral-Raw Resources of Siberia. Novosibirsk, pp. 62–71.

Hall, C.M., Higueras, P.L., Kesler, S.E., Lunar, R., Dong, H., Halliday, A.N., 1997. Dating of alteration episodes related to mercury mineralization in the Almaden distrist, Spain. Earth Planet. Sci. Lett. 148, 287–298. http://dx.doi.org/10.1016/S0012-821X(97)00041-1.

Hand, M., Reid, A., Jagodzinski, L., 2007. Tectonic framework and evolution of the Gawler craton, Southern Australia. Econ. Geol. 102, 1377–1395. http://dx.doi.org/10.2113/gsecongeo.102.8.1377.

Haynes, D.W., Cross, K.C., Bills, R.T., Reed, M.H., 1995. Olympic Dam ore genesis; a fluid-mixing model. Econ. Geol. 90, 281–307. http://dx.doi.org/10.2113/gsecongeo.90.2.281.

Heitt, D.G., Dunbar, W.W., Thompson, T.B., Jackson, R.G., 2003. Geology and geochemistry of the deep star gold deposit, Carlin Trend, Nevada. Econ. Geol. 98, 1107–1135. http://dx.doi.org/10.2113/gsecongeo.98.6.1107.

Hennings, P.H., Olson, J.E., Thompson, L.B., 2000. Combining outcrop data and three-dimensional structural models to characterize fractured reservoirs: an example from Wyoming. Am. Assoc. Pet. Geol. Bull. 84, 830–849. http://dx.doi.org/10.1306/A967340A-1738-11D7-8645000102C1865D.

Hernández, A., Jébrak, M., Higueras, P., Oyarzun, R., Morata, D., Munhá, J., 1999. The Almadén mercury mining district, Spain. Miner. Depos. 34, 539–548. http://dx.doi.org/10.1007/s001260050219.

Higueras, P., Munhá, J., Oyarzun, R., Tassinari, C.C.G., Ruiz, I.R., 2005. First lead isotopic data for cinnabar in the Almadén district (Spain): implications for the genesis of the mercury deposits. Miner. Depos. 40, 115–122. http://dx.doi.org/10.1007/s00126-005-0471-2.

Higueras, P., Oyarzun, R., Lillo, J., Morata, D., 2013. Intraplate mafic magmatism, degasification, and deposition of mercury: the giant Almadén mercury deposit (Spain) revisited. Ore Geol. Rev. 51, 93–102. http://dx.doi.org/10.1016/j.oregeorev.2012.12.004.

Hitzman, M.W., Oreskes, N., Einaudi, M.T., 1992. Geological characteristics and tectonic setting of proterozoic iron-oxide (Cu-U-Au-Ree) deposits. Precambr. Res. 58, 241–287.

Hodgetts, D., Imber, J., Childs, C., 2001. Sequence stratigraphic responses to shoreline-perpendicular growth faulting in shallow marine reservoirs of the Champion field, offshore Brunei Darussalam, South China Sea. Am. Assoc. Pet. Geol. Bull. 85, 433–457. http://dx.doi.org/10.1306/8626C915-173B-11D7-8645000102C1865D.

Hu, R.-Z., Bi, X.-W., Jiang, G.-H., Chen, H.-W., Peng, J.-T., Qi, Y.-Q., Wu, L.-Y., Wei, W.-F., 2012. Mantle-derived noble gases in ore-forming fluids of the granite-related Yaogangxian tungsten deposit, Southeastern China. Miner. Depos. 47, 623–632.

Hudec, M.R., Jackson, M.P.A., 2006. Advance of allochthonous salt sheets in passive margins and orogens. Am. Assoc. Pet. Geol. Bull. 90, 1535–1564. http://dx.doi.org/10.1306/05080605143.

Hunt, John M., 1991. Generation and migration of petroleum from abnormally pressured fluid compartments: reply. Am. Assoc. Pet. Geol. Bull. 75, 325–328. http://dx.doi.org/10.1306/0C9B27E5-1710-11D7-8645000102C1865D.

Hutchinson, D., Foster, J., Prichard, H., Gilbert, S., 2015. Concentration of particulate platinum-group minerals during magma emplacement; a case study from the Merensky Reef, Bushveld Complex. J. Petrol. 56, 113–159. http://dx.doi.org/10.1093/petrology/egu073.

Ianshin, A.L., Zharcov, M.A., 1977. Salt Accumulation Problems. Nauka Publishing House.

Isaksen, G.H., Ledje, H.I., 2001. Source rock quality and hydrocarbon migration pathways within the greater Utsira high area, Viking Graben, Norwegian North Sea. Am. Assoc. Pet. Geol. Bull. 85, 861–883. http://dx.doi.org/10.1306/8626CA23-173B-11D7-8645000102C1865D.

Johnson, J.P., Cross, K.C., 1995. U-Pb geochronological constraints on the genesis of the Olympic Dam Cu-U-Au-Ag deposit, South Australia. Econ. Geol. 90, 1046–1063. http://dx.doi.org/10.2113/gsecongeo.90.5.1046.

Judson, S., Richardson, S. (Eds.), 1995. Glossary of Geologic Terms. Department of Geological and Atmospheric Am. Sci.

Kalbas, J.L., Ridgway, K.D., Gehrels, G.E., 2007. Stratigraphy, depositional systems, and provenance of the Lower Cretaceous Kahiltna assemblage, western Alaska Range: Basin development in response to oblique collision. In: Special Paper 431: tectonic growth of a collisional continental margin: crustal evolution of Southern Alaska. Geological Society of America, pp. 307–343. http://dx.doi.org/10.1130/2007.2431(13).

Kamitani, M., Hirano, H., 1990. Important carbonatite-alkaline complexes and related mineral resources in the world. Bull. Geol. Surv. Jpn. 41, 631–639.

Kattenhorn, S.A., Pollard, D.D., 2001. Integrating 3-D seismic data, field analogs, and mechanical models in the analysis of segmented normal faults in the Wytch Farm oil field, southern England, United Kingdom. Am. Assoc. Pet. Geol. Bull. 85, 1183–1210. http://dx.doi.org/10.1306/8626CA91-173B-11D7-8645000102C1865D.

Katz, D.A., Eberli, G.P., Swart, P.K., Smith, L.B., 2006. Tectonic-hydrothermal brecciation associated with calcite precipitation and permeability destruction in Mississippian carbonate reservoirs, Montana and Wyoming. Am. Assoc. Pet. Geol. Bull. 90, 1803–1841. http://dx.doi.org/10.1306/03200605072.

Kelley, K.D., Lang, J.R., Eppinger, R.G., 2013. The giant pebble Cu-Au-Mo deposit and surrounding region, Southwest Alaska: introduction. Econ. Geol. 108, 397–404. http://dx.doi.org/10.2113/econgeo.108.3.397.

Khafizov, F.Z., 2012. Oil and Gas of Tyumen. Zauralye Publishing House, Tyumen. Russia. 524p.

Kiselev, A.I., Yarmolyuk, V.V., Egorov, K.N., 2009. Potassium basalts and picrobasalts from the devonian kimberlite fields of Western Yakutia, Russia, and their relations to kimberlite magmatism. In: Geol. Ore Depos. 51, 33–50. http://dx.doi.org/10.1134/S1075701509010036 (in Russian).

Klemm, L.M., Pettke, T., Heinrich, C.A., Campos, E., 2007. Hydrothermal evolution of the El Teniente deposit, Chile: porphyry Cu-Mo ore deposition from low-salinity magmatic fluids. Econ. Geol. 102, 1021–1045. http://dx.doi.org/10.2113/gsecongeo.102.6.1021.

Knott, S.D., 1993. Fault seal analysis in the North Sea. Am. Assoc. Pet. Geol. Bull. 77, 778–792. http://dx.doi.org/10.1306/BDFF8D58-1718-11D7-8645000102C1865D.

Kogarko, L.N., Ukhanov, A.V., Nicolskaya, N.E., 1994. New data about platinum group elements of ijolite-carbonatite formation: massifs Guli, Kugda, Maimecha-Kotui province, Polar Siberia. Geochem. Int. 11, 1568–1576 (in Russian).

Kolla, V., Bourges, P., Urruty, J.M., Safa, P., 2001. Evolution of deep-water Tertiary sinuous channels offshore Angola (west Africa) and implications for reservoir architecture. Am. Assoc. Pet. Geol. Bull. 85, 1373–1405. http://dx.doi.org/10.1306/8626CAC3-173B-11D7-8645000102C1865D.

Korzhinsky, D.S., 1982. Theory Metasomatic Zones. Nauka Publishing House, Moscow, Russia. 104p (in Russian).

Kozary, M.T., Dunlap, J.C., Humphrey, W.E., 1968. Incidence of Saline Deposits in Geologic Time. Special Paper 88, The Gelogical Society of America, pp. 43–58. http://dx.doi.org/10.1130/SPE88-p43.

Krasnov, S.G., Chercashev, G.A., Ainemer, A.I., 1992. Hydrothermal Sulfide Ores and Metalliferous Ocean Sediments. Nedra Publishing House, Saint-Petersburg, Russia. 278p (in Russian).

Kupriyanova, I.I., Shpanov, E.P., 2011. Russia Beryllium Deposits. GEOS Publishing House, Moscow, Russia. 353p (in Russian).

Kupriyanova, I.I., Shpanov, E.P., Galchenko, V.I., 2009. Ermackov Fluorite-Beryllium Deposit (West Trans-Baikal). VIMS Publishing House, Moscow. 309p.

Lampe, C., Song, G., Cong, L., Mu, X., 2012. Fault control on hydrocarbon migration and accumulation in the Tertiary Dongying depression, Bohai Basin, China. Am. Assoc. Pet. Geol. Bull. 96, 983–1000. http://dx.doi.org/10.1306/11031109023.

Lang, J.R., Gregory, M.J., Rebagliati, C.M., Payne, J.G., Oliver, J.L., Roberts, K., 2013. Geology and magmatic-hydrothermal evolution of the giant Pebble porphyry copper-gold-molybdenum deposit, southwest Alaska. Econ. Geol. 108, 437–462. http://dx.doi.org/10.2113/econgeo.108.3.437.

Laznicka, P., 2006. Giant metallic deposits: future sources of industrial metals, Giant Metallic Deposits: Future Sources of Industrial Metals. http://dx.doi.org/10.1007/3-540-33092-5.

Le Bas, M.J., Kellere, J., Kejie, T., Wall, F., William, C.T., Peishan, Z., 1992. Carbonatite dykes at bayan Obo, inner Mongolia, China. Mineral. Petrol. 46, 195–228.

Lebedev, B.A., 1992. Geochemistry of Epigenesis in Sedimentary Basins. Nedra Publishing House, Leningrad. Russia. 240p.

Lebedev, B.A., Pinsky, E.M., 2000. Mass transfer mechanisms of fluids and genesis of hydrocarbon and ore deposits. Russ. J. Domest. Geol. 2, 13–17 (in Russian).

Lebedev, B.A., Aristova, G.B., Bro, E.G., Kusmina, G.S., Lebedeva, G.V., Sakhibgareev, R.S., Scubelina, L.S., 1976. The role of epigenesis for parameters of reservoirs and fluidsealsproofs in West Siberian Mesozoic sediments. Nedra Publishing House, Leningrad, Russia. 132p (in Russian).

Lee, M.-K., Williams, D.D., 2000. Paleohydrology of the Delaware Basin, Western Texas: overpressure development, hydrocarbon migration, and ore genesis. Am. Assoc. Pet. Geol. Bull. 84, 961–974. http://dx.doi.org/10.1306/A9673B80-1738-11D7-8645000102C1865D.

Li, C., Ripley, E.M., Naldrett, A.J., 2003. Compositional variations of olivine and sulfur isotopes in the Noril'sk and Talnakh intrusions, Siberia: implications for ore-forming processes in dynamic magma conduits. Econ. Geol. 98, 69–86. http://dx.doi.org/10.2113/gsecongeo.98.1.69.

Lightfoot, P.C., Naldrett, A.J., Gorbachev, N.S., Fedorenko, V.A., Hawkesworth, C.J., Hergt, J., Doherty, W.V., 1994. Chemostratigraphy of Siberian trap lavas, Noril'sk district: implications for the source of floodbasalt magmas and their associated Ni-Cu mineralization. In: Sudbury – Noril'sk Symposium. Ontario Geol. Surv. Spec. 5. pp. 283–312.

Likhachev, A.P., 2006. Pt-Cu-Ni and Pt Deposits. Eslan Publishing House, Moscow, Russia. 496p.

Lunina, O.V., 2009. Prebaikal Rift Troughs: Tectonic and History of the Development. GEO Publishing House, Novosibirsk, Russia. 316p (in Russian).

Lykhin, D.A., Kostitsyin, Y.A., Kovalenko, V.I., Yarmolyuk, V.V., Sal'nikova, E.B., Kotov, A.B., Kovach, V.P., Ripp, G.S., 2001. Ore-bearing magmatism at the ermakov beryllium deposit in the Western Transbaikal Region: age, magma sources, and relationships to ore mineralization. Geol. Ore Depos. 43, 52–70 (in Russian).

Lykhin, D.A., Kovalenko, V.I., Yarmolyuk, V.V., Sal'nikova, E.B., Kotov, A.B., Anisimova, I.V., Plotkina, Y.V., 2010. The Yermakovsky beryllium deposit, Western Transbaikal region, Russia: geochronology of igneous rocks. Geol. Ore Depos. 52, 126–152. http://dx.doi.org/10.1134/S1075701510020029 (in Russian).

Macdonald, K.C., 1982. Mid-ocean ridges: fine scale tectonic, volcanic and hydrothermal processes within the plate boundary zone. Annu. Rev. Earth Planet. Sci. 10, 155–190. http://dx.doi.org/10.1146/annurev.ea.10.050182.001103.

Magoon, L.B., Dow, W.G., (Eds.) 1994. The petroleum system. In: The Pet. System – From Source to Trap. Am. Amer. Petrol. Geol. Mem. 60, pp. 3–24.

Maksaev, V., Munizaga, F., Mc Williams, M., Fanning, M., Marther, R., Ruiz, G., Zentili, M., 2004. New chronology for El Teniente, Chilean Andes, from U/Pb, 40Ar/39Ar, Re/Os and fission-track dating: implications for the evolution of a supergiant porphyry Cu-Mo deposit. Soc Econ. Geol. Spec. Publ. 11, 15–54.

Maksaev, V., Munizaga, F., Fanning, M., Palacios, C., Tapia, J., 2006. SHRIMP U-Pb dating of the Antucoya porphyry copper deposit: new evidence for an Early Cretaceous porphyry-related metallogenic epoch in the Coastal Cordillera of Northern Chile. Miner. Depos. 41, 637–644. http://dx.doi.org/10.1007/s00126-006-0091-5.

Malich, K.N., Kostoyanov, A.I., 1999. Model Re-Os age of Gulin massif platinum mineralization (North of Siberia platform). Geol. Ore Depos. 41, 143–153 (in Russian).

Mann, P., Escalona, A., Verónica, M., 2006. Regional geologic and tectonic setting of the Maracaibo supergiant basin, western Venezuela. Am. Assoc. Pet. Geol. Bull. 90, 445–477. http://dx.doi.org/10.1306/10110505031.

Matukhin, R.G., 1991. Devonian and Early Carbonic of Siberian Platform. Nauka Publishing House, Novosibirsk, Russia. 164p (in Russian).

McDonnell, A., Loucks, R.G., Galloway, W.E., 2008. Paleocene to Eocene deep-water slope canyons, western Gulf of Mexico: further insights for the provenance of deep-water offshore Wilcox Group plays. Am. Assoc. Pet. Geol. Bull. 92, 1169–1189. http://dx.doi.org/10.1306/05150808014.

McLeod, A.E., Underhill, J.R., Davies, S.J., Dawers, N.H., 2002. The influence of fault array evolution on synrift sedimentation patterns: controls on deposition in the strathspey-brent-statfjord half graben, northern North Sea. Am. Assoc. Pet. Geol. Bull. 86, 1061–1093. http://dx.doi.org/10.1306/61eedc24-173e-11d7-8645000102c1865d.

Mironov, A.G., Plusnin, A.M., 2002. Exploration of Buriatia: The Past, the Present, the Future. University of Ulan-Ude, Russia. 272p (in Russian).

Mitchum, R.M., Uliana, M.A., 1985. Seismic stratigraphy of carbonate depositional sequences, Upper Jurassic-Lower Cretaceous, Neuquen Basin, Argentina. AAPG Mem. 39 Seism. Stratigr. II An Integr. Approach to Hydrocarb. Explor. 255–274.

Montgomery, S.L., Chidsey Jr., T.C., Eby, D.E., Lorenz, D.M., Culham, W.E., 1999. Pennsylvanian carbonate buildups, Paradox basin: increasing reserves in heterogeneous, shallow-shelf reservoirs. Am. Assoc. Pet. Geol. Bull. 83, 193–210.

Naboko, S.I., 1980. The Metals of the Contemporary Hydrotherms in the Structure-Magmatic Activation Regions. Nauka Publishing House, Moscow, Russia. 198p (in Russian).

Naldrett, A.J., 2004. Magmatic Sulfide Deposits Geology, Geochemistry and Exploration. Springer, Heidelberg, Berlin, New York. http://dx.doi.org/10.1007/978-3-662-08444-1. 728p.

Nguyen, B.T.T., Jones, S.J., Goulty, N.R., Middleton, A.J., Grant, N., Ferguson, A., Bowen, L., 2013. The role of fluid pressure and diagenetic cements for porosity preservation in Triassic fluvial reservoirs of the Central Graben, North Sea. Am. Assoc. Pet. Geol. Bull. 97, 1273–1302. http://dx.doi.org/10.130e/01151311163.

Oreskes, N., Einaudi, M.T., 1992. Origin of hydrothermal fluids at Olympic Dam: preliminary results from fluid inclusions and stable isotopes. Econ. Geol. 87, 64–90. http://dx.doi.org/10.2113/gsecongeo.87.1.64.

Osborne, M.J., Swarbrick, R.E., 1997. Mechanisms for generating overpressure in sedimentary basins: a reevaluation. Am. Assoc. Pet. Geol. Bull. 81, 1023–1041. http://dx.doi.org/10.1306/E4FD2D89-1732-11D7-8645000102C1865D.

Ossandon, C.G., Freraut, C.R., Gustafson, L.B., Lindsay, D.D., Zentilli, M., 2001. Geology of the chuquicamata mine: a progress report. Econ. Geol. 96, 249–270. http://dx.doi.org/10.2113/gsecongeo.96.2.249.

Paffengoltz, K.N. (Ed.), 1978. Geological Glossary. second ed. Nedra Publishing, Moscow, Russia (in Russian).

Palero-Fernández, F.J., Martin-Izard, A., Zarzalejos Prieto, M., Mansilla-Plaza, L., 2015. Geological context and plumbotectonic evolution of the giant Almadén mercury deposit. Ore Geol. Rev. 64, 71–88. http://dx.doi.org/10.1016/j.oregeorev.2014.06.013.

Pardo, M.V., Garcia-Alcalde, J.L., 1984. Biostratigrafia del Devonico de la region de Almaden (Ciudad Real, Espana). Trab. Geol. 14, 79–120.

Pašava, J., Křibek, B., Dobeš, P., Vavřín, I., Žák, K., Delian, F., Tao, Z., Boiron, M.-C., 2003. Tin–polymetallic sulfide deposits in the eastern part of the Dachang tin field (South China) and the role of black shales in their origin. Miner. Depos. 38, 39–66. http://dx.doi.org/10.1007/s00126-002-0269-4.

Pavlis, T.L., Roeske, S.M., 2007. The Border Ranges fault system, southern Alaska. In: Special Paper 431: Tectonic Growth of a Collisional Continental Margin: Crustal Evolution of Southern Alaska. Geological Society of America, pp. 95–127. http://dx.doi.org/10.1130/2007.2431(05).

Payton, C.E., (Ed.), 1976. Seismic Stratigraphy—Applications to hydrocarbon exploration. American Association of Petroleum Geologists. Mem. 26, 516p. http://dx.doi.org/10.1306/M26490.

Peng, B., Frei, R., 2004. Nd-Sr-Pb isotopic constraints on metal and fluid sources in W-Sb-Au mineralization at Woxi and Liaojiaping (Western Hunan, China). Miner. Depos. 39, 313–327. http://dx.doi.org/10.1007/s00126-004-0409-0.

Petrov, O.V., Prasolov, E.M., Sergeev, S.A., Kapitonov, I.N., Khalenev, V.A., Gruzdov, K. A., 2011. Isotope correlations of rocks and ores in Norilsk intrusions. In: Petrov, O.V. (Ed.), Russian Platinum VII. Krasnoyarsk, Russia, pp. 467–475 (in Russian).

Pilcher, R.S., Blumstein, R.D., 2007. Brine volume and salt dissolution rates in Orca Basin, northeast Gulf of Mexico. Am. Assoc. Pet. Geol. Bull. 91, 823–833. http://dx.doi.org/10.1306/12180606049.

Pilcher, R.S., Kilsdonk, B., Trude, J., 2011. Primary basins and their boundaries in the deep-water northern Gulf of Mexico: origin, trap types, and petroleum system implications. Am. Assoc. Pet. Geol. Bull. 95, 219–240. http://dx.doi.org/10.1306/06301010004.

Pinsky, E.M., 2012. Geology and Metallogeny of the Norilsk Ore District. Guidebook: The Russian-Chinese Geological Field Trip. VSEGEI Publishing House, Saint-Petersburg, Russia, p. 35p.

Piquer, J., Skarmeta, J., Cooke, D.R., 2015. Structural evolution of the Rio Blanco-Los Bronces District, Andes of Central Chile: controls on stratigraphy, magmatism, and mineralization. Econ. Geol. 110, 1995–2023. http://dx.doi.org/10.2113/econgeo.110.8.1995.

Pirajno, F., Hoatson, D.M., 2012. A review of Australia's Large Igneous Provinces and associated mineral systems: implications for mantle dynamics through geological time. Ore Geol. Rev. 48, 2–54. http://dx.doi.org/10.1016/j.oregeorev.2012.04.007.

Plafker, G., Moore, J.C., Winkler, G.R., 1994. Geology of the southern Alaska margin. In: The Geology of Alaska: Geological Society of America. Geological Society of America, pp. 389–448.

Pletnev, P.A., Alferova, M.S., Spiridonov, E.M., 2001. Achtarandite from Talnakh region. Zap. RMO 130, 74–78 (in Russian).

Pokrovskii, B.G., Sluzhenikin, S.F., Krivolutskaya, N.A., 2005. Interaction conditions of Noril'sk trap intrusions with their host rocks: Isotopic (O, H, and C) evidence. Petrology 13, 56–80 (in Russian).

Pollard, P.J., 2006. An intrusion-related origin for Cu–Au mineralization in iron oxide–copper–gold (IOCG) provinces. Miner. Depos. 41, 179–187. http://dx.doi.org/10.1007/s00126-006-0054-x.

Pranter, M.J., Ellison, A.I., Cole, R.D., Patterson, P.E., 2007. Analysis and modeling of intermediate-scale reservoir heterogeneity based on a fluvial point-bar outcrop analog, Williams Fork Formation, Piceance Basin, Colorado. Am. Assoc. Pet. Geol. Bull. 91, 1025–1051. http://dx.doi.org/10.1306/02010706102.

Prasolov, E.M., Khalenev, V.O., Gruzdov, K.A., Sergeev, S.A., 2008. Noble gases isotopic features of mafic intrusions (Taimyr-Norilsk area) as the indicator of Cu-Ni-PGE ore accumulation scale. In: 33 IGC, MPC01220P. Oslo.

Randall, R.J.A., Saldana, A.E., Clark, K.F., 1994. Exploration in a volcano-plutonic center at Guanajuato, Mexico. Econ. Geol. 89, 1722–1751. http://dx.doi.org/10.2113/gsecongeo.89.8.1722.

Ripley, E.M., Li, C., 2013. Sulfide saturation in mafic magmas: is external sulfur required for magmatic Ni-Cu-(PGE) ore genesis? Econ. Geol. 108, 45–58. http://dx.doi.org/10.2113/econgeo.108.1.45.

Riveros, K., Veloso, E., Campos, E., Menzies, A., Véliz, W., 2014. Magnetic properties related to hydrothermal alteration processes at the Escondida porphyry copper deposit, northern Chile. Miner. Depos. 49, 693–707. http://dx.doi.org/10.1007/s00126-014-0514-7.

Rossland, A., Escalona, A., Rolfsen, R., 2013. Permian-Holocene tectonostratigraphic evolution of the Mandal High, Central Graben, North Sea. Am. Assoc. Pet. Geol. Bull. 97, 923–957. http://dx.doi.org/10.1306/12031212093.

Rundquist, D.V., Tkachev, A.V., Cherkasov, S.V., Gatinsky, I.G., Sobolev, P.O., Tikhoretsky, S.A., Romaniuk, T.V., Pavlenkova, N.I., Gorshkov, A.I., Solovov, A. A., Abramovich, I.I., Vrevsky, A.B., Khiltova, V.I., Vishnevskya, N.V., Chesalova, E. I., Arbusova, E.E., Lebedev, I.O., Kutusova, N.I., 2006. Giant ore Deposits. P.I. Global Distribution Regularity. IGEM RAN Publishing House, Moscow, Russia. 390p (in Russian).

Rüpke, L.H., Schmalholz, S.M., Schmid, D.W., Podladchikov, Y.Y., 2008. Automated thermotectonostratigraphic basin reconstruction: viking graben case study. Am. Assoc. Pet. Geol. Bull. 92, 309–326. http://dx.doi.org/10.1306/11140707009.

Ryabov, V.V., Shevko, A.Y., Zateeva, S.N., 2005. "Abnormal formations" in the Siberian platform traps – indicators of geodynamic conditions of plateau basalts forming. Russ. J. Lithosph. 4, 165–177 (in Russian).

Ryseth, A., Fjellbirkeland, H., Osmundsen, I.K., Skålnes, Å., Zachariassen, E., 1998. High-resolution stratigraphy and seismic attribute mapping of a fluvial reservoir: middle Jurassic Ness Formation, Oseberg Field. Am. Assoc. Pet. Geol. Bull. 82, 1627–1651. http://dx.doi.org/10.1306/1D9BCB5B-172D-11D7-8645000102C1865D.

Salop, L.J., 1982. Geological Evolution of the Earth During the Precambrian. Springer, Berlin Heidelberg, New York. http://dx.doi.org/10.1007/978-3-642-68684-9. 459p.

Saupe, F., 1990. Geology of the Almaden mercury deposit, Province of Ciudad Real, Spain. Econ. Geol. 85, 482–510. http://dx.doi.org/10.2113/gsecongeo.85.3.482.

Saupé, F., Arnold, M., 1992. Sulphur isotope geochemistry of the ores and country rocks at the Almadén mercury deposit, Ciudad Real, Spain. Geochim. Cosmochim. Acta 56, 3765–3780. http://dx.doi.org/10.1016/0016-7037(92)90169-J.

Schmidt, P.W., Clark, D.A., Logan, K.J., 1997. Palaeomagnetism, magnetic petrophysics and magnetic signature of the Porgera intrusive complex, Papua New Guinea. Explor. Geophys. 28, 276–280. http://dx.doi.org/10.1071/EG997276.

Shellnutt, J.G., 2014. The Emeishan large igneous province: a synthesis. Geosci. Front. 5, 369–394. http://dx.doi.org/10.1016/j.gsf.2013.07.003.

Sheriff, R.E., 1980. Seismic Stratigraphy. International Human Resources Development Corporation, Boston, p. 227.

Sillitoe, R.H., 1997. Characteristics and controls of the largest porphyry copper-gold and epithermal gold deposits in the circum-Pacific region. Aust. J. Earth Sci. 44, 373–388. http://dx.doi.org/10.1080/08120099708728318.

Skewes, M.A., Arevalo, A., Floody, R., Zúñiga, P., Stern, C.R., 2002. The Giant El Teniente Breccia deposit: hypogene copper distribution and emplacement. Soc. Econ. Geol. Spec. Publ. 9, 299–332.

Skirrow, R.G., Bastrakov, E.N., Barovich, K., Fraser, G.L., Creaser, R.A., Fanning, C.M., Raymond, O.L., Davidson, G.J., 2007. Timing of iron oxide Cu-Au-(U) hydrothermal activity and Nd isotope constraints on metal sources in the Gawler craton, South Australia. Econ. Geol. 102, 1441–1470. http://dx.doi.org/10.2113/gsecongeo.102.8.1441.

Spencer, E.T., Wilkinson, J.J., Creaser, R.A., Seguel, J., 2015. The distribution and timing of molybdenite mineralization at the El Teniente Cu-Mo porphyry deposit, Chile. Econ. Geol. 110, 387–421. http://dx.doi.org/10.2113/econgeo.110.2.387.

Spiridonov, E.M., 2010. Ore-magmatic systems of the Noril'sk ore field. Russ. Geol. Geophys. 51, 1059–1077. http://dx.doi.org/10.1016/j.rgg.2010.08.011.

Stern, C.R., Funk, J.A., Skewes, M.A., Arevalo, A., 2007. Magmatic anhydrite in plutonic rocks at the El Teniente Cu-Mo Deposit, Chile, and the role of sulphur- and copper-rich magmas in its formation. Econ. Geol. 102, 1335–1344. http://dx.doi.org/10.2113/gsecongeo.102.7.1335.

Szadeczky-Kardoss, E., 1961. Characteristic events of migration processes in the petrogenesis. In: Physical and Chemical Problems of Formation of Rocks and Ores. USSR Academy of Science, Moscow, vol. 1, pp. 88–106. (in Russian).

Tosdal, R.M., Richards, J.P., 2001. Magmatic and structural controls on the development of porphyry Cu±Mo±Au deposits. Rev. Econ. Geol. 14, 157–181.

Trop, J.M., Ridgway, K.D., 2007. Mesozoic and Cenozoic tectonic growth of southern Alaska: a sedimentary basin perspective. In: Special Paper: Tecton. Growth a Collisional Cont. Margin Crustal Evol. South-Central Alaska, 431, pp. 55–94. http://dx.doi.org/10.1130/2007.2431(04).

Turovtzev, D.M., 2002. Contact Metamorphism of Norilsk Intrusions. Nauchnyi Mir Publishing House, Moscow, Russia. 319p (in Russian).

Vail, P.E., Mitchum, R.M., Thomson, S., 1977. Relative changes of sea level from coastal onlap. Am. Assoc. Pet. Geol. Bull. 26, 63–72.

Vejbek, O.V., 2008. Disequilibrium compaction as the cause for Cretaceous-Paleogene overpressures in the Danish North Sea. Am. Assoc. Pet. Geol. Bull. 92, 165–180. http://dx.doi.org/10.1306/10170706148.

Villaseca, C., Orejana, D., Belousova, E., Armstrong, R.A., Pérez-Soba, C., Jeffries, T.E., 2011. U-Pb isotopic ages and Hf isotope composition of zircons in Variscan gabbros from central Spain: evidence of variable crustal contamination. Mineral. Petrol. 101, 151–167. http://dx.doi.org/10.1007/s00710-010-0142-6.

Von-der-Flaass, G.S., 1997. Structural and genetic model of an ore field of the Angaro-Ilim Type (Siberian Platform). Geol. Ore Depos. 39, 530–544 (in Russian).

Vry, V.H., Wilkinson, J.J., Seguel, J., Millán, J., 2010. Multistage intrusion, brecciation, and veining at El Teniente, Chile: evolution of a nested porphyry system. Econ. Geol. 105, 119–153. http://dx.doi.org/10.2113/gsecongeo.105.1.119.

Vysotsky, V.I., Isaev, E.N., Kleshchev, K.A. (Eds.), 1995. World Map of Oil and Gas Basins. Scale: 1:15 000 000. Rus. Inst. VNIIzarubezhgeologia, Moscow, Russia. (in Russian).

Wade, C.E., Reid, A.J., Wingate, M.T.D., Jagodzinski, E.A., Barovich, K., 2012. Geochemistry and geochronology of the c. 1585Ma Benagerie Volcanic Suite, southern Australia: Relationship to the Gawler Range Volcanics and implications for the petrogenesis of a Mesoproterozoic silicic large igneous province. Precambr. Res. 206–207, 17–35. http://dx.doi.org/10.1016/j.precamres.2012.02.020.

Warnaars, F.W., Holmgren, D.C., Barassi, F.S., 1985. Porphyry copper and tourmaline breccias at Los Bronces-Rio Blanco, Chile. Econ. Geol. 80, 1544–1565. http://dx.doi.org/10.2113/gsecongeo.80.6.1544.

Wei, W., Hu, R., Bi, X., Peng, J., Su, W., Song, S., Shi, S., 2012. Infrared microthermometric and stable isotopic study of fluid inclusions in wolframite at the Xihuashan tungsten deposit, Jiangxi province, China. Miner. Depos. 47, 589–605. http://dx.doi.org/10.1007/s00126-011-0377-0.

White, D.E., Hutchinson, R.A., Hutchinson, K., Terry, E.C., 1988. The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park, Wyoming. U.S. Geological Survey Professional Paper 1456, 84p.

White, S.H., de Boorder, H., Smith, C.B., 1995. Structural controls of kimberlite and lamproite emplacement. J. Geochem. Explor. 53, 245–264. http://dx.doi.org/10.1016/0375-6742(94)00033-8.

Wignall, P., 2005. The link between large igneous province eruptions and mass extinctions. Elements 1, 293–297. http://dx.doi.org/10.2113/gselements.1.5.293.

Wilkinson, B.H., Kesler, S.E., 2009. Quantitative identification of metallogenic epochs and provinces: application to phanerozoic porphyry copper deposits. Econ. Geol. 104, 607–622. http://dx.doi.org/10.2113/gsecongeo.104.5.607.

Wilkinson, M., Haszeldine, R.S., Fallick, A.E., 2006. Hydrocarbon filling and leakage history of a deep geopressured sandstone, Fulmar Formation, United Kingdom North Sea. Am. Assoc. Pet. Geol. Bull. 90, 1945–1961. http://dx.doi.org/10.1306/06270605178.

Williams, P., Barton, M., 2005. Iron oxide copper-gold deposits: geology, space-time distribution, and possible modes of origin. Econ. Geol. Anniversary 371–405. http://dx.doi.org/10.5382/AV100.13.

Wills, S., Anders, M.H., Christie-Blick, N., 2005. Pattern of Mesozoic thrust surfaces and Tertiary normal faults in the Sevier Desert subsurface, west-central Utah. Am. J. Sci. 305, 42–100. http://dx.doi.org/10.2475/ajs.305.1.42.

Witte, J., Bonora, M., Carbone, C., Oncken, O., 2012. Fracture evolution in oil-producing sills of the Rio Grande Valley, northern Neuquén Basin, Argentina. Am. Assoc. Pet. Geol. Bull. 96, 1253–1277. http://dx.doi.org/10.1306/10181110152.

Wood, S.H., 1994. Seismic expression and geological significance of a lacustrine delta in neogene deposits of the western Snake River Plain, Idaho. Am. Assoc. Pet. Geol. Bull. 78, 102–121. http://dx.doi.org/10.1306/BDFF9028-1718-11D7-8645000102C1865D.

Wu, C., Gu, L., Zhang, Z., Ren, Z., Chen, Z., Li, W., 2006. Formation mechanisms of hydrocarbon reservoirs associated with volcanic and subvolcanic intrusive rocks: examples in Mesozoic-Cenozoic basins of eastern China. Am. Assoc. Pet. Geol. Bull. 90, 137–147. http://dx.doi.org/10.1306/07130505004.

Zabaluev, V.V. (Ed.), 1980. Geology, Oil and Gas of East Siberia Sedimentary Basins. Nedra Publishing, Leningrad, Russia. 200p. (in Russia).

Zou, C., Yang, Z., Dai, J., Dong, D., Zhang, B., Wang, Y., Deng, S., Huang, J., Liu, K., Yang, C., Wei, G., Pan, S., 2015. The characteristics and significance of conventional and unconventional Sinian-Silurian gas systems in the Sichuan Basin, central China. Mar. Pet. Geol. 64, 386–402. http://dx.doi.org/10.1016/j.marpetgeo.2015.03.005.

Further reading

Ehsan, S.A., Carbonell, R., Ayarza, P., Martí, D., Pérez-Estaún, A., Martínez-Poyatos, D. J., Simancas, J.F., Azor, A., Mansilla, L., 2014. Crustal deformation styles along the reprocessed deep seismic reflection transect of the Central Iberian Zone (Iberian Peninsula). Tectonophysics 621, 159–174. http://dx.doi.org/10.1016/j.tecto.2014.02.014.

Hawkesworth, C.J., Wooden, J.L., Ebel, D., 1996. Petrogenesis of the floodbasalt sequence at Noril'sk, north central Siberia. Int. Geol. Rev. 38, 99–135.

Hunt, G.M., 1990. Generation and migration of petroleum from abnormally pressured fluid compartments. Am. Assoc. Pet. Geol. Bull. 74, 1–12.