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The Polymetallic Deposits of the Western European Plate and Structure of the Earth's Crust According to GOCE Gravity Data

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Abstract: For the first time, the results of modern studies of the earth's crust based on gravity data from the GOCE satellite Project are used for a comparative regional metallogenic analysis of the geodynamic settings of the formation of polymetallic deposits in Western Europe and the Mediterranean segment of the Tethys belt. It is shown that exhalative sulfide deposits (SEDEX) and cuprous sandstones and shales (SSC) are mainly located in the earth's crust with a predominant development of the lower "basalt" layer of the earth's crust. Pyrite copper and lead-zinc deposits in volcanogenic rocks (VMS), as well as some occurrences of the SEDEX type, are found in supra-subduction island-arc and accretionary crustal settings with a predominant development of the middle "granite" layer. Lead-zinc ores of the Mississippi type (MVT) are localized in deep pericratonic sedimentary basins with petroleum-bearing specialization on the shelf and continental slope, regardless of the stratification of the earth's crust. The results obtained can be used for regional forecasting and metallogenic constructions, prospecting and assessment of new deposits.

Keywords: Western Europe, Tethys, lithosphere, Earth's crust, base metal, deposit, SEDEX, MVT, VMS, SSC.

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Research Article

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1. Introduction

Lead-zinc deposits, widespread in the world, are one of the most important sources of strategic metals: Cu, Pb, Zn, Ag, Au, PGE, Te, Se, Ge, Ga, Bi, Cd, In, Re, REE [*Bortnikov et al.*, 2016; *Galyamov et al.*, 2021]. Such large Pb-Zn deposits are known in the world as Red Dog, Green Creek (Alaska, USA), Selwyn, Howard Pass, Pine Point (Canada), Broken Hill, McArthur River (Australia), Sullivan, Kidd Creek, Faro, Brunswick in Canada, Citronen in Greenland, Rio Tinto in Spain, Falun in Sweden, Anguran in Iran, Kholodninskoye, Ozernoye, Sardana and Pavlovskoye in Russia, as well as many others. The bulk of the world's reserves of lead and zinc (60%) are in pyrite-polymetallic deposits in terrigenous and carbonate-terrigenous formations (SEDEX type); reserves of lead-zinc deposits in carbonate formations (MVT type) and pyrite-polymetallic deposits in volcanogenic formations (VMS type) are about 20% each [*Dergachev and Eremin*, 2008]. Moreover, more than 40% of the reserves and about half of the resources come from SEDEX-type objects in Precambrian rocks.

In Western Europe, about four hundred lead-zinc and copper objects are known, including two dozen large deposits. Pyrite deposits are located in the Caledonides and Alps-Kristineberg, Garpenbergsfaltet, Renstrom, Boliden (Sweden), Rammelsberg (Germany), Rio Tinto, Angostura (Spain), Horni Kalna, Kostalov (Czech Republic). Stratiform deposits are known in the Hercynian and Alpine complexes of Poland (Upper Silesia, Miedziana, Pomorzany, etc.), Italy (Iglesiente), Sweden (Horntraskviken, etc.), Ireland (Navan, etc.) (Figure 1). Vein polymetallic (including silver) deposits are located in the Alpides and Hercynides of Bulgaria (Madan, etc.), North Macedonia (Sasa, etc.), Slovakia (Banska Stiavnica, etc.), France (L'Argentiere, etc.)

The origin of large concentrations of base metals and, especially, their sources are of great interest for forecasting and identifying new deposits. Modern forecasting and metallogenic studies are impossible without Earth remote sensing materials; generalization and analysis of geological, geotectonic, geochemical and other spatial data, as well as information on metallogeny [*Volkov et al.*, 2020].

Previous studies [*Blundell et al.*, 2007] show that the location of polymetallic deposits in Europe is closely related to geodynamic settings that correspond to deep processes in the earth's crust-subduction, rifting and orogenesis. The features of the deep structure of the earth's crust are of significant interest to study the geodynamic conditions of the formation of deposits in the lithosphere. This article used a global geophysical model of the earth's crust, the CRUST1.0 model, compiled from the results of remote gravitational measurements from space within the framework of the GOCE project [*Laske et al.*, 2013; *Reguzzoni and Sampietro*, 2015]. The modern ideas about the structure and geodynamic development of the earth's crust were taken into account.

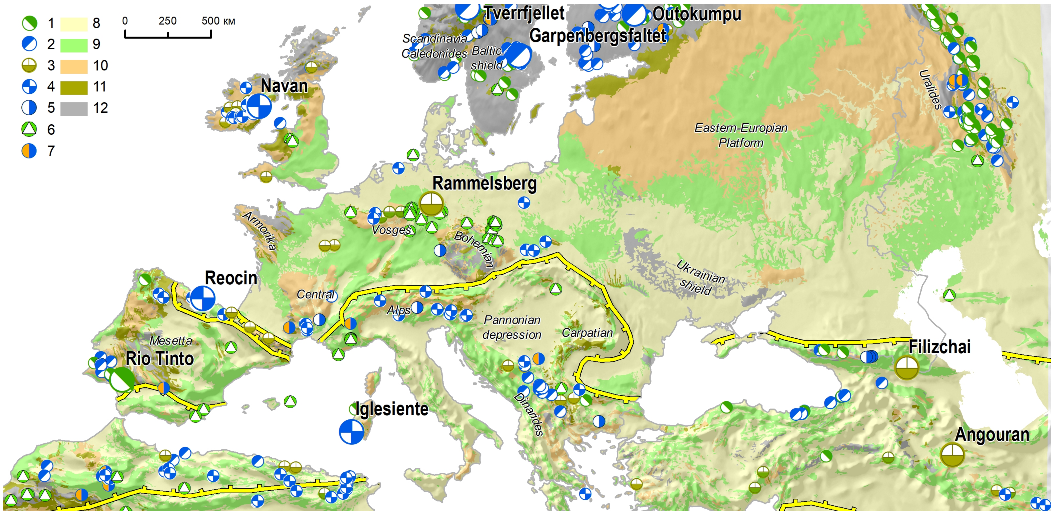


Figure 1. Location of polymetallic deposits in Europe (based on materials from [*Asch*, 2003]).
1–7 – Types of deposits: 1 – copper-pyrite in volcanogenic-sedimentary rocks, 2 – lead-zinc volcanic-carbonate stratiform, 3 – pyrite-polymetallic in terrigenous rocks, 4 – lead-zinc stratiform in carbonate rocks, 5 – polymetallic vein, 6 – cuprous sandstones and shales, 7 – silver-polymetallic vein.
8–12 – Age of geological formations: 8 – Cenozoic, 9 – Mesozoic, 10 – late Paleozoic (D-P), 11 – early Paleozoic (Cm-S), 12 – Precambrian.

This article continues the study of global and regional trends of location of lead-zinc deposits [*Galyamov et al.*, 2021, 2022, 2023] and focuses on the spatial relationships of polymetallic ores and features of the deep structure of the earth's crust within Western Europe and the Mediterranean segment of the Tethys belt.

2. Model of the deep structure of the Earth's crust CRUST1.0

Currently, a huge amount of material has been accumulated as a result of seismic studies of the earth's crust using the DSS (deep seismic sounding) and MOV-CDP (reflected wave – common depth point) methods. The DSS method makes it possible to determine the thickness of the earth's crust, identify seismic boundaries, deep faults, etc. in its thickness. In Western Europe, seismic studies at the end of the last century were carried out on a variety of profiles with an average profile density (4.5 linear km) per thousand km^2, providing study of the earth's crust and upper mantle [*Fountain et al.*, 1993; *Hasterok et al.*, 2022].

Currently, one of the most complete and spatially distributed modern systems of remote sensing data on the earth's crust, based on measurements over a uniform network, are the results of space gravimetric measurements under the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) project. The GOCE spacecraft (weighing 1 ton) was launched from the Russian Plesetsk cosmodrome by the Rokot launch vehicle into low-Earth sun-synchronous orbit on March 17, 2009. GOCE is a satellite of the European Space Agency (ESA), combining gravity reconnaissance and GPS tracking to determine the average gravitational field of the Earth with unprecedented accuracy and spatial resolution [*Klyuykov*, 2018]. To ensure the highest possible accuracy of measurements, a very low orbit was chosen – 260 km above the Earth's surface.

Based on the results of the GOCE mission, the shape of the planet was determined in more detail, the gravitational force in various regions and the density of the Earth's crust were measured, and a new global gravitational map of the Earth was compiled. The maximum resolution of GOCE gravimetry is 50 km; in general, for many parameters, the resolution is 100 km. But the GOCE equipment made it possible to measure field values over a uniform network, which made it possible to build global models of seismic surfaces, and additional parameters - a rheological model of the upper mantle to a depth of 100 km.

The gravimetric data stimulated the development of global models of the deep structure of the earth's crust and upper mantle (GEMMA1.0, CRUST1.0), which contributed to the understanding of the metallogenic specialization of large ore regions and provinces. The GEMMA (GOCE Exploitation for Moho Modeling and Applications) project, also funded by ESA, based on GOCE data, carried out an updated assessment and significantly detailed the boundaries of the Moho [*Reguzzoni and Sampietro*, 2015].

The global model CRUST1.0 is based on a uniform one-degree network and is the most complete and combines data on the depth of the Moho (half-degree network GEMMA), a three-layer sedimentary cover, as well as the upper, middle and lower layers of the consolidated crust [*Laske et al.*, 2013]. We used this model to explain the spatial patterns of the location of polymetallic deposits in the structure of the earth's crust. In addition, the GEMMA model was used – the density and thermal regime of the upper mantle [*Cammarano and Guerri*, 2017]. According to the model, the total thickness of the earth's crust on the continents ranges from 16 km to 72 km. On 95% of the area of all continents, the thickness of the continental crust varies in the range of 22–57 km.

The sedimentary cover forms the uppermost layer of the earth's crust [*Laske et al.*, 2013]. Its thickness varies from zero on shields to more than 20 km in deep sedimentary basins. The rocks of the sedimentary cover are often metamorphosed and seismically indistinguishable from the crystalline basement rocks. In many regions, metamorphosed Paleozoic sediments are included in the upper crystalline crust. The upper horizon, up to 2 km thick, represented by the least dense and weakly metamorphosed sedimentary complexes, has the widest distribution (more than 500 million km^2), occupying vast oceanic spaces. Its complexes make up individual deep troughs confined to oil and gas provinces (for example, the North Sea-German, Cis-Carpathian, Transylvanian, etc.). In general, hydrocarbon specialization is much weaker in the oceanic and continental sediments of this horizon [*USGS*, 2012].

Oil and gas bearing formations are most often confined to the deepest parts of the sedimentary crust, to areas of development of strata of the middle and lower horizons. The middle horizon, up to 4 km thick, has a relatively smaller distribution (about 100 million km^2) and covers many hydrocarbon provinces (the Arabian Peninsula, South America, Western Siberia, etc.) and their frame. The lower horizon of the sedimentary layer of the lithosphere, the least widespread in the world (less than 20 million km^2), is composed of the most powerful complexes (over 14 km), to which the central sections of the large hydrocarbon provinces of the world are confined.

The consolidated crust, according to the CRUST1.0 model, consists of three layers. The upper and middle layers of the continental crust are composed mainly of metamorphic complexes, gneisses, granites and granodiorites. The boundary between the upper "metamorphic" and middle "granite" layers is often conditional and runs along the velocity section of about 6.3 km/s. The lower "basaltic" crust is believed to be composed of rocks of the amphibolite facies, although it is possible that the lower crust may be composed of andesites and dacites [*Hacker et al.*, 2015].

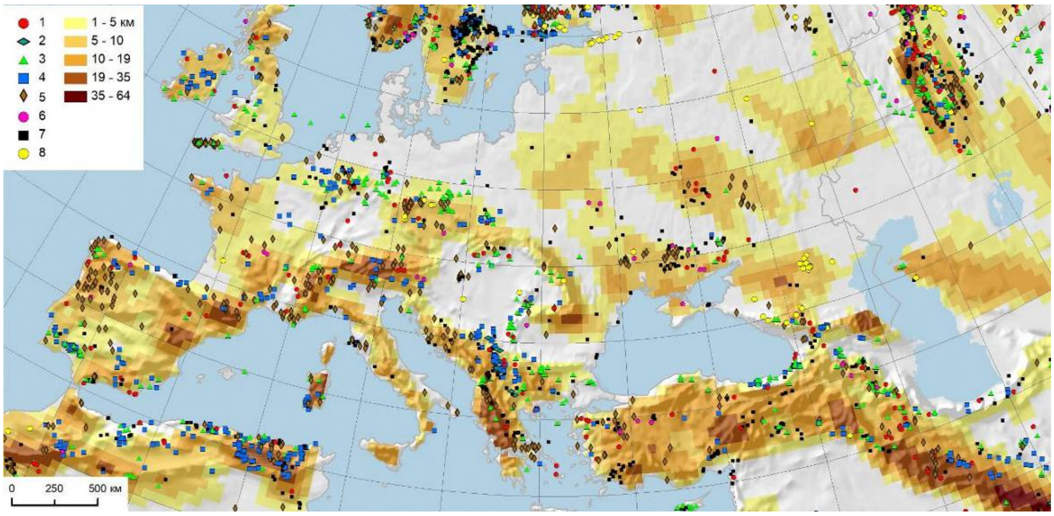


Figure 2. Local thickening of the earth's crust (in km) and location of ore deposits (using materials from [*Laske et al.*, 2013]).
1–8 – deposits: 1 – precious metals, 2 – copper-nickel, 3 – copper, 4 – lead-zinc, 5 – base (W, Sn, etc.), 6 – rare, 7 – ferrous and 8 – radioactive metals.

Seismological and geological-geophysical studies have shown that the lower, middle and upper layers of the consolidated crust are inconsistent in thickness. The deformation of the crustal layers is expressed in the form of contrasting protrusions and depressions of the Moho surface, anomalous swelling and thinning of the lower and middle crust. Among such deep areas, geodynamic areas of different ranks and different types according to the mechanism of formation are distinguished. They are associated with mantle processes, on the one hand, and tectonic horizontal movements during the interaction of lithospheric plates and terranes. Mantle processes, the trigger of the geodynamic situation in the near-surface region of the crust, cause new deformations in the latter, expressed by uplifts, troughs and flexures.

Local thickenings – structures of the second and higher orders, are reflected on maps in the form of stripes and individual areas (Figure 2), identified by calculating average values in a sliding window. Local areas of increased thickness are clearly distributed throughout the world, often have linear outlines and most likely highlight the nature of plate interactions. The thickening of the crust reflected in the seismic section is explained as a result of the decompression of the upper mantle material and the corresponding lowering of its upper boundary.

Local thickening of the earth's crust and its layers is characterized by variability. Sharp variability is often explained by the block structure of the section, features of rifting and other tectonic and rheological reasons and is revealed by a sharp change in the slope of the Moho surface. General spatial statistics show that within zones of local crustal thickening, significantly more than half of all the world's deposits and occurrences of noble, non-ferrous, rare, ferrous and radioactive metals are located.

3. Deep structure of the Earth's crust of Western Europe and location of polymetallic deposits

The Western European young platform has, in general, a Paleozoic folded basement and a Mesozoic-Cenozoic cover. It is characterized by a distinct block structure: massifs (Bohemian, Rhine, Armorican, Central), ancient protrusions (Harz, Vosges, Black Forest) and superimposed depressions (Polish-German, North German, Parisian, Aquitaine, Thuringian, Sub-Hercynian).

Cenozoic (Rhine) and Mesozoic (North Sea) intracratonic rift systems are developed. The largest oil and gas deposits are associated with the latter, and deposits of rock and potassium salts are confined to the fields of development of Late Permian deposits, and deposits of hard and brown coal are confined to the Carboniferous, Permian and Neogene territories.

The crust of Western Europe differs from the crust of the East European Platform [*Belousov and Pavlenkova*, 1989; *Galyamov et al.*, 2023]. Its greatest thickness (average 30 km) does not exceed 48 km compared to 57 km (average 39 km) in the east of the European continent. Average speeds there are also somewhat lower: 6.3–6.4 km/s compared to 6.5–6.6 km/s on the ancient platform. The consolidated crust is divided into three layers – upper ("granite-gneiss"), middle ("granite") and lower ("mafic"). A feature of the crust of Western Europe is the reduced average thickness of its layers and significant stratification of the lower layer (based on materials from CDP profiles). Spatial analysis also shows that the ancient highs (Bohemian, Armorican and Central) are confined to areas of thickened lower "mafic" layer of the crust, while areas of the Alpine orogeny are spatially associated with areas of increased thickness of the upper (Pontids and Taurids in Turkey) and, in part, middle layer.

The basement of the Western European Platform was formed during the Baikal, Caledonian and Hercynian eras of orogenesis (Figure 3). Ancient consolidated elements of the earth's crust, complicated by the development of rift structures, repeatedly experienced orogenesis; ultimately, the age and contours of the main geodynamic regions of Western and Central Europe are determined by recent orogenic processes that caused extensive metamorphic restructuring and magmatism [*Plant et al.*, 2005]. In the areas of the British Isles, the North Sea and the Norwegian Sea shelf, the northern part of the North German Basin and the border of the East European Platform, the basement is Caledonian age mainly.

In the southern part of the platform, the basement in the form of protrusions (Armorican, Central, Vosges, Black Forest and Bohemian massifs) is composed of Hercynian complexes. These formations also compose Ardennes, the Rhine Slate Mountains, Harz, Thuringian Forest, Ore Mountains, Sudetenland, and in the western and central parts of the Iberian Peninsula [*Plant et al.*, 2005]. The development of Cenozoic extended grabens of the European rift system, 1100 km long, in the Alpine foreland complicates the modern tectonic activity of the Hercynides. The Rhine Grabens remain seismically active currently.

Polymetallic deposits are unevenly distributed in the geological structure (Figure 3). In general, on the territory of Western Europe, within volcanic and magmatic arcs, the VMS deposits of Sweden (Renstrom, Kristineberg, Boliden, etc.) and Finland (Pyhasalmi, Outokumpu, Vihanti, Pirttilampi, Verttuunjärvi, Korppisjärvi, Muittari, etc.) predominate (more than 30% of the number of polymetallic occurrences).

In orogenic areas, VMS pyrite-volcanogenic deposits (more than 20%) of Norway (Tverrfjellet, Fosdalen, Sel, Nordre Gjetryggen, Grimsdalen, etc.) and Spain (Arinteiro, Bama, Filon Sur-Esperanza, Vuelta Falsa, etc.) are predominantly widespread, as well as exhalative (about 15%) deposits (Germany – Rammelsberg, Meggen, etc.). Next to them, in the clastic and clay redbed facies, there are stratiform deposits of cuprous sandstones and shales (SSC) – in Germany (Leitmar, Korbach, Konrad), in Poland (Lubin, Malomice), in Spain (Granada, Menorca, Santomera) , in France (Bancairon, Cap Garonne, Cerisier).

Carbonate formations of the Paleozoic basement and Mesozoic-Cenozoic cover contain MVT type deposits (about 15%) in Ireland (Navan, Abbeytown, Ballinalack, Tatestown, etc.),

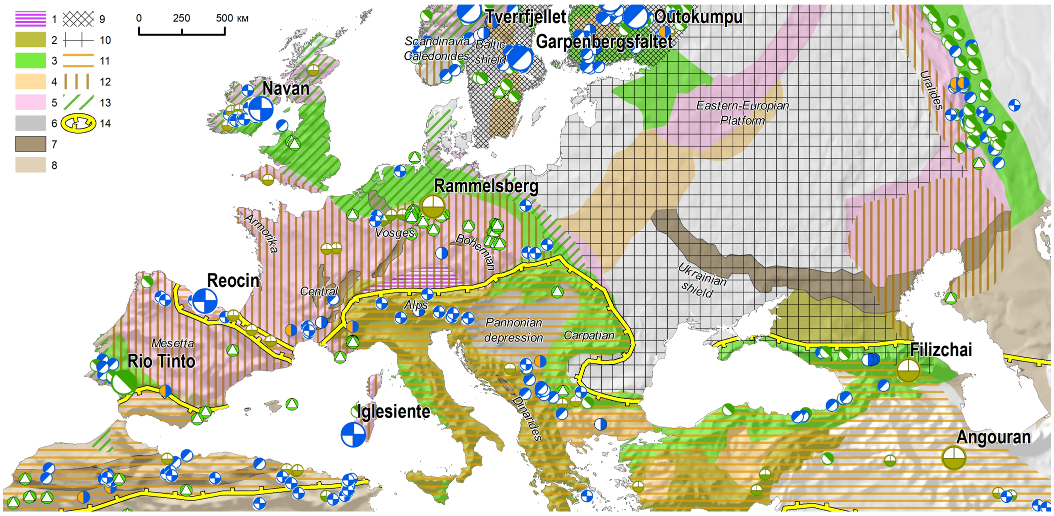


Figure 3. Location of polymetallic deposits and geodynamic regions of Europe (based on materials from [*Hasterok et al.*, 2022; *Richards*, 2015]).
1 – foredeeps, 2 – accretionary complexes, 3 – island arcs, 4 – magmatic arcs, 5 – orogenic belts, 6 – superimposed basins, 7 – rifts, 8 – passive margin, 9 – shields, 10 – cratons; 11–13 – age of orogenesis: 11 – Alpides (Ap, MZ-KZ basins), 12 – Hercynides (Hz, Hz+Ap), 13 – Caledonides (Kd); 14 – contours of the Tethys belt.

Belgium (Verviers), Poland (Upper Silesian basin, Pomorzany), Spain (Reocin, Rubiales, Picos de Europa, Troya). Some small this type deposits occur in Early Paleozoic formations on the periphery of the Hercynian block massifs (Central French, Mesetta, Czech, etc.). The stratiform occurrencesare mostly transformed into skarnoids (Svardsjo, Lovasfaltet, Kalvbacksfaltet).

Within shields with a Precambrian age of orogenesis, there are predominantly copper and polymetallic VMS deposits (more than 30%), occurring in ancient metamorphosed island-arc volcanogenic-sedimentary deposits and metamorphic complexes of volcanic and magmatic arcs (Kristineberg, Renstrom, Boliden, Outokumpu, Vihanti, etc.) .

The depth of the Moho surface within the Precambrian protrusions of the Baltic Shield fluctuates on average about 44 km (Figure 4), the maximum value is 48–50 km, the temperature of the upper mantle at a depth of 60 km is reduced to 500 °C [*Reguzzoni and Sampietro*, 2015].

The concentration of pyrite volcanogenic deposits in Sweden and Finland occurs in areas of the thickened upper “metamorphic” layer of the consolidated crust, as well as in areas of increased thickness of the middle layer and decreased thickness of the lower layer. Similar patterns of crustal structure and placement of VMS ores are also noted in the frame of the East European and Siberian platforms [*Galyamov et al.*, 2023]. This feature of the deep structure of the earth's crust is also observed in the Norwegian Caledonides zone in the north of the Scandinavian Peninsula.

In the areas of the Caledonian orogeny of Europe, pyrite-base metal VMS ores occur mainly in metamorphosed complexes of Norway (Bjornefjell, Espelandsmyr, Solberg, etc.) and Sweden (Fosdalen, Joma, Grimeli, Rostvangen, Hersjo, Killingdal, etc.). Along with them, isolated SEDEX pyrite exhalation occurrences are known (Laisvall in Sweden, Mofjellet and Bleikvassli in Norway, Ben Eagach in Great Britain, etc.), occurring in terrigenous and carbonate formations of the Riphean-Vendian and Early Paleozoic, as well as stratiform MVT deposits of Ireland (Navan, Gortdrum, Garrycam, Abbeytown, Ballinalack, etc.). The depth of the Moho here is characterized by shallower depths within 20 km on the Iberian Peninsula and 32–38 km on the British Isles and Norway (Figure 4), while the temperature of the upper mantle at a depth of 60 km is increased to 900–1000 °C [*Reguzzoni and Sampietro*, 2015].

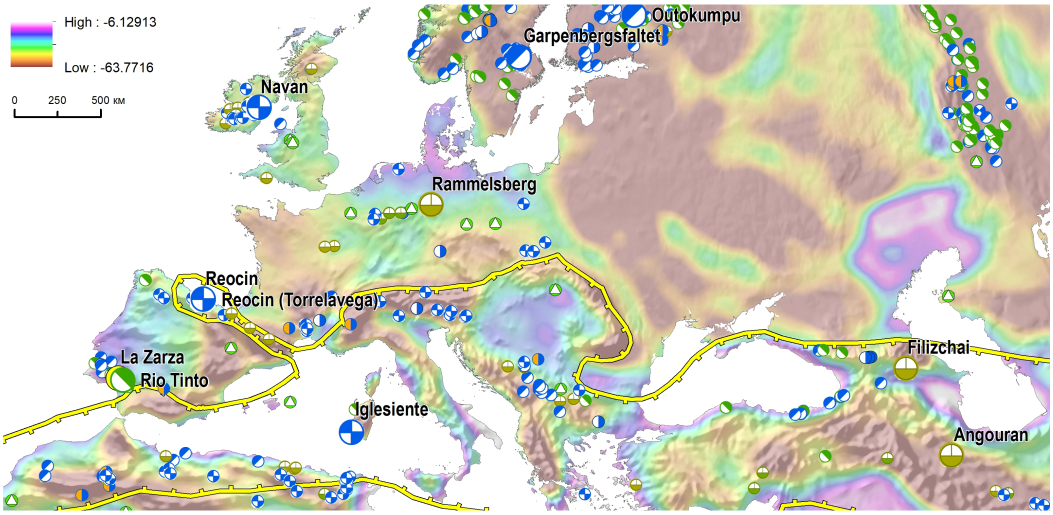


Figure 4. Polymetallic deposits of Western Europe and Moho depth in km (based on materials from [*Reguzzoni and Sampietro*, 2015]). Symbol see Figure 1, Figure 3.

VMS-type deposits predominate both in areas of the Hercynian volcanic belts (Spain – Angostura, Rio Tinto, Cueva de la Mora, San Telmo, San Miguel, etc.) and in accretionary complexes of supra-subduction zones (Serbia – Zimovnik, Tisovik, Brskovo Zuta Prla, Koporic, etc.).

The Iberian (Iberian) pyrite belt is one of the world's largest concentrations of volcanogenic deposits of non-ferrous metals – Angelita, Esperanza and San Miguel. Polymetallic mineralization here was probably formed under pre-arc extensional conditions [*Blundell et al.*, 2007]. Previous collisional and lateral movements contributed to the opening of weakened zones in the earth's crust, where deep magmas and anomalous heat flows were intruded. Large pyrite-volcanogenic deposits formed in the back-arc basins at the epicenter of these anomalies. The most intense metal content of the belt appeared with the end of syn-collisional extension, immediately before post-collisional extension during granulitization of the lower crust. The most likely source of metals is lower crustal granulites [*Blundell et al.*, 2007].

In the Hercynides of Central Europe, especially in areas of widespread development of rift structures (Rhine Grabens, Vosges, Hesse and Eger), exhalation SEDEX deposits of Germany (Rammelsberg, Meggen, etc.), France (Bodennec, Porte Aux Moines) and occurrencea of cuprous sandstones and SSC type shales – Konrad, Korbach, etc. (Germany), Nowy Kosciol, Sierozovice, etc. (Poland) and France (Cerisier, Giordannet, Liouc, etc.). This also includes numerous hydrothermal polymetallic deposits associated with the Hercynian and younger granite intrusions of the Rudnoga polymetallic province.

Of the Mississippian-type deposits in Paleozoic and Mesozoic carbonate rocks, the French Villemagne and Malines, the Spanish Antonina and Rubiales, karst-type deposits (Iglesiente and Monteponi in Italy, Upper Silesian objects in Poland, the Belgian Pb-Zn deposit Schmalgraf, as well as lead-zinc deposits in Ireland) are known .

The Irish Navan, Tynagh, Silvermines, Lisheen and Galmoy deposits, which occur in Early Carboniferous carbonate layers, contain a large number of strata deposits, formed partly in the muds of the coastal zone, but generally during diagenesis (dolomitization and brecciation), sometimes against a background of volcanic activity.

Stratified deposits of the Upper Silesian ore district occur in shallow Triassic limestones and dolomites and belong to the type of replacement of cavities, veins and mineralized breccias [*Vos et al.*, 2005]. Under conditions of folding and faulting deformations during the formation of stratiform deposits of this type, the development of karst occurred together with the redeposition of sulfides and barite with productive ore deposition at the end of the Hercynian orogeny [*Boni and Amstutz*, 1982]. In southwestern Poland there are deposits of cuprous sandstones and shales, possibly of exhalative origin. The ores of these deposits were formed as a result of the movement of brine through permeable zones in the basement during the Triassic rifting period [*Blundell et al.*, 2007].

A significant part of the Hercynian belts of Western Europe is covered by the Mesozoic-Cenozoic cover, with the exception of the Paleozoic block massifs (Parisian, Czech, etc.). The Moho surface within the massifs is distinguished by significant depth, compared with the areas hidden under the Mesozoic-Cenozoic cover (Figure 1). In general, the Hercynides are characterized by a thick lower "mafic" layer of the earth's crust, within the block massifs its thickness is one and a half to two times or more greater than that of the middle and upper layers (Figure 5). A significant part of the SEDEX and SSC deposits in Germany, Belgium, Poland and the Czech Republic are located on the periphery of the Vosges and Czech massifs, above areas of thickening of the lower crustal layer, relative to the middle layer (Figure 6).

Alpine activation in Western Europe is manifested mainly in the form of active zones of the Mediterranean segment of the Tethys belt. The axis of the belt segment is located between the southern continental margin of Eurasia and the Afro-Arab plate. To the north, as a result of stretching of the Hercynian crust, the rift system of Western Europe developed, accompanied by alkali-basalt and alkaline volcanism [*Trifonov*, 2017].

The Tethys volcanic belts host numerous small and large porphyry Cu-Mo-Au deposits and associated epithermal Au-Cu occurrences. The Tethys Belt also hosts stratiform and exhalative polymetallic deposits, accompanied by skarn and epithermal polymetallic and silver occurrences.

The vast majority of polymetallic deposits here occur in Mesozoic complexes. The most represented lead-zinc deposits of the Mississippian type are in Spain (Reocin, Troya), Italy (Salafossa, Raibl and Gorno), as well as Slovenia, Switzerland and Austria. There are also exhalative occurrences of lead and zinc in France (Arrens), Spain (Arditurri) and cuprous sandstones and shales (Granada and Santomera in Spain, Darno-Hegy in Hungary, Giordannet in France, etc.).

Within the Tethyan belt, the depth of the Moho varies between 35–45 km, while the depth of the Pannonian Basin, which is part of the belt, is 22 km [*Reguzzoni and Sampietro*, 2015]. The temperature of the upper mantle within the belt is characterized by elevated values, varying around 1100°C, in some places exceeding 1300 °C. The thickness of the lower layer of crust in the Tethys belt on average does not exceed 15 km; in areas conjugating with the Hercynian blocks, the values rarely exceed 25 km (Figure 5). The middle layer has a more uniform thickness within the range of 8–15 km, while the thickness within the Pannonian Basin is reduced to 7–8 km.

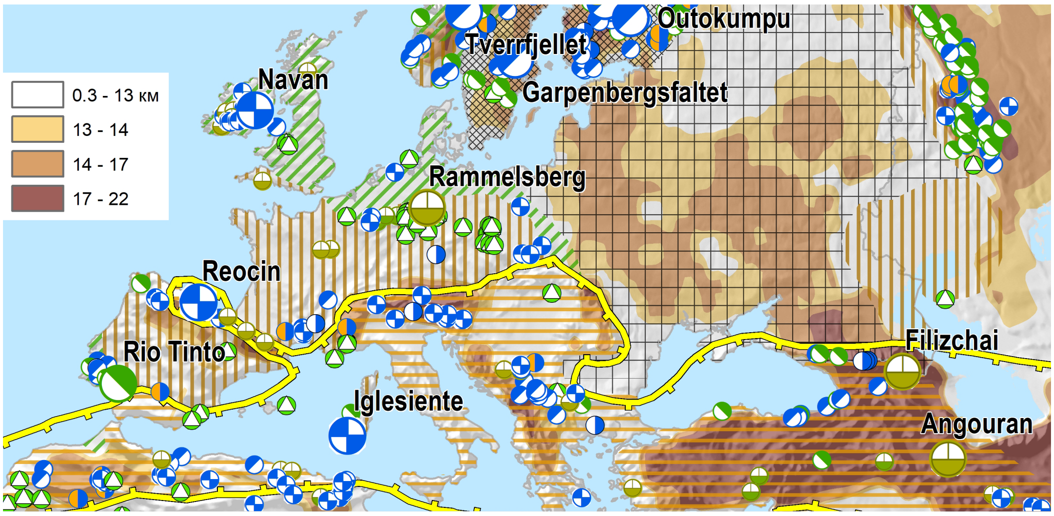
The belt also shows a correlation between the placement of deposits of VMS and SEDEX types, depending on the ratio of the thickness of the lower and middle layers of the earth's crust. In areas with a layer thickness ratio of 1.5–2:1, exhalation deposits are common (Figure 6), and in areas with a layer thickness ratio of 0.5:1, VMS ores are predominant. The upper layer of the crust, in general, has an increased thickness (about 15–20 km), but in the Pannonian Basin the values do not exceed 8 km.

4. The discussion of the results

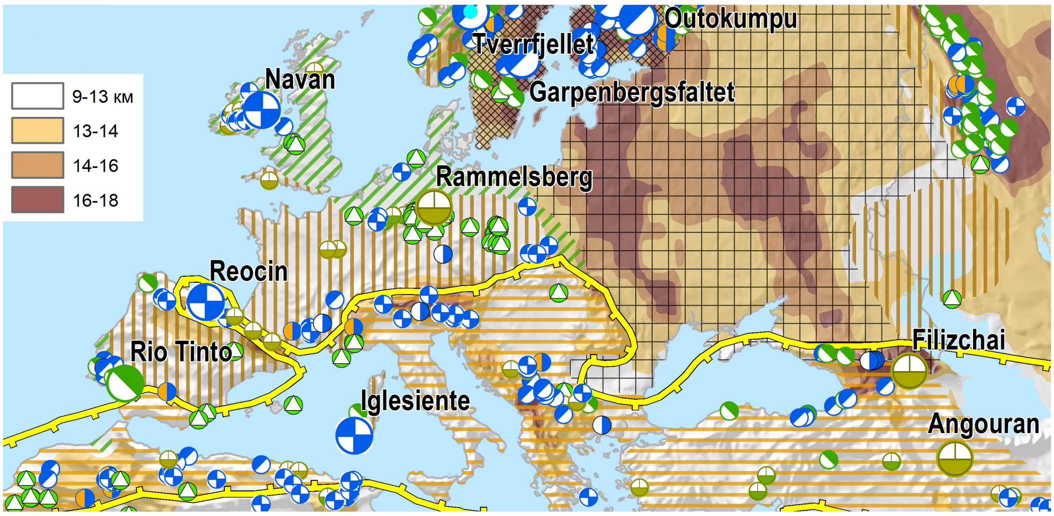
4.1. Thickening of the earth's crust, types, causes and consequences

The main reasons for the increase in the volume of the earth's crust are: tectonic interaction of plates and thermochemical mantle influence, accompanied by magmatism, underplating and separation of the crust and mantle. The main consequence of crustal thickening is delamination, convection, metasomatism and subsequent decompression of the crust and upper mantle, which is accordingly reflected in the form of thickening on seismic sections.

Tectonic thickening of the earth's crust is usually associated with collision processes during collision, subduction of plates, etc. (African and Eurasian). During the collision, an almost doubling of the thickness of the earth's crust is noted, which is expressed in the relief by intense folded-block uplifts (Pyrenees, Alps, Apennines, Dinarides, Carpathians).



(a)



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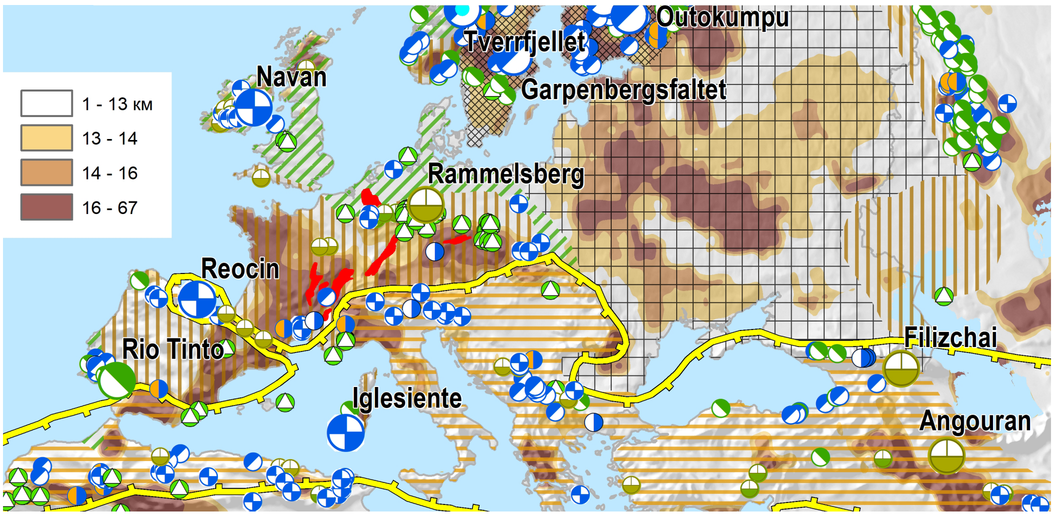

(c)

Figure 5. Thickness of the upper (a), middle (b) and lower (c) layers of the earth's crust and the location of polymetallic deposits in Western Europe (using materials from [*Laske et al.*, 2013]). Rifts are shown in red, rest. conventional designation see Figure 1, Figure 3.

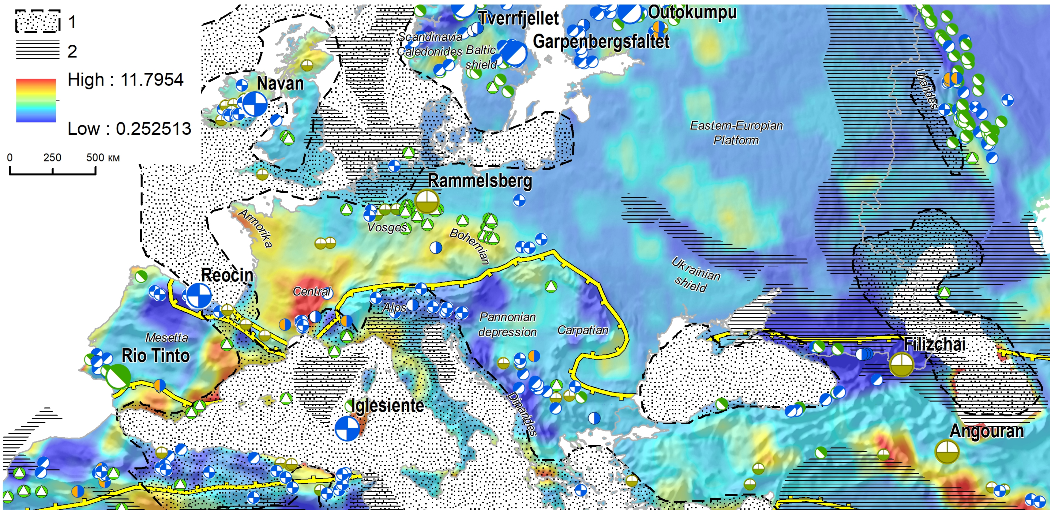

Figure 6. Polymetallic deposits of Europe and the ratio (from 4:1 to 1:11) of the lower and middle layers of the earth's crust (based on materials from [*Laske et al.*, 2013; *Richards*, 2015; *USGS*, 2012]). 1 – troughs of the sedimentary crust, 2 – oil and gas provinces.

As a result of orogenic thickening of the crust, thermal erosion occurs [*Zhang*, 2007] and delamination, in which the lower "mafic" crust and the underlying lithospheric mantle are stratified into blocks of varying buoyancy, the denser of which sink into the asthenosphere [*Hacker et al.*, 2015; *Houseman and Molnar*, 1997; *Pirajno*, 2009]. This leads to a rapid compensatory rise of the less dense asthenospheric mantle, followed by decompression melting [*Luchitskaya*, 2014], mafic underplating, and partial melting of lower crust materials [*Artemieva and Meissner*, 2012; *Pirajno*, 2009] and intraplate basaltic magmatism [*Mo et al.*, 2007]. All this leads to a general decompression of the crust and thickening in seismic imaging. This is evidenced by the results of geophysical studies, according to which decompression of the crust and upper mantle under the Central Tien Shan has been established, which is associated with retrograde metamorphism of rocks [*Makarov*, 2005]. A decrease in the speed of seismic waves due to decompaction is also observed under mountainous areas (Tibet, the Caucasus, the Carpathians and the Alps).

4.2. Subduction, accretion and VMS deposits

The thickness of the upper "granite-gneiss" crust can also be increased due to subduction, obduction, accretion and magmatism during collisional orogenesis [*Artemieva and Meissner*, 2012]. This is reflected in the existence of a thick "felsic" middle crust beneath deformed complexes of volcanic arcs and accretionary prisms. This feature is clearly manifested in the structure of the Dinarides and Western Alps system (Figure 5b).

The subduction paleothethic island arc process in the Alps determined back-arc spreading, rifting, and ophiolite formation in the Devonian period [*Graciansky et al.*, 2010]. Later, the formation complexes that had formed by this time were accreted to the subduction and obduction zone under the Apulian-African plate. The continuation of the collision of the European and African plates led to a thickening of the accretionary prism.

The Dinarides, like the Alps, are a fold-and-thrust belt that extends from the Southern Alps in the northwest to the Hellenides in the southeast [*van Unen et al.*, 2019]. The main structural elements of the Dinarides are manifested in Early-Middle Triassic rift troughs and accompanying magmatism [*Huismans et al.*, 2002; *Robertson et al.*, 2009]. Subduction and subsequent decompression of the continental crust led to the formation of a back-arc basin with ophiolitic melange, the influence of which is associated with the formation of VMS (Cypriot) type pyrite deposits in the Serbo-Macedonian volcanic belt.

It should also be mentioned that VMS pyrite deposits are confined to areas of thickening of the middle crust in the Svecofennian accretionary orogen [*Balagansky et al.*, 2016]. The Svecofennian orogenic block was formed as a result of the subduction of oceanic crust under the Karelian craton, the subsequent formation of island arcs containing numerous pyrite volcanogenic deposits, and their accretion. The multi-stage nature of accretion determined the complex nature of the Svecofennian accretionary structures and the subsequent rifting of the Karelian craton, which determined intraplate magmatism and the accompanying copper-nickel mineralization.

At the same time, there is no evidence of thickening of the middle crust in the Iberian pyrite belt, which hosts VMS and SEDEX pyrite ores of the Cadomian and Hercynian age. The Hercynian metallogenesis of the belt was caused by transpressional deformations of the crust [*Tornos et al.*, 2004], which represented an active continental margin. With subsequent movements, it was transformed into a collision zone, which could have affected the thickening of the upper and middle crust relative to the lower crust. However, recent seismic studies have shown that at a depth of 10–15 km, under the Ossa Morena zone, a large flat and dense magmatic body is found, possibly of mafic-ultrabasic composition and Hercynian age (Figure 5b). The parameters and properties of this body could have caused a general increase in the density of this part of the middle layer and a corresponding upward displacement of the seismic roof of the lower crust.

4.3. Rifting and SEDEX and SSC deposits

The process of thickening of the earth's crust associated with mantle influence is usually accompanied by diapirism of the asthenosphere [*Mazukabzov et al.*, 2011], basification (in the understanding of Academician V. V. Belousov) and eclogitization [*Pavlenkova et al.*, 2016]. The thickness of the crust also increases during the formation of large igneous provinces [*Artemieva and Meissner*, 2012]. The thickness of the earth's crust within the provinces averages about 40 km, while the lower crust, due to powerful basaltic magmatism, has an increased thickness (20 km), sometimes due to the reduction of the overlying "granite-gneiss" layer.

The consequence of thickening, layering and decompression of the earth's crust is rifting [*Pirajno*, 2009], the development of which is associated with the formation of many deposits (Carlinsky, stratiform, epithermal and other types). In general, rifting is also characterized by thinning of the middle "acidic" layer and thickening of the "mafic" layer of the earth's crust [*Artemieva and Shulgin*, 2019].

Confinement of polymetallic SEDEX deposits to areas of back-arc and continental-margin rifting is a common phenomenon in the world [*Groves and Bierlein*, 2007]. At the same time, for riftogenic areas, a feature of the deep structure of the earth's crust is noted – a local thickening of its lower "mafic" layer (Figure 5b). Thickening of the lower "mafic" crust is observed mainly in broad areas of spreading and rifting of the continental margin.

In the Western Alps, where local thickening of the lower crust is noted (Figure 5b), rifting occurred in the Early Cretaceous period and was caused by stretching and thinning of the continental lithosphere [*Graciansky et al.*, 2010]. Early phases of extension are associated with the development of Tethys in the Eastern Mediterranean.

The deposits of Central Europe (Rammelsberg, Bieber, etc.) were formed during the early rift phase of the development of the passive continental margin [*Leach et al.*, 2005]. The position of pyrite lead-zinc ores gravitates to the area of thickening of the lower crust (Figure 5b), on the passive continental margin with rift structures (Limanskaya, Bresskaya, Rhine, etc.), among organic-rich Middle Devonian siliceous-clastic rocks.

In areas of rifting there are also deposits of cuprous sandstones and shales (France, Germany, Poland). The currently accepted model for the formation of these ores during the period of diagenesis. Copper sandstone and shale (SSC) occurrences occur in Zechstein rocks in the Permian basin, extending from Great Britain through the southern North Sea, northern Germany and Poland to Lithuania. The basin is an inland trough and contains carboniferous sediments with thick coal deposits. The role of metalliferous fluids was played by seawater, which migrated down through the sediments into the basement [*Blundell et al.*, 2007]. In areas of Triassic rifting and elevated thermal conditions, ore-bearing fluids migrated upward along faults and fractures.

The Iberian Axial Zone in the northeast of the Iberian Peninsula, which hosts Ordovician lead-zinc deposits of the SEDEX type, is part of the Alpine orogeny associated with the collision between the Iberian block and the European plate. This fold belt is characterized by local thickening of the Earth's crust, with thickening of the lower crust covering larger areas (Figure 5b). The earlier history of the development of the Zone affects the Late Jurassic rifting in the Northern Iberian and Sub-Pyrenean basins, which separated the Iberian Peninsula from the Armorican massif.

In the Western Mediterranean, the redbed facies is similar in age, lithology, sedimentation history, diagenesis and orogenesis to individual Mesozoic deposits of the interior Apennines and Maghreb [*Perri et al.*, 2013]. They consist primarily of siliciclastic clastic materials, including sandstone, silt and clays, brought from areas of Paleozoic metasedimentary and metvolcanic rocks. Copper mineralization is represented by chrysocolla, azurite and malachite. The burial depth of the ores is at least 4–6 km with temperatures of 140–160 °C typical of the diagenetic stage.

The association of exhalation polymetallic deposits of the SEDEX and SSC types with paleorift structures may be associated with the processes of interaction of lower crustal and mantle fluid material due to delamination and mantle convection. Pyrite VMS deposits in volcanic rocks are determined by upper- and middle-crustal fluids, which, as a result of subduction and orogenesis, subsequent thickening of the crust, its delamination and metasomatism, are ultimately a product of the interaction of mantle-lower crustal and middle-upper crustal matter. All this does not contradict established ideas about the commonality of conditions and the mechanism of formation of ores of these types, as members of a continuous series [*Donets and Konkin*, 2017; *Ruchkin*, 1984].

4.4. Sedimentary cover and Pb-Zn deposits of MVT type

Mississippian and similar deposits, unlike VMS and SEDEX, were formed from sources with a very complex history. As spatial analysis shows, the formation of ores is not associated with the dynamic interaction of plates, and no patterns are observed in the placement of ores relative to the ratio of crustal layers. According to popular ideas [*Leach et al.*, 2005], the formation of these ores was determined by tectonic deformations and metasomatic changes in the ore-bearing strata of the subplatform cover. Deposits of this type are localized on the flanks of intra- and pericratonic basins formed in the extensional regime of the passive margin with terrigenous-carbonate sedimentation with hydrocarbon specialization and crustal sources of metals and sulfur [*Gorzhevsky and Makeeva*, 1982; *Leach et al.*, 2005; *Pavlov and Galyamov*, 1988; *Ruchkin and Donets*, 2002]. At the same time, the deposits gravitate towards deep sedimentary basins in the upper and middle layers of the sedimentary non-metamorphosed crust. There are many examples of this in Western Europe.

Consedimentation tectonic movements associated with rifting of deep Mesozoic basins in the Cantabrian region (with stratiform MVT deposits) caused facies variability of sediments, the presence of unconformities and paleokarst [*Velasco et al.*, 2003]. At the Reocín deposit, the productive ore stage appeared in the late stages of dolomitization, when ore was deposited in karst.

The circulation of metal-bearing fluids and the filling of karst occurred in post-Albian times. Carbon and oxygen isotopic signatures indicate that the metalliferous fluids were typical bottom brines [*Velasco et al.*, 2003]. The main source of metals was most likely siltstones and black carbonaceous shales. Metal chloride-rich brines were likely displaced from underlying sediments during burial compaction and diagenesis. The main reservoir of metals was most likely the underlying ones. Lead isotopy indicates its upper crustal origin [*Velasco et al.*, 2003].

In the Triassic deposits of the Eastern and Southern Alps, numerous lead-zinc occurrences of the Mississippian type are known. They are also found in the Central Alps and the adjacent European Plate of Austria. Economically important deposits are Bleiberg (Austria), Mesice and Topla (Slovenia) and the Italian Raibl and Salafossa in the south. All these Pb-Zn deposits were classified as the Alpine subtype [*Schroll*, 2005] and are located along the northern periphery of the Po oil and gas basin [*USGS*, 2012]. Ore-bearing Mesozoic carbonates overlie Permian and Early Triassic sandstones overlying the metamorphic basement. The origin of deposits of this subtype is associated with the development of the basin at the platform stage and subsequent tectonic events. In general, the characteristics of these deposits define the subclass of "low-temperature Pb-Zn objects in carbonate rocks," the ores of which were located in the bottom conditions of platform carbonate sedimentation, not exposed to thermal sulfate reduction [*Schroll*, 2005].

Stratiform deposits of the MVT type are also common in the North-East of Algeria, which represents the most important metallogenic zone of Pb-Zn-Fe-Ba (Cu, F, Sr) ore deposits. The mineral assemblage is represented by galena, sphalerite, barite, celestine, pyrite, chalcopyrite and marcasite in dolomite and limestone [*Ysbaa et al.*, 2021]. Stratiform lead-zinc deposits and occurrences of the MVT type (Ain Kahla, Chellala, Djebel Gustar, El Abed, etc.) are located in the section near the Hercynian basement, on the periphery of Mesozoic sedimentary basins. The formation of the deposits is associated with basin brines, the migration of which was caused by Atlas folding and, probably, Miocene tectonic activation.

In addition, general spatial analysis shows that the areas of MVT mineralization are located in areas with a reduced overall seismic thickness of the earth's crust (Figure 4), which can be explained by eclogitization of its lower horizons. In these environments, the process of crustal subsidence and the formation of oceanic basins with rifting intensifies. At the same time, the superimposed transformations of sedimentary rocks are limited by autometasomatosis, and mobile hydrocarbons were involved in the mechanism of migration and unloading of ore-bearing fluids during stratiform lead-zinc ore formation. Further superimposed transformations of ores and host rocks determined the epigenetic appearance of ores and metasomatic formations.

Thus, a comparison of the position of polymetallic deposits in different tectonic settings shows that there are two typical relationships of layers of the earth's crust (Table 1, Figure 5, Figure 6): 1) supra-subduction and back-arc riftogenic areas of local thickening of the middle "granite" and upper "metamorphic" left of the earth's crust (Balkan Dinarides, Taurids and Pontids in Turkey); 2) rift structures of the passive margin with the predominant development of the lower "mafic" layer of the crust (Central Europe, Iberian Zone, Turkish Taurides). Separately, the settings of pericratonic troughs with subplatform oil and gas complexes are highlighted (basins – Anglo-Danish, Po in Italy, Zagros in Turkey).

5. Conclusion

Spatial analysis of the distribution of Pb-Zn deposits in the folded frame of the Western and Eastern European platforms and the Mediterranian segment of the Tethys belt and comparison of the geodynamic settings of their formation indicates the following:

1. Sedimentary-exhalation polymetallic and silver-polymetallic deposits are confined to territories with the predominant development of the lower "mafic" layer of the earth's crust. SEDEX ores, as well as cuprous sandstones and shales (SSC), which were deposited closely simultaneously with the host rocks, are closely related to the rifting settings of mafic volcanism of the active and passive continental margin, with deep sources of fluids at the lower crustal and upper mantle levels.
2. VMS copper and lead-zinc deposits are located, more often, in supra-subduction island-arc and accretionary settings on consolidated crust with the predominant development of the middle "granite" layer. SEDEX-type mineralization also occurs in these settings, due to bottom fluid activation associated with island arc volcanism.

Table 1. Typical relationships of crustal layers and geodynamic regimes framing the Western European Platform and the Mediterranean segment of the Tethys belt.

Relationship between layers of the earth's crust	Thickened middle "granite" layer	Thickened lower "basaltic" layer	Platform frame
Geodynamic mode	Suprasubduction and accretion settings	Rifting on the passive margin and in the back arcs zone of active margins	Pericratonic platform basins with hydrocarbon specialization
Mechanism of mass transfer "mantle-crust"	Subduction and delamination transport crustal material into the mantle, building up continental crust	Mafic mantle magmatism transports mantle material upward and participates in the growth of new crust.	
Depth of metal sources	Middle and lower crust	Mantle – lower crust	Sedimentary and upper crust
Ore-formation type of deposits	Volcanogenic VMS deposits	SEDEX and SSC deposits	MVT Pb-Zn deposits in carbonate rocks

3. MVT-type stratabound lead-zinc ores are closely associated with pericratonic deep sedimentary petroleum basins on the shelf and continental slope. At the same time, their spatial connection with the stratification of the earth's crust is not obvious. The ores of this type were formed at the platforms frame in a carbonate host environment in sedimentary basins with hydrocarbon specialization for a long time, which determines the polychronism of their genesis and the epigenetic appearance of the ores. According to recent research results [*Zhou et al.*, 2022] in Chinese SEDEX- and MVT-type deposits, the source of sulfur in SEDEX ores was a sea water, and in MVT ores – a catagenetic elision fluids. The source of metals for SEDEX ores was mainly the deep basement rocks, and for MVT ore – the host sedimentary strata. Rifting determined the occurrence of synsedimentary SEDEX mineralization, and the formation of MVT ores at shallow levels of the earth's crust was determined by orogenesis.

At the same time, despite the numerous studies of hydrothermal ore-forming processes, an important objective still remains the identification of the mechanism of structural and matter interaction between the crust and the mantle and the evolution of fluids when moving from deep sources to the area of ore formation.

The results obtained can be used for regional forecasting and metallogeny, prospecting and assessment of new gold deposits.

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