Study on geological features and exploration methods of MVT Pb-Zn deposits

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Abstract. After a comprehensive research on geological features and exploration methods of MVT Pb-Zn deposits, this paper reach some conclusions as follows: 1) MVT Pb-Zn deposits are generally distributed on some major strata. 2) From a regional prospective, their ore bodies resemble strata-bound ore deposits in some aspects. 3) With simple associations, host minerals mainly include sphalerite, PbS, pyrite and marcasite. 4) Structurally, these deposits are mostly massive, brecciated, impregnated, spiderweb-shaped, vein-like and stripped. 5) MVT Pb-Zn deposits are epithermal generally with alternation, whereas their varieties are relatively simple and are not so intense. 6) Stratigraphic system and structure are critical symbols for exploring this kind of deposits. 7) Physiochemical exploration is effective for exploring such deposits, and 6 major indicators are available for ore exploration.

1. Introduction

With remarkable epigenetic characteristics, so Mississippi River is well-known for typical development of deposits. Up till now, this type of deposits has been explored for over a century. Focusing on discussing hydrothermally metallogenic causes of these deposits, earlier research defined NVT Pb-Zn deposits as hydrothermal deposits in the postigneous stage or tele-hydrothermal deposits. By 1970s, many scholars had further investigated these deposits according to theory of strata-bound ore deposit, intensively analyzing and summarizing their metallogenic backgrounds, their associations with igneous rocks, their spatial distribution, and spatial distribution of their ore bodies, ore-controlling factors and ore features. In particular, they acquired numerous new geochemical and mineralogical materials about the deposits such as Pb isotopes, S isotopes, fluid inclusions and ore-forming fluids. Substantial geological and geochemical materials of the deposits have fully demonstrated that the metallogenesis of these deposits is not associated with magma or hot magma. Nowadays, it has been generally acknowledged that MVT Pb-Zn deposits are epigenetic deposits under the control of stratigraphic horizons, arising from filling and metasomatism of underground hot (brine) water sedimented under strata within space of carbonatite, including pores, crevices, karst caves, plane of unconformity and intercalated crushed zones.

These years, people have paid more attention to MVT Pb-Zn deposits with the increase in demands for lead and zinc in the global market. In this paper, geological features and exploration methods of these deposits are summed up based on previous research materials.

2. Tectonic Background and Metallogenic Environment

MVT Pb-Zn deposits were previously considered to be irrelevant to tectonics and activity of plates, because it was deemed that MVT Pb-Zn mineralization would be possible as long as there was carbonatite on meseta. However, since 1980s, more and more studies have suggested that MVT Pb-Zn deposits were mostly generated because massive ore-forming fluids flew through fore-land basins and their metal sulfides precipated with the drive of gravity of adjacent orogenic belts (Garven, 1985; Ge et al, 1992; Appold et al, 1999). Although adjacent rocks, basin brine, driving forces of fluids and places where ore bodies deposit play critical roles in genesis of deposits, all these conditions are attributable to movements of tectonic structures under consistent tectonic structures, so it is particularly important for exploring metallgenic causes and guiding prospecting by exploring the tectonic backgrounds. According to research of the past years, MVT Pb-Zn deposits mostly form in foreland basins of orogenic belts, generated in thrust-nappe belts in very few cases and rarely produced under the environment where continents extend. This view was questioned at the very beginning after its proposal, but finally generally acknowledged.

Forelands lie in front of orogenic belts, and foreland basins are sedimentation basins between the orogenic belts and front cratons as zones for holding detritus of the orogenic belts after orogeny. In the world, MVT Pb-Zn deposits mostly exist in orogenic belts where island arcs collide with continents, Anden orogenic subduction belts and orogenic belts of continent-continent collision, which are located in forelands of orogenic belts (Fig.1, a) (Leach et al., 2005). The most representave includes American Ouachita (i.e. an island arc), Ozark MVT Pb-Zn ore belts (including several Pb-Zn ores in southern Missouri, northern Arkansas, Tri-State and middle Missouri) (Bradley et al., 1991), and MTV Pb-Zn ore belts in Sichuan, Yunnan and Anhui provinces of China (Wang et al., 2001). Above instances suggest that although MVT Pb-Zn deposits mostly exist in carbonatite strata on flat meseta of foreland basins, they are also distributed in thrust-nappe belts, which are deformed zones of orogenic belts. In thrust-napple belts, ore bodies would appear under reversed faults or on reversed sheets because mineralization and tectonic activity took place in different order (Bradley et al, 2003).

Since MVT Pb-Zn deposits are universal in island arcs, namely foreland basins where passive margins collide with orogenic belts, and a complete orogeny of such a orogenic belt can create all conditions necessary for Pb-Zn mineralization, Brandley et al. (2003) built a model for the process of MVT Pb-Zn mineralization under such environment (Fig.1, b) (Leach et al., 2005), thus underpinning subsequent discussion of metallogenic causes of MVT Pb-Zn deposits on the forelands of orogenic belts.

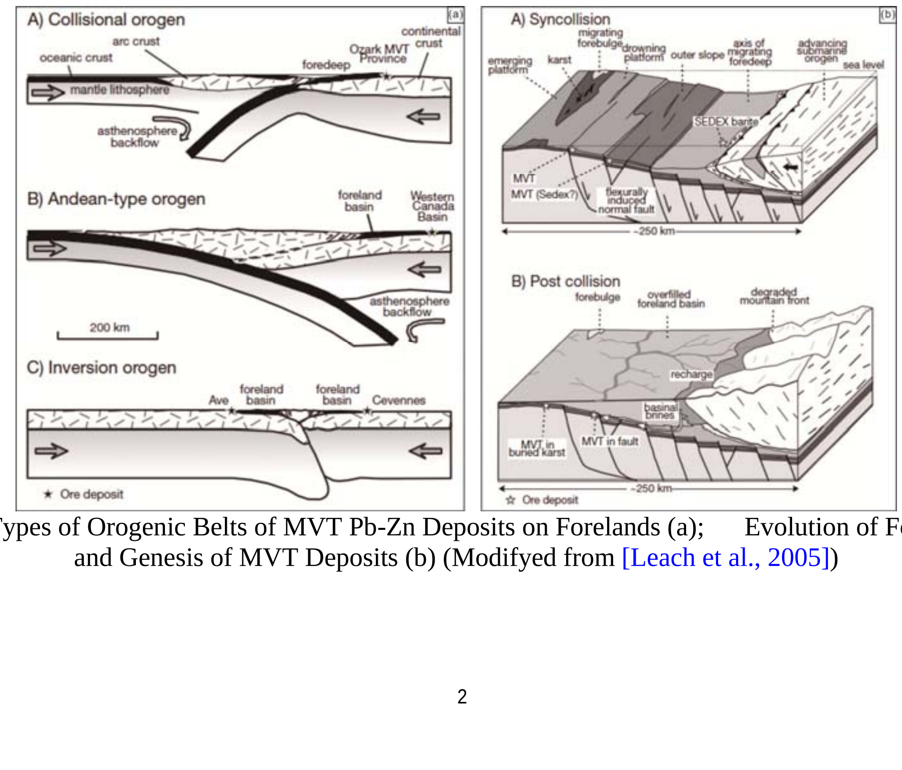

Fig 1.Three Types of Orogenic Belts of MVT Pb-Zn Deposits on Forelands (a); Evolution of Foreland Basins and Genesis of MVT Deposits (b) (Modifyed from [Leach et al., 2005])

3. Formation of Ore-bearing Adjacent Rocks

In general, MVT Pb-Zn deposits are distributed on fixed ore-bearing strata and several strata are usually simultaneously mineralized within an ore district, whereas there is usually only one or just a few major ore-bearing strata. For instance, MVT Pb-Zn deposits hosted in Sinian Dengying Formation, Lower Carboniferous Baizuo Formation, Middle Ordovician Daqing Formation, Middle Silurian and Lower Permian Strata on the southwestern margin of the Yangtze platform, whereas the Dengying Formation is the main area of their hosting (Wang et al., 2001). Ore-bearing formations are characterized by development of carbonatite and usually adjacent to dolomite but rarely limestones. Concerning stratigraphic sequence, lower permeable layers and upper isolation layers (shale or limestone) play important roles in genesis of deposits. For instance, all three ore-bearing strata of Chinese Tarim - Kalangu Ore Zone are composed of lower permeable detrital rocks or dolomite and upper limestones. In Maozu, Daliangzi and Chipu deppsits of ore districts in Sichuan, Yunnan and Guizhou provinces, the stratigraphic sequence is made up of water permeable dolomite and upper shale. The sponginess or permeability of dolomite is relatively high, which is possibly the mjor reason why ore bodies are hosted on dolomite, or one of the reasons why MVT deposits are larger on these rocks with higher-grade Pb, Zn and Ag. However, dolomization is mostly seen before, during and after metallogenesis in many areas. Its relationships with mineralization still remain to be further explored.

4. Morphology of Ore bearing rock series

According to scales of ore districts, ore bodies are generally layer-bound in MVT Pb-Zn deposits. However, it may be observed from scale of a single deposit that ore bodies are extremely morphologically irregular, not only including stratiform-like, plate-shaped and line-shaped deposits generated along strata, but also tubular, chimney-shaped, massive, vein-like, lenticular and irregular ore bodies forming through strata. The layer-bound ore bodies can usually extend for scores to hundreds of meters along strata, and are generally several decimetres to scores of meters thick. The ore bodies are interconnected, wedged out and recapituled. With tremendous changes to their morphology and size, fracture-controlled ore bodies include thinner lenticular, sack-like and vein-like ones under the control of steep tilted cracks, and thicker tubular ones, with clear boundaries with their adjacent rocks. The ore bodies controlled by palaeokarst are usually irregular. These three categories of ore bodies may co-exist within a mine like Pb-Zn ore bodies in intersections of Sichuan, Yunnan and Guizhou provinces of China (Zhang et al., 2008), where there are stratiform-like, lenticular (e.g. Maozu and Chipu), tubular (controlled by faults and fold structures), vein-like (e.g. Daliangzi, Lehong and Tianbaoshan), and irregular ore bodies controlled by palaeokarst like Qilin Plant.

5. Features of Mineral Associations

With simple mineral associations, MVT deposits mainly contain host minerals such as sphalerite, PbS, pyrite and marcasite, together with gangue minerals like dolomite, calcite and quartz, excluding chalcopyrite, bornite and native copper. In some ore districts, fluorite and barite are more developed, often accompanied by minerals containing Ag, Cd, Ge, Ga and Ni. Generally, the content of Ag is lower, but can be extremely high in some deposits, including Yinchang Po, Tianbao Mountain and Daliangzi Pb-Zn Ore in Sichuan, Yunnan and Guizhou provinces, where the Ag grade is 181g/t, 111g/t and 83g/t respectively (Hu et al., 2000).

Metal elements of MVT deposits are distributed in non-diverse ways and seldom mineralized in different belts (e.g. Pine Point). With extraordinary mineral associations, their Pb, Zn, Fe, Cu, Ni and Co are mineralized across belts. In Pine Point, tubular ore bodies are distributed outward, with a higher ratio of Fe/(Fe+Zn+Pb) to Zn/(Zn+Pb) (Kyle, 1981). In southeastern Missouri, deposits extend outwards, including Pb, Zn, Fe, Cu, Ni and Co (Hagni, 1983). Lehong Pb-Zn Deposit is mainly endogenetically composed of zinc minerals, but gradually turns into a pyrite belt exogenetically.

6. Tectonic Features of Ores

In MVT deposits, precipitation of sulfides is associated with multiple factors, including sedimentation, solution, metasomatism, open space filling and brecciation. Corresponding sulfides are mostly grannular, metasomatic, metasomatie-relict, colloidal, inclusive, corrosive, mixed, strawberry-shaped and granular with massive, brecciated, impregnated, spiderweb-shaped, vein-like and stripped textures. The ores, sulfides and gangue minerals formed during open space filling are mostly granular, corrosive, branch-shaped and colloidal with different textures; the sulfides are mostly massive, brecciated and spiderweb-shaped,; gangue minerals are mainly stripped and veinlike; at times, coarse sphalerite crystals tend to grow like strata, generating snow-on-roof on the top of alloclastic breccia or adhering to the roof of miarolitic cavity (Leach et al., 1993). During dissolution and collapse of brecciation, the ores formed are mostly corrosive, metallogenetic and mixed with brecciated, spiderweb-shaped, embedded, colloidal, veinlike and rhythmic bedding textures. The metasomatic ores are alternative. For instance, the metasomatism of hydrothermal dolomite is alternative in Pb-Zn deposits like Newfoundland and perturbs limestones, thus creating stripped and pseudobrecciated textures. In deposits such as Pine Point, Robb Lake, Monarch Kicking and Pend Oreille, hydrothermal dolomite is metasomatic with several kinds of in-situ rocks to generate stripped textures. Silicon stripes form from alternative hydrothermal metasomatisic carbonatite in deposits like Tianbao Mountain and Maozu (Liu et al., 1999). Under the effects of sedimentation, granular structures, stratiform-like and impregnated structures develop. In this case, great changes happen to grain size of sulfides from thin to thick grains. According to the deposition sequence, pyrite (marcasite) deposits first, followed by sphalerite and galenite.

7. Alternation Features

As epithermal deposits, MVT Pb-Zn deposits mostly develop through alternation, but in relatively simple varieties and with weaker strength. Distributed within a limited scope, they are generally distributed on ore bodies and adjacent rocks of nearby ores. In places far away from the ore bodies, the strength becomes increasingly weaker, and the deposits are thereby unseen. The alternation of MVT Pb-Zn deposits is usually associated with dissolution of adjoining carbonatite, recrystallization, hydrothermal metasomatism and hydrothermal brecciation, which mostly result from acid-based reactions of reduced S-included fluids and metal bearing fluids.

In MVT Pb-Zn deposits, dolomitization, calcitation and pyritization are the most common. In a moniroty of these deposits, organic mineralization, silicification, clayzation, micacization, feldspathization, jasperization and barytization take place. It is noteworthy that deposits generally differ from each other in alternation mineral assemblage and strength no matter they are in different or the same mines. For instance, dolomitization is the major type of alternation in ViburnumTrend and Old Lead belt of Missouri, the United States, accompanied by little silicification, feldspathization, dickitization and illitization. In Elmwood and Gordonvale Pb-Zn mines of middle Tennessee, the main types of alternation incude calcitation, fluoritization and barytization, accompanied by little dickitization, marcasitization and celestitization.

8. Indicators for Prospecting

8.1. Indicators for strata and ore-bearing strata

MVT Pb-Zn deposits have evident features of stratigraphical distribution. In a single mine concession, important deposits are mainly distributed on one or several ore-bearing strata, becoming major strata for prospecting. For instance, there are three ore-bearing strata in Tamu-Kalangu Pb-Zn-Cu ore belt, but what matters most lies in nearby areas of the belts where the bottom of the carboniferous system contacts the devonian clastic rocks (Zhu,et al., 2000). In Sichuan, Yunnan and Guizhou provinces, metallogenic strata mainly include Yuhucun Formation, Baizuo Formation and Dengying Formation (Wang et al., 2001). The Yuhucun Formation is made up of two fragments of clasolite, one fragment of phosphorite and two fragments of dolomite, while the Baizuo Formation is composed of dolomite in the lower part and limestones in the upper part. A common feature of such ore-bearing system consists in that the lower part is rich in relatively pervious clasolite or dolomite and impervious limestones. The scale of ore-included system is closely associated with that of ore-bearing ones, which is also reflected from degree of dolomitization. In Tamu-Kalangu belts, the ore-bearing strata at the bottom of the carboniferous system are the most important ore-bearing strata with extensive dolomitization and hosted with economically significant deposits. There are over 500m thick clasolite in the lower part and thick carbonatite in the upper part. At the bottom of carbonatite, large-scale regional dolomitization took place, and the thickness is above 100m, which indicates massive regional hydrothermal activities along this stratum.

For above stratigraphic systems, regional dolomitization is a prerequisite for metallogenesis of MVT Pb-Zn deposits and appears to be stratiform-like. The residual brecciated structures are widely distributed on interfaces along the ore-baring stratigraphic systems for up to thousands of kilometers and contribute to the formation of one hundred to thounsands of meters of dolomite strata. According to geochemical profiles of the strata, in belts where the stratiform-like dolomite are heavily altered, there are much more trace elements related to metallogenesis. In Tamu-Kalangu belts, trace elements are heavily enriched on the top of devonian purple-red sandstones at the bottom of the carboniferous system, namely the belt with intense dolomitization, where the content of MgO increases by 20% to 30%. The results of metasomatism between dolomite and calcite are indicated. According to the research rsults, the content of elements such as Cu, Pb, Zn, As, Sb, Bi, Au and Ag increases drastically, which is positively correlated to content changes of MgO. Among these elements, the cntent of as increases by approximately 100 times, distributed in a wider range, followed by Cu, Pb, Zn and Ba. With abnormal and relatively weak formation, Au, Ag, Bi and Sb are distributed more narrowly (Yin et al., 2003).

After summing up their experiences in prospecting and exploration over the past decades, people have realized that geological-geochemical interfaces are effective for guiding prospecting. Based on this, Si/Ca interface ore controlling has been progressively applied in prospecting Pb-Zn ores. As lithological interfaces that form between silicate rocks (Si) and carbonate rocks (Ca), Si-Ca interfaces are not only for changes to physiochemical conditions of rocks, but also for changes to geochemical conditions. In terms of petrology, these changes are lithologic, namely taking place in physical interfaces between carbonatite and silicate. From the perspective of geochemistry, absupt changes to environment are refected, which do not only involve changes to element composition, temperature and pressure conditions, but also cover changes to acidity, alkalinity, oxidation and reduction environment. The Si/Ca interfaces related to MVT Pb-Zn deposits are mostly between carbonatite and clasolite, among which the latter includes siltstones, argillite and grit sandstones. Characterized by small grain size, lower sponginess and permeability, they have been turned into strata that block transport of ore-bearing fluids, and Pb-Zb ore body forms on one side of the interface near the carbonatite. Similar characteristics are also detected in ore deposits of Sichuan, Yunnan and Guizhou provinces, including Chipu Deposit and Daliangzi Deposit. Chipu Pb-Zn deposits are typical MVT Pb-Zn deposits, where mineralized elements are distributed on sliding and broken fracture zones among multiple layers on the top of the Dengying Formation. From the top to the bottom, there are 3 mineralized layers, among which the Ith mineralized layer is the mine ore body, surrounded by microcrystal dolomite and siliceous microcrystal dolomite, mineralized in the carbonatite under the Si/Ca interface between sinian carbonatite and cambrian clasolite (Zhang et al., 2012).

8.2. Indicators for breccia

MVT Pb-Zn deposits are closely connected with breccia, from which ore bodies are produced. Breccia is generally fully mineralized. Thus, breccia has become crucial indicators for prospecting and evaluation. Once it is discovered, efforts can be made to evaluate breccia for prospecting. Such breccia differs from sedimentary conglomerate and simple tectonic breccia, where the cements usually have drainage pores with sulfide as direct indicators for evaluating if they bear ores. . In view that the content of Pb-Zn sulphides is rather low in most breccia and the sphalerite is so light-colored that can't be easily observed, special attention shall be paid to pores left after oxidation. The breccia present considerable morphological changes, and in general, the breccia is spread along or near strata.

8.3. Indicators for gossans and diamonds

Gossans are essential indicators for prospecting and evaluating base-metal sulphide deposits. In prospected Pb-Zn deposits, including Tamu-Kalangu belts and northeastern Yunnan province, gossans exist above known Pb-Zn deposits at different scale. Generally, gossans usually tectonically keep like original rocks. In oxidation zones of ore deposits such as Tamu and Kalangu as well as mineralized breccia belts, it is often discovered in lixiviated breccia that pores are lft after the sulfide is leached in breccia cements, including certain limonite and jarosite. In particular, impregnated gossans form in mines with more pyrite. The content of pyrite is relatively low in ores of MVT Pb-Zn deposits and generally below 10%, which is unfavorable for massive rust colors resulting from pyrite oxidation.
Since most sulfide ores are exposed on the subsurface and not fully oxidized. In many mines, diamonds of Pb-Zn sulfide ores are common. The history of discovery of Pb-Zn deposits in Tamu-Kalangu belts suggests that sulfide diamonds are important indicators for prospecting evaluation.

8.4. Tectonic indicators

The controls of faulted structures over mineral deposit are reflected from many aspects. For instance, the main ore bodies are located on one side of carbonatite in deep faults on the edge of Tamu-Kalangu ore belts. According to development features of host breccia, their linear distribution suggests that mineralization and mineralized breccia mostly form along certain fault structures, particularly near interlaminar fractures. Within the extent of ore deposits, the ore shoots are almost under the control of areas where multiple formations intersect, including Tamu and Kalangu. There are usually some relatively massive horizontal structures in belts where Pb-Zn deposits develop, while lead and zinc are mineralized on both sides of these transverse ruptures. In Kalangu deposits, interlaminar fractures close to the eastwest and main faulted structures close to the north or south are particularly effective for controlling metallogenesis.

8.5. Indicators for physiochemical prospecting

At present, some MVT Pb-Zn deposits have been discovered in China, totally explored and prospected in exposed subsurface ores or along outcrop mines. Meanwhile, brecciated ore bodies of Pb-Zn deposits are often accompanied by large-scale breccia belts. Being much larger than ore bodies, they are over 100m wide, and intensive geochemical anomaly is caused on the surface after weathering and denudation. MVT Pb-Zn deposits are relatively rich in Pb, Zn, Cu, As, Sb, Ag, Co, Ni and Ge. For these deposits, geochemical anomaly is detectable in ore bodies or ore-bearing breccia belts or near these belts. In the Tamu-Kalangu Belt, positive Pb and Zn anomalies, extending for 6km2 or so, have been detected in Kalangu and Wusulike deposits by scanning dispersed flow at 1:100,000.

On the other hand, MVT Pb-Zn deposits are characterized by low ore-forming temperature, weak wall rock alteration and narrow range of alteration. The effects of alteration are generally within mineralized belts, and the geochemical anomalies thereby formed, particularly the primary halos are usually extremely narrow. Besides, the geochemical anomaly zoning is not evident. On low-density or even rather low-density geochemical coverages, especially when ore bodies are hidden and semi-hidden, ideal effects can’t be achieved.

Ores MVT Pb-Zn deposits are mostly massive and rich in sulphide. In general, carbon is not included in ore bodies and their wall rocks, so geochemical prospecting methods such as IP and TEM can usually achieve ideal results in similar areas. In northwestern Guizhou Province and Northwestern Yunnan Province, positive TEM geophysical anomalies are still detectable above Pb-Zn deposits with an embedded depth above 300m.

9. Prospecting and Exploration Models

Based on abovementioned metallogenic rules and prospecting indicators of MVT Pb-Zn deposits, following models can be generally built for deposit exploration.

(1) Favorable tectonic structures, namely carbonatite platforms with stable craton edges, can be created to be far away from intrusive rocks of the same period.

(2) Favorable ore-bearing strata are combined with lithological characters. In other words, the old water bearing bed is made up of lower relatively permeable rocks and upper limestones.

(3) Dolomitization is regionally seen along strata.

(4) Geochemical anomalies exist.

(5) Transverse stratigraphic systems have transverse structures, where the dolomitization is more intense near fractures.

(6) Breccia belts and ore bodies have been found to contain sulfide.

In the early research stage of large-scale zoning, the research work is equivalent to geological work performed at a scale of 1:200,000 to 1:50,000. It is necessary to identify stratigraphic-lithologic formations helpful for MVT Pb-Zn deposits and favorable regional tectonic structures by making full use of remote sensing technologies based on existing 1:200,000 geological data.

The geological work carried out at relatively high scales focuses on identifying distribution of deposits in known ore belts. In this stage, it is important for exploring deposits by acquiring geological mapping at different scales from basic geological data. In other words, regional reconnaissance is realized according to tectonic environment, favorable lithological associations and stratigraphic units of MVT Pb-Zn deposits. Subsequently, prospecting targets are delimited in combination with geophysical and geochemical prospecting data, in order to discover new Pb-Zn deposits and finally prospect diamonds pursuant to the data. Detailed field geological surveys and large-scale geological mapping are extremely important for discovering deposits. The wall rocks are altered within such a narrow extent in MVT Pb-Zn ores that the breccia and wall rocks can be hardly discriminated in the fields. Very few sulfides exist in breccia and can be seldom distinguished owing to weathering and runoff. In addition, great importance is attached to impacts of lithological characters of wall rocks upon varieties of developed ores. Copper mineralization, lead mineralization, some barites, fluorites and some related low-temperature ores (including hematite, and pyrite with framboidal texture) would become evidences for evaluating prospects of MVT Pb-Zn ores in certain are and prospecting clues for Pb-Zn deposits.

The ore bodies are explored at a larger scale for the purpose of identifying locations of concealed ore bodies. MVT Pb-Zn deposits are low-temperature hydrothermal deposits, which are more or less similar to some hydrothermal deposits in exploration methods and models of themselves or their ore bodies, but they have no apparent associations with magmatic rocks. With ore bodies that form more complex ways, the MVT Pb-Zn deposits have developed some of their own characteristics. Intensive research on control of faulted structures over metallogenesis is of great help for predicting ore shoots. ore shoots of MVT Pb-Zn deposits are usually controlled by multiple fractured formations, particularly in areas where transverse faulted structures are intersected. In this process, dolomitization and brecciation take place. Karst structures are possibly retained in some parts of ore bodies. In this stage, geophysical exploration may play important roles. Since lead and zinc rich ores are industrial ore bodies of MVT Pb-Zn deposits and neither ore bodies nor wall rocks contain much carbon, geophysical exploration methods such as TEM and IP are effective and feasible for exploration. The content of magnetic minerals is extremely low in ores, so no magnetic exploration method has been ever applied in exploration of MVT Pb-Zn deposits.

Conclusion

After a comprehensive summary of previous research materials, conclusions are reached as folllows. 1) MVT Pb-Zn deposits, with features of stratabound ore deposits, are mainly distributed on some strata. 2) Minerals mainly include sphalerite, PbS, pyrite and marcasite. 3) Their textures tend to b massive, brecciated, impregnated, spiderweb-shaped, and stripped. 4) As epithermal deposits, MVT Pb-Zn deposits generally develop via alternation, mainly in forms of calcitation, fluoritization and brecciation. 5) indicators for strata and ore-bearing stratigraphic systems are pretty important for exploration of MVT Pb-Zn deposits; 6) Indicators for physiochemical exploration are effective for exploring MVT Pb-Zn deposits;7) Main faulted structures are critical for the metallogenesis of Pb-Zn ores and MVT Pb-Zn deposits are explored based on 6 indicators.

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