Genetic concepts on the formation of the Austrian magnesite and siderite mineralizations in the Eastern Alps of Austria

Walter Prochaska

University of Leoben, Department of Geological Sciences, A-8700 Leoben, Austria

31-38 9 Figs. doi: 10.4154/gc.2016.03

Article history:
Received October 15, 2015
Revised and accepted January 21, 2016
Avaliable online February 29, 2016

ABSTRACT

A consanguineous origin of the sparry siderite and magnesite mineralizations of the Eastern Alps has been repeatedly discussed in the past, often without the back-up of sound scientific arguments. Here, it is shown that the characteristics of these mineralizations including structures, fluid parameters, timing etc. are amazingly similar suggesting in fact the genetic linkage of these deposits.

The siderite as well as the magnesite mineralizations of the Eastern Alps exhibit metasomatic-epigenetic structures of lens-shaped orebodies with dolomitic alteration rims as dominant features. The basic chemical characteristics of the ore forming fluids in these mineralizations are those of highly fractionated hypersaline fluids exhibiting all the features of residual bittern brines. Fluid invasion and mineralization structures strictly depend on the original lithology of the host rocks, mainly carbonatic sedimentary rocks. In Late Triassic times, these buried evaporitic brines were mobilized either by magmatic/metamorphic processes in the underlying crystalline units or by the superimposed sedimentary upload of the Triassic platform carbonates thus leading to magnesite formation. Initially these residual, bittern brines were completely free of Fe and rich in Mg suitable for the formation of magnesite. Deeper and more extensive circulation of these fluids and their interaction with the host-rock, resulted in the uptake of Fe and the formation of siderite.

Keywords: siderite, magnesite, mineralizing fluids

1. INTRODUCTION

Numerous magnesite and siderite mineralizations of various sizes can be observed in the Eastern Alps of Austria (Fig. 1), some of them were of considerable economic importance and were exploited. The minerogenetic map of Austria exhibits their locations.

Today, only one siderite mine, the Erzberg siderite deposit, situated in the province of Styria, is in operation. The present Austrian iron production is about 750.000 tpa (Fe-content) and is exclusively produced from this mine.

The well-developed Austrian magnesite industry is of worldwide importance, and is to a large extent still based on the Austrian mines. Magnesite production in Austria is approximately 750.000 tpa (ranked 5th worldwide) and is mined from 10 different deposits.

Similar mineralizations occur in Upper Carboniferous strata of the Gemeric units of Slovakia, which can be directly compared to the Greywacke Zone. The discussion about the genesis of these magnesite and siderite mineralizations throughout previous decades is very similar to the controversial views of the Austrian examples and reflects the changing opinions concerning these mineralizations throughout the history of their investigation.

It is beyond the scope here to give a complete review of the innumerable publications on the siderite and magnesite deposits of the Eastern Alps, so only a brief summary is given. However,

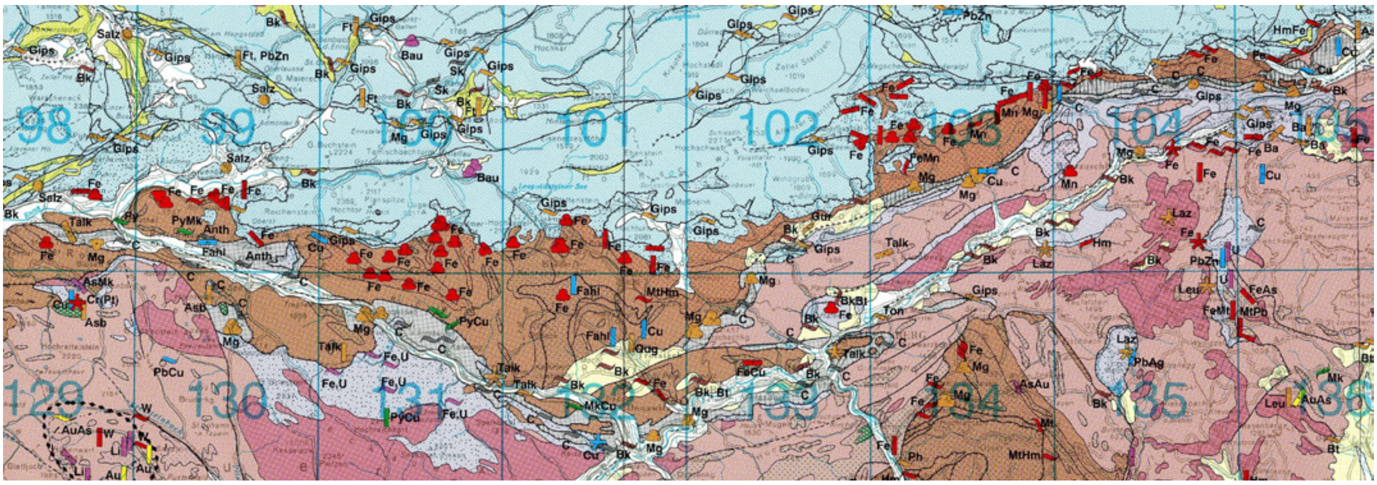

Figure 1. Part of the minerogenetic map of Austria showing the Fe- and magnesite mineralizations of the Greywacke Zone (WEBER, 1997).

during recent decades some considerable progress was made in the understanding of these mineralizations using modern scientific methods. Therefore the main focus of this paper is to discuss the results obtained by the investigation and characterization of the chemistry of the fluid inclusions forming these mineralizations. Furthermore, direct radiometric age determination of the carbonate minerals of the hydrothermal events during recent years contributed substantially to the revised models of ore-formation.

Finally, on the basis of these new results, an attempt is made to demonstrate that there is a genetic link between the carbonate-hosted sparry magnesite and the siderite mineralizations of the Eastern Alps. The arguments are mainly based on the investigations of the fluid chemistry from inclusions that allow characterization of the ore forming fluids showing an overall evaporitic signature of the hydrothermal fluids responsible for these mineralizations. Another crucial aspect for the genesis of both siderite and magnesite deposits is the timing of the mineralizing event.

The focus of this paper is on the magnesite and siderite mineralizations of the Palaeozoic series of the Eastern Alps. The important siderite/haematite iron-ore province of Hüttenberg-Waldenstein in the Austroalpine Crystalline Complex is not discussed in this paper. This iron-ore province is related to hydrothermal processes in connection to young tectonic activity without any relation to the mineralizations in the Palaeozoic series discussed here.

2. GENETIC MODELS PROPOSED IN THE PAST

It is far beyond the scope of this chapter even to list the enormous amount of papers, published on the Austrian siderite and magnesite mineralizations since the start of modern geoscientific investigation in approximately 1850. Therefore only the general trend in the genetic opinion is referred to and discussed.

Opinions concerning the genesis of the siderite mineralizations of the Greywacke Zone are inconsistent (cum. cit. TOLLMANN, 1977), and discussion about this topic is a longstanding tradition. Different genetic models, including a synsedimentary origin or an eoalpine vein-type and a metasomatic mineralization type have been proposed in the past. Early workers (e.g. SCHOUPPE, 1854; VACEK, 1903) on this topic favoured syngenetic models, and at the turn of the century epigenetic models for the Erzberg type mineralization were proposed.

More recent research concentrated on the investigation of structural and geochemical features and also on comparative studies (e.g. POHL, 1986) of the siderite mineralizations. In the 1970s, syngenetic models were favoured for the Erzberg mineralizations mainly because of the findings of minor banded ore structures that were interpreted as primary sedimentary ore bands (BERAN, 1973, 1975, 1977, 1979a, 1979b; BERAN & THALMANN, 1977, 1978). Following these arguments SCHULZ et al. (1997) described ore textures of the Erzberg deposit and postulated a marine-synsedimentary origin for the mineralization. Recently an epigenetic genesis for siderite mineralization in the Greywacke Zone was reintroduced on the basis of microthermometric, geochemical, and isotope data (FRIMMEL, 1988; PROCHASKA, 1991; SPINDLER, 1992; BELOCKY, 1992; POHL & BELOCKY, 1994; LAUBE et al., 1995; PROCHASKA, 1997). These authors generally postulate an epigenetic origin, nevertheless there is no unanimous opinion concerning the most important metallogenetic features, the timing of the hydrothermal event, and the origin of the hydrothermal fluids.

Similarly, there is no consensus on the genetic model and not even about the principal mechanisms for magnesite mineralization. Starting soon after the discovery of the world´s first magnesite deposits in the Eastern Alps after 1850, syngenetic models (e.g. RUMPF, 1873; LEITMEIER, 1917) and epigenetic models (e.g. KOCH, 1893; VACEK, 1903; REDLICH, 1907) were published. Starting in the 1950s, a general trend towards syngenetic and early diagenetic models can be observed (De LLARENA, 1953; LEITMEIER & SIEGL, 1954). NIEDERMAYR (1989) argued for synsedimentary or early diagenetic genesis for magnesite mineralization in the Permian series of the Eastern Alps and extended this model to the alpine sparry magnesites.

POHL & SIEGL presented an extensive overview of the magnesite mineralizations of the Eastern Alps in 1986. MÖLLER (1989) edited a monograph on magnesite summarizing the recent geochemical and mineralogical facts on the “magnesite problem”. During more recent years, new fluid inclusion and isotope data for the sparry magnesite deposit of the Eastern Greywacke Zone provide strong evidence for formation of the magnesite deposits by metasomatic replacement due to infiltrating salinar residual brines which originated in the Upper Permian/Lower Triassic (e.g. PROCHASKA, 2000; PROCHASKA, 2001; PROCHASKA & HENJES-KUNST, 2007). These observations are considered to be of fundamental importance not only for the genetic aspects of carbonate-hosted sparry magnesite deposits but also hinting towards a consanguineous origin of the magnesite and siderite deposits of the Eastern Alps in general. Very recent results obtained by radiometric age dating of the carbonate formation provide proof for Triassic ore formation (HENJES-KUNST et al., 2014; PROCHASKA & HENJES-KUNST, 2009).

Earlier workers, especially PETRASCHECK (1926, 1932) in his classic work on the metallogenetic zonation in the Eastern Alps, already mentioned a consanguineous origin of the alpine sparry magnesite mineralizations and the siderite deposits as proposed here. Also other early investigators (REDLICH, 1907, 1909; CLAR, 1956; FRIEDRICH, 1959, etc.) generally argued for hydrothermal fluids of different origin like magmatic or metamorphic fluids of alpine (Neogene) age. Nevertheless these concepts never gained general acceptance at that time.

3. GEOLOGIC POSITION AND STRUCTURAL FEATURES OF THE MAGNESITE AND SIDERITE MINERALIZATIONS

The magnesite and siderite mineralizations occur in the Greywacke Zone, which is the Palaeozoic basement of the Mesozoic platform carbonates of the Upper Austroalpine nappe. Fundamental overviews of the geology and tectonostratigraphy of the Greywacke Zone were given by SCHÖNLAUB (1982), NEUBAUER (1994) and NEUBAUER et al. (1994). The rock series of the Greywacke Zone range from the Ordovician to the Carboniferous and com-

Figure 2. Pinolitic sparry magnesite with late quartz-veins of Eoalpine age from the Veitsch deposit.

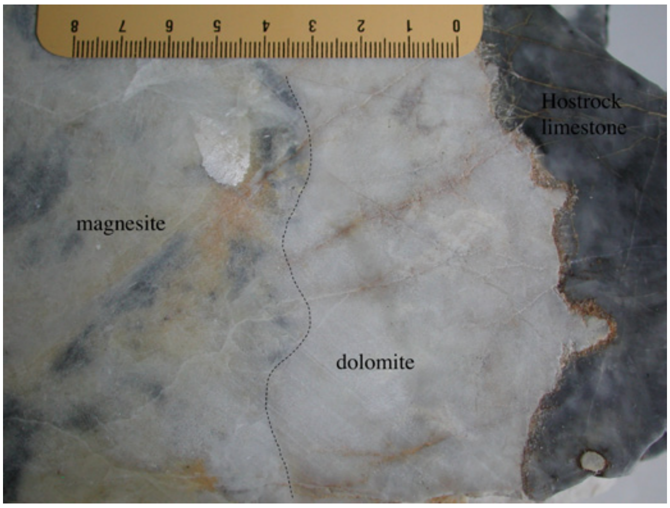

Figure 3. „Metasomatic front" between the fine-grained host-rock marble and the sparry magnesite. An intermediate reaction product between the magnesite and the host-rock is sparry dolomite.

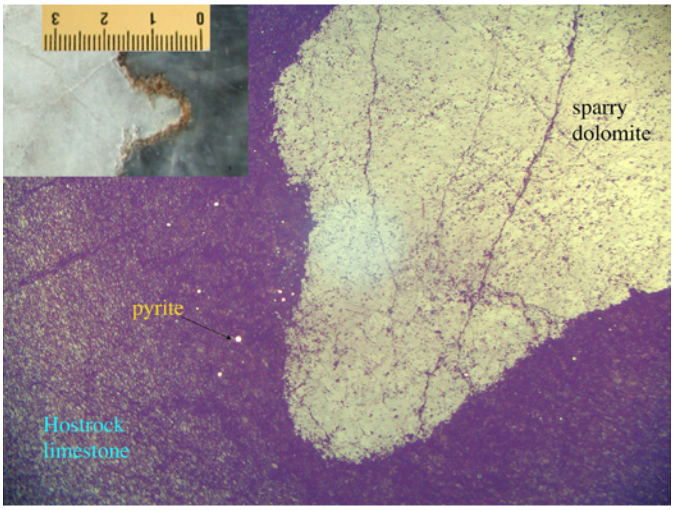

Figure 4. The reducing nature of the ore forming fluid causes a pyrite halo in the host-rock carbonate before the „Metasomatic front" while pyrite is usually lacking in these host-rocks.

prise carbonates, metapelites, and metamorphosed acid volcanics. The grade of metamorphism is generally lower greenschist facies both in the Variscan and in the eoalpine tectonometamorphic event. The tectonically lower Veitsch nappe is affected only by the alpine metamorphism of greenschist facies grade.

Generally, magnesite mineralizations tend to form irregular lenses and stocks whereas no veins are known. The siderite deposits occur as stocks in the carbonate environment and as veins in different host-rock lithologies (see below).

3.1. MAGNESITE MINERALIZATIONS

In the Eastern Greywacke Zone, carbonate-hosted sparry magnesite mineralization occurs mainly in Lower Carboniferous strata of the Veitsch nappe. A set of lens-shaped magnesite bodies of various sizes can be observed in a sequence of sericite schists, greywackes, conglomerates and metatuffs. Carbonate series hosting the magnesite bodies are of Upper Tournéan/Viséan age and characterise shallow water, marine environments. An exception is the Breitenau mine, which is located in a Palaeozoic series of deep-water environments of probably Silurian to Lower Devonian age.

One of the most prominent examples of sparry magnesite deposits in the Eastern Alps is the abandoned Veitsch mine, which is the type locality of carbonate hosted sparry magnesite deposits.

In the Western Greywacke Zone, magnesite can be seen in Palaeozoic strata of a remarkable age spread from Upper Silurian to Middle Devonian series. The most abundant host-rocks of magnesite mineralization in this area are dolomites of the Lower to Middle Devonian, but also black dolomite of Silurian age hosts magnesite occurrences (e.g. Entachen Alm). SIEGL (1969) reported magnesite components in the Permian basal breccia of the Alpidic orogenic cycle.

The position of the highly metamorphosed Radenthein deposit is unclear. Some authors (ANGEL et al., 1953) consider it to be a tectonic wedge of Upper Austroalpine Palaeozoic rocks thrust into the tectonically deeper Austroalpine Crystalline Units during the alpine tectonic event while others (TUFAR et al., 1989) regard it as an original member of the rock sequence.

The most obvious and striking textural feature of these mineralizations is the coarse-grained, sparry structure of the magnesites. These "pinolitic" structures are defined by coarse-grained magnesite crystals which occur in a dark/black fine-grained matrix. These structures are especially developed when the host-rocks are grey to black marbles. It is obvious that this structure is due to the hydrothermal growth of coarse-grained, white magnesite crystals, while the organic pigment is concentrated in the fine-grained matrix.

The hydrothermal-epigenetic nature of the magnesite mineralizations is reflected by the fact that the orebodies are enveloped by alteration zones of variable width. Hydrothermal, mottled dolomite, often exhibiting banding and zebra structures of several metres thickness, prevails in these zones. These reaction fronts can sometimes be reduced to a few cm as demonstrated in Fig. 3. The first signs of hydrothermal substitution forming sparry dolomite and magnesite on account of the host-rock calcite are small specs of pyrite formed in the host-rock in the immediate vicinity of the reaction front testifying to the reducing nature of the hydrothermal fluid (Fig. 4).

3.2. SIDERITE MINERALIZATIONS

The siderite mineralizations of the Eastern Alps are concentrated in two different metallogenetic provinces, the Hüttenberg-Waldenstein Fe-ore province and the Erzberg-type mineralizations of the Greywacke Zone (Fig. 1). This paper refers only to the latter Fe-ore province. Many abandoned deposits and the Erzberg mine belong to this metallogenetic province. The fact that these mineralizations do not occur in deeper tectonic units of the Greywacke Zone supports a timing of mineralization before the stacking of the Austroalpine nappes. Another significant feature is that this type of mineralization shows indications of a continuation into deeper parts of the overlying Lower Triassic carbonates of the Northern Calcareous Alps of the Upper Austroalpine units, however, the thick units of platform carbonates of the Northern Calcareous Alps were not affected by the mineralizing events.

The other set of siderite/haematite mineralizations is concentrated in the amphibolite facies metamorphic complexes of the Austroalpine Crystalline units to the south. The most important mineralization of this group is the former siderite mine of „Hüttenberg“ which was abandoned in the 1970`s. This Tertiary siderite province is of different origin to the Greywacke Zone deposits and is not covered further in this paper.

The siderite occurrences in the Greywacke Zone are neither stratabound nor stratiform and exhibit different modes of occurrence. Host-rock lithology strongly influences the structure of the mineralizations. Vein type mineralizations usually occur in competent host-rocks such as Ordovician quartz porphyries or Palaeozoic metapelites and sandstones, while more reactive host-rocks including the Devonian carbonates and Permoscythian carbonate conglomerates host metasomatic bodies, lenses and stocks of siderite.

3.2.1. Siderite veins in Ordovician quartz porphyries

Underground exposures of this ore type are best exposed in the abandoned Schendleck siderite mine (Fig. 1.). The structure of this mineralization is that of a typical vein type deposit with siderite-quartz veins cross-cutting Ordovician quartz porphyries exhibiting prominent alteration zones with intense sericitization. These structures were previously interpreted (BAUMGARTNER, 1976) as tuff layers, and accordingly a synsedimentary formation was deducted. The abandoned Hirschwang, Altenberg and Grillenberg siderite mines are in close vicinity of this mineralization, but hosted by Permoskythian siliciclastic series. In the area of the Erzberg siderite mine, which is generally hosted by Devonian limestones (see below) many smaller siderite veins are located in altered quartz porphyry host-rock.

3.2.2. Metasomatic siderite bodies in Devonian limestones and Upper Permian carbonate conglomerates

The most prominent example of this type of siderite mineralization is the Erzberg siderite mine in the province of Styria. The siderite orebodies are generally hosted by fine-grained limestones of Devonian age. Metasomatic-epigenentic structures are dominant and usually coarse-grained siderite ore exhibits discordant contacts with the unmineralized limestones. The only ore mineral is siderite, but frequently ankerite haloes around the siderite orebodies can be observed. Fig. 5 shows the metasomatic front between the carbonatic breccia and the orebody cutting single components of the breccia, demonstrating clearly the metasomatic-hydrothermal nature of the mineralization. Furthermore, no single siderite components in the calcite breccia are known as should be the case with a pre-Permian siderite mineralization.

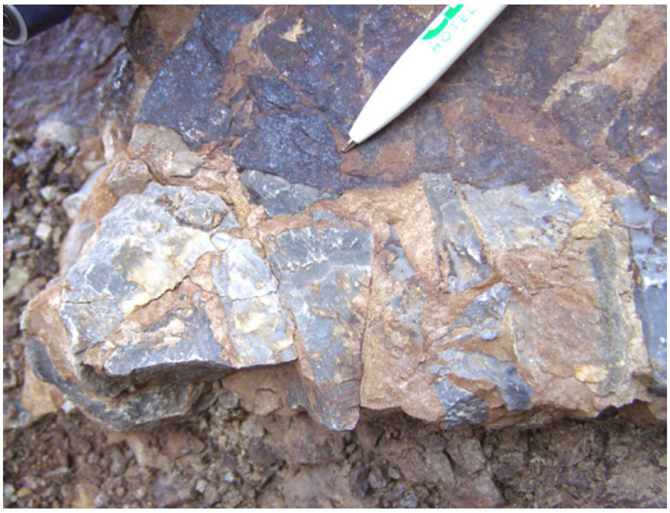

Figure 5. The metasomatic siderite front in the mineralized "Basisbrekzie" cuts the single carbonate components thus proving the hydrothermal metasomatic nature of the mineralization.

Eoalpine tectonic structures and weak metamorphic overprints are described from the Erzberg deposit.

3.2.3. Vein type mineralizations in Permoskythian siliciclastic host-rocks

Different occurrences of this type of mineralization were investigated within the course of this work (Gollrad, Grillenberg, Sohlenalm, Altenberg). The mineralizations are usually hosted by Permoskythian quartz-conglomerates (Präbichel series), and sandstones (Werfen formation) forming the base of the Upper Austroalpine Northern Calcareous Alps. The usual structure is that of siderite veins cross-cutting Permoskythian sandstones and conglomerates, but in some cases haematite is the dominant ore mineral. The former Gollrad siderite/haematite mine was recently reinvestigated for its economic potential of specular haematite.

4. CHEMICAL CHARACTERISTICS OF INCLUSION FLUIDS OF THE SIDERITE AND MAGNESITE MINERALIZATIONS

Because of the conformable chemical characteristics of the mineralizing fluids the results concerning the magnesite as well as the siderite mineralizations are presented and discussed together in this chapter. In order to characterize the nature of the ore-forming fluids the chemistry of the inclusion fluids of the siderite and magnesite deposits was investigated by mechanical extraction and subsequent analysis (POLGARI et al., 2010; PROCHASKA, 2012). The method applied here is based on the "crush-leach" extraction of the inclusion fluids and chemical analyses by ion chromatography of the most diagnostic components. The methodological approach used is modified after BOTTRELL et al. (1988) and is explained in detail in PROCHASKA (2000).

The characterization of the total dissolved solutes chemistry of inclusion fluids was first and most widely applied to the study

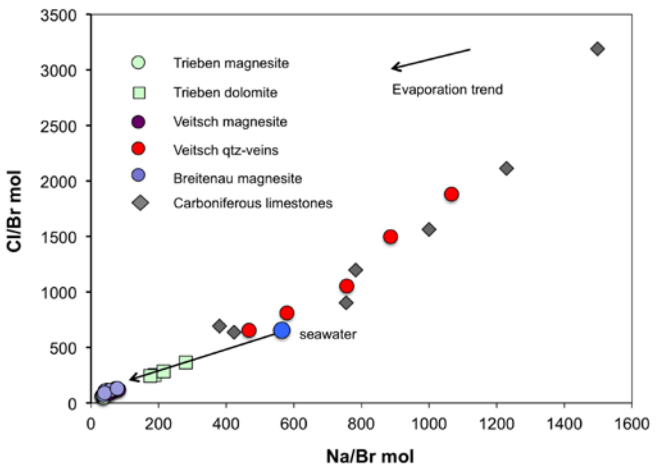

Figure 6. Na-Cl-Br ratios of the magnesite mineralizations of the Eastern Alps. The fluid composition clearly plots on the very end of the seawater evaporation trend proving the evaporitic origin of the fluids. Host-rock limestones are relatively close to seawater composition as well as the fluid composition of the Eoalpine quartz-veins (see also Fig. 3).

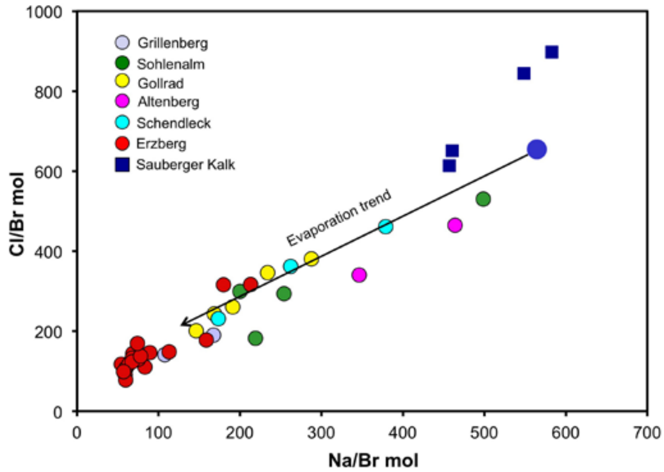

Figure 7. Na-Cl-Br ratios of the Erzberg type siderite mineralizations. The fluid composition plots on the seawater evaporation trend.

of Mississippi Valley type Pb-Zn mineralization in order to obtain information on the sources of solutes in ore-forming brines and to explore genetic linkages among deposits (e.g. HALL & FRIEDMAN, 1963; VIETS & LEACH, 1990; BÖHLKE et al., 1992; KESLER et al., 1996). Despite the similar ionic radii of chlorine (1.81 Å) and bromine (1.96 Å) the fractionation of these elements in evaporitic processes is quite different. In an initial stage of evaporation Na, Cl, and Br are concentrated in a hypersaline environment, and their ratios do not change. At an evaporation index of > 10, halite is precipitated. Br has a very conservative behaviour and is not incorporated into the halite lattice. At an evaporation index of approx. 70, Mg-salts start to precipitate and Br is still concentrated in the residual brines. The cation systematics changed from an original Na preponderance to Mg and K dominated systems (McCAFFEREY et al., 1987).

On the Cl/Br and Na/Br molar ratio diagrams for magnesite (Fig. 6) and siderite (Fig. 7) the evolution of the fluids by fractionation of halite from seawater is demonstrated. According to the fractionation behaviour of the Na-Cl-Br system explained earlier, the composition of an evaporating brine shifts along the "evaporation trend" when halite starts to precipitate at an evaporation index of about 10. In contrast, fluids percolating through the crust acquiring salinity by dissolution of halite, plot towards higher Cl/Br and Na/Br molar ratios above the seawater composition, and their composition is close to the „halite dissolution trend".

In the Cl/Br and Na/Br molar ratio diagrams for magnesite as well as siderite (Figs. 6, 7) the inclusion chemistry of the investigated samples clearly plot on the seawater evaporation trend, thus indicating an origin of the fluids from subaerial evapo-concentration of seawater. In general the magnesite fluids show a stronger fractionation and the composition of the fluids plot on the very end of the evaporation trend. The plots of the dolomites of the alteration zone exhibit a transitional position between the magnesite composition and that of seawater.

Despite the general similarity and the overall evaporitic nature of the fluids, the siderite fluid composition shows in some cases an intermediate position between extreme fractionation and seawater composition. In general the Erzberg-fluids are highly fractionated and plot at the end of the evaporation trend (Fig. 7) while the projection points of smaller, vein-type systems (e.g. Altenberg, Sohlenalm…) are not as Br-rich as the big and voluminous Erzberg siderites. The reasons for these fluid characteristics may be the result of the differences in the degree of the fluid-rock interaction where in the smaller systems the composition of the fluid is altered while in the bigger systems the original fluid characteristics prevail.

A prerequisite for the formation of hydrothermal-metasomatic deposits described here is a highly saline fluid capable of leaching Fe from the host-rocks while percolating through the crust. In the case of the Austroalpine sparry carbonate deposits the ore-forming fluids originally were bittern brines. However, the siderite deposits in Tunesia and Algeria/North Africa, investigated by POHL et al. (1986) exhibit highly saline fluids, which were generated by partial dissolution of salt diapirs. Accordingly these fluids are characterized by extremely high Cl/Br and Na/Br ratios (Prochaska unpublished) and plot on the halite dissolution trend.

5. TIMING OF THE MINERALIZING EVENT

Timing of the mineralization is one of the most important pieces of information needed to establish a genetic model within the geodynamic frame of the alpine or prealpine orogenic cycles, and therefore detailed investigations on radiometric dating were carried out during recent years. The fact that the mineralized structures and the mineralizations cut Permo-Mesozoic strata exclude a syngenetic Devonian formation for these deposits. However, the Eoalpine metamorphic event is considered by some authors to be responsible for modification and remobilization of early syngenetic mineralizations finally producing epigentic vein type deposits. In this study no indication of two fundamentally different sets of fluid compositions (e.g. marine-sedimentary and alpine hydrothermal) in the ore minerals (siderite and magnesite) were discovered. There are some localities where the mineralized Devonian limestones can be found in close proximity to totally unmineralized Carboniferous limestones of the tectonically deeper Veitsch nappe. In the case of an

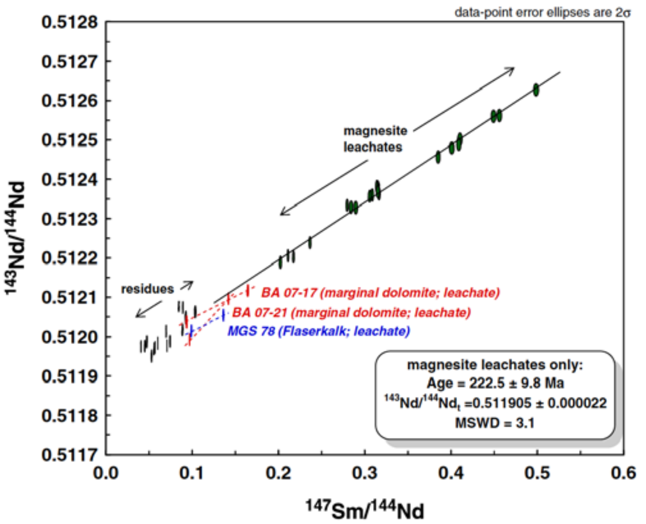

Figure 8. Sm-Nd isochron of the Breitenau magnesite deposit (HENJES-KUNST et al., 2014). For explanation see text.

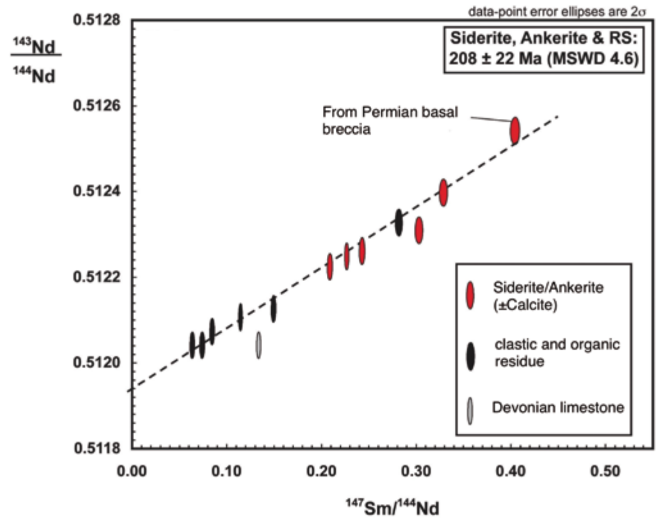

Figure 9. Sm-Nd isochron of the siderites from the Erzberg deposit (PROCHASKA & HENJES-KUNST, 2009). For explanation see text.

extensive Cretaceous metamorphic mobilization, the mineralized structures should also cut the tectonic units. However, all observations support the formation of the siderites before the alpine stacking of the nappes.

Some attempts have been made to obtain radiometric ages from sericites from the alteration zones of a siderite mineralization in the quartz porphyries (PROCHASKA et al., 1996). A plateau age (Ar-Ar) of approximately 160 Ma for the Schendleck deposit was calculated. This age seems to be of some regional importance at the eastern margin of the Eastern Alps and is probably not the age of the hydrothermal ore-forming event. It coincides with an extensional phase in the Austroalpine area due to the opening of the South Penninic ocean. Furthermore, a prominent rejuvenation due to the Cretaceous metamorphic event (~90 Ma) can be observed from the Ar-Ar investigations. Consequently, from a geological point of view and from Ar-Ar data, the siderite-forming hydrothermal activity is not older than Permoskythian and predates the Eoalpine tectono-metamorphic event.

Essential progress on the age determination of the hydrothermal event responsible for the formation of the siderite and magnesite deposits of the Eastern Alps was the direct age dating of the carbonate minerals using the Sm-Nd radiometric system. During recent years radiometric information of some magnesite and siderite mineralizations were obtained and the formation ages cluster in the Middle to Upper Triassic (Figs. 8, 9).

The method is explained comprehensively in HENJES-KUNST et al. (2014) where a detailed investigation and a sound model for the formation of the Breitenau magnesite deposit is presented. The Sm-Nd isochron age for this deposit is 222.5 ± 9.8 Ma (Fig. 8), which coincides very well with the unpublished isochron age for the Wald/Schober magnesite deposit of the Greywacke Zone with an age of approx. 220 Ma. PROCHASKA & HENJES-KUNST (2009) published an isochron age of 208 ± 22 Ma (Fig. 9) for the Erzberg siderite deposit, which is in the range of the above mentioned magnesite deposits.

6. GENETIC MODEL

The genetic model presented here is based on the following observations:

1. The mineralizing event is post-Variscan and pre-Eoalpine because of the lack of siderite components in Upper Permian Variscan basal conglomerates and the termination of hydrothermal features at alpine nappe boundaries.
2. In general the magnesite as well as the siderite mineralizations are neither stratabound nor stratiform.
3. The high salinity of the fluids and especially the fractionated, Br-rich composition indicate that the mineralizing fluids were originally oxidized evaporitic, bittern brines which, while percolating through the crust became modified and reduced by water-rock reactions thus facilitating the capability to take up Fe by leaching the host-rocks.
4. The sharp transition in the fluid composition (evapo-concentrations of seawater) between marine host-rock carbonates and the mineralizations is not compatible with a simple marine-sedimentary model.
5. The structure of the mineralizations is hydrothermal-metasomatic. No indications of a synsedimentary concentration of Mg or Fe can be observed.
6. Radiometric dating provides proof for the formation of these mineralizations in the Upper Triassic. Only in one case so far (Hohentauern) has a Late Carboniferous to Early Permian age been reported by AZIM ZADEH et al. (2015).

In Permian (to Lower Triassic) times evaporitic basins are ubiquitous in the Austroalpine realm. Deposition of thick series of evaporites is widespread in the Permoscythian strata of the Upper Austroalpine unit. High degrees of evaporation (evaporation index 20 to 90) produced residual „bitterns“ with high salinities and high concentrations of Br, Mg, K, and SO_4 in the fluids. The peculiar fluid composition of the siderite and magnesite mineralizations can only be achieved in the wide evaporitic areas during the Permo-Mesozoic of the Eastern Alps.

For the earlier magnesites (e.g. Hohentauern), AZIM ZADEH et al. (2015) propose an intraformational circulation of Carboniferous evaporitic fluids causing metasomatic replacement of the host-rocks. However, extensive evaporitic systems which could produce brines with the corresponding high evaporation index, are not known so far in the Carboniferous.

For the siderite and magnesite deposits of Middle to Upper Triassic age, two genetic models are plausible: High heat flow in the rift-environment induced hydrothermal convection systems mobilizing the residual evaporitic brines. Lithospheric extension and long-lasting thermal activity related to igneous and metamorphic activities are documented in the basement rocks of the Adriatic plate (THÖNI, 2002). Mineral assemblages are reported in rocks ranging from 285 to 225 Ma in age. Generally this process can be responsible for the formation of the siderite and magnesite mineralizations in the Upper Triassic. Another possibility for mobilizing the palaeobrines of Upper Permian to Lower Triassic age in the Upper Triassic is the dewatering of the sedimentary basins by the increasing load caused by the sedimentation of the platform carbonates of several km in thickness, triggering the upward movement of the fluids. Of course these two mechanisms could have operated in concert.

Initially these fluids are ± free of Fe and rich in Mg with the capacity to transform the carbonatic host-rocks into magnesite. When these fluids travel longer distances through the crust, diagenetic reactions and host-rock alterations changed these brines into acidic and reducing fluids with the capacity of leaching Fe from the country rocks, with the corresponding metasomatic product being siderite. This is compatible with the generally higher formation temperatures of siderite showing the formation of the Fe-carbonates in deeper levels where higher temperatures prevail.

Vein-type siderite-haematite-sulfide mineralizations were formed in the metapelitic and metavolcanic host-rocks. Within the Devonian platform carbonates metasomatic siderite bodies were formed. Metasomatism and mimetic crystallization of the marine host-rock carbonates often preserved primary sedimentary textures very well, which led earlier researchers to postulate syngenetic models.

However, the proposed hydrothermal-metasomatic model of Permoscythian evolved evaporitic brines being mobilized in the Upper Triassic can explain all the observed features of the siderite and magnesite mineralizations of the Greywacke Zone regardless of their stratigraphic and tectonic position. This model is consistent with features such as the overall high salinity of the fluids, the uniform and special fluid chemistry and the published Sr- and stable isotope ratios which cannot be explained by either sedimentary scenarios or by alpine remobilization models.

A phenomenon that cannot be explained satisfactorily so far is the observation that the magnesite deposits exclusively occur in the lower tectonic unit of the Greywacke Zone (Carboniferous Veitsch nappe) while the siderite mineralizations are strictly bound to the higher unit (Paleozoic Noric nappe). A more detailed knowledge of the palaeogeography of the Upper Triassic is needed to elucidate this problem.

REFERENCES

ANGEL, F., AWERZGER, A., KUSCHINSKY, A. & MEIXNER, H. (1953): Die Magnesitlagerstätte Milstätter Alpe bei Radenthein.– Carinthia II, 143, 98–118.

AZIM ZADEH, A.M., EBNER, F. & JIANG, S. (2015): Mineralogical, geochemical, fluid inclusion and isotope study of Hohentauern/Sunk sparry magnesite deposit (Eastern Alps/Austria): implications for a metasomatic genetic model.– Mineralogy and Petrology, 109/5, 555–575.

BAUMGARTNER, W. (1976): Zur Genese der Erzlagerstätten der östlichen Grauwackenzone und der Kalkalpenbasis etc.– BHM, 121, 51–54.

BELOCKY, R. (1992): Regional vergleichende Untersuchung lagerstättenbildender Fluide in den Ostalpen als Hinweis auf eine mögliche metamorphe Ableitung.– Unpubl. Thesis, Univ. Braunschweig, 103 p.

BERAN, A. (1973): Vorläufige Mitteilung über Mikrosondenuntersuchungen an einigen Ankeriten und Sideriten vom Steirischen Erzberg.– Österr. Akad. Wiss., Math.-Naturwiss. Kl., 3, 19–20.

BERAN, A. (1975): Mikrosondenuntersuchungen von Ankeriten und Sideriten des Steirischen Erzberges.– TMPM, 22, 250–265. doi: 10.1007/BF01087844

BERAN, A. (1977): Die Kluftankerite des Steirischen Erzberges und ihre mögliche Verwendung als Geothermometer.– Mineral. Deposita, 12, 90–95.

BERAN, A. (1979 a): Die Stellung der Ankeritgesteine im Rahmen der Genese von Sideritlagerstätten der östlichen Grauwackenzone.– TMPM, 26, 217–233.

BERAN, A. (1979b): Die Mineralogie von Ankeriten und Sideriten des Steirischen Erzberges und der Radmer.– Verh. Geol. B.-A., 3, 237–239.

BERAN, A. & THALMANN, F. (1977): Feinkörnige gebänderte Siderite im Spateisensteinbergbau Radmer-Buchegg.– Österr. Akad. Wiss., Math.-Naturwiss. Kl., 4, 57–62.

BERAN, A. & THALMANN, F. (1978): Der Bergbau Radmer-Buchegg – ein Beitrag zur Genese Alpiner Sideritlagerstätten.– TMPM, 25, 287–303.

BÖHLKE, J.K. & IRWIN, J.J. (1992): Laser microprobe analyses of Cl, Br, I, and K in fluid inclusions: Implications for sources of salinity in some ancient hydrothermal fluids.– Geochimica et Cosmochimica Acta, 56, 203–255. doi: 10.1016/0016-7037(92)90127-5

BOTTRELL, S.H., YARDLEY, B.W.D. & BUCKLEY, F. (1988): A modified crush-leach method for the analysis of fluid inclusion electrolytes.– Bull. Mineral., 111, 279–290.

CLAR, E. (1956): Zur Entstehungsfrage der ostalpinen Spatmagnesite.– Carinthia II, 60, 22–31.

DE LLARENA, J.G. (1953): Über die sedimentäre Entstehung des ostalpinen Magnesits „Typus Veitsch".– Montan-Zeitung, 69, 55–62.

FRIEDRICH, O. (1959): Zur Genesis der ostalpinen Spatmagnesit-Lagerstätten.– Radex Rundschau, 393–420.

FRIMMEL, H. (1988): Strontium isotopic evidence for the origin of siderite, ankerite and magnesite mineralizations in the Eastern Alps.– Mineralium Deposita, 23, 268–275. doi: 10.1007/BF00206407

HALL, W.E. & FRIEDMAN, I. (1963): Composition of fluid inclusions, Cave-in-rock fluorite district, Illinois, and Upper Mississippi Valley zinc-lead district.– Economic Geology, 58, 886–911. doi: 10.2113/gsecongeo.58.6.886

HENJES-KUNST, F., PROCHASKA, W., NIEDERMAYR, A., SULLIVAN, N. & BAXTER, E. (2014): Sm-Nd dating of hydrothermal carbonate formation: An example from the Breitenau magnesite deposit (Styria, Austria).– Chem. Geol., 387, 184–201.

KESLER, S.E., MARTINI A.M., APPOLD M.S., WALTER, L.M., HUSTON T.J. & FURMAN, F.C. (1996): Na-Cl-Br systematics of fluid inclusions from Mississippi valley-type deposits, Appalachian basin: Constraints on solute origin and migration paths.– Geochimica et Cosmochimica Acta, 60/2, 225–233. doi: 10.1016/0016-7037(95)00390-8

KOCH, M. (1893): Mittheilung über einen Fundpunkt von Untercarbon-Fauna in der Grauwackenzone der Nordalpen.– Z. Dtsch. Geol. Ges., 45, 294–298.

LAUBE, N., FRIMMEL, H.E. & HOERNES, S. (1995): Oxygen and carbon isotopic study on the genesis of the Steirischer Erzberg siderite deposit (Austria).– Mineral. Deposita, 30, 285–293. doi: 10.1007/BF00196364

LEITMEIER, H. (1917): Einige Bemerkungen über die Entstehung von Magnesit- und Sideritlagerstätten.– Mitt. Geol. Ges. Wien, 9, 159–166.

LEITMEIER, H. & SIEGL, W. (1954): Untersuchungen an Magnesiten am Nordrande der Grauwackenzone Salzburgs und ihre Bedeutung für die Entstehung der Spatmagnesite der Ostalpen.– BHM, 99, 201–208 and 221–235.

McCAFFREY, M.A., LAZAR, B. & HOLLAND, H.D. (1987): The evaporation path of seawater and coprecipitation of Br^- and K^+ with halite.– J. Sediment. Petrol., 57, 928–937.

MÖLLER, P. (1989): Magnesite – Geology, Mineralogy, Geochemistry, Formation of Mg-Carbonates.– Mongraph Series On Mineral Deposits, Borntraeger, Berlin, 300 p.

NEUBAUER, F., HANDLER, R., HERMANN, S. & PAULUS, G. (1994): Revised Lithostratigraphy and Structure of the Eastern Graywacke Zone (Eastern Alps).– Mitt. Österr. Geol. Ges., 86, 61–74.

NEUBAUER, F. (1994): Kontinentkollision in den Ostalpen.– Geowissenschaften, 12, 136–140.

NIEDERMAYR, G. (1989): Die Magnesite im Perm und Skyth des Drauzuges.– Carinthia II, 179/99, 391–399.
PETRASCHECK, W. (1926): Metallogenetische Zonen in den Ostalpen.– C.R. XIV, Congr. Geol. Intern., Madrid 1926, 1243–1253.
PETRASCHECK, W. (1932): Die Magnesite und Siderite der Alpen. Vergleichende Lagerstättenstudien.– Anz. Österr. Akad. Wiss., math.- nat. Kl., 141, 195–242.
POHL, W. (1986): Comparative Metallogeny of Siderite Deposits.– Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaften Komm., 8, 271–282. doi: 10.1007/978-3-7091-5822-7_22
POHL, W. & BELOCKY, R. (1994): Alpidic Metamorphic Fluids and Metallogenesis in the Eastern Alps.– Mitt. Österr. Geol. Ges., 86, 141–152.
POHL, W., AMOURI, M., KOLLI, O., SCHEFFER, R. & ZACHMANN, D. (1986): A new genetic model for the North African metasomatic siderite deposits.– Mineral. Deposita, 21, 228–233. doi: 10.1007/BF00199805
POLGÁRI, M., PROCHASKA, W. & BERAN, A. (2010): Alpine carbonate minig sites: Aspects of carbonate mineralizations related to the manganese mine of Úrkút, Hungary, the magnesite deposit of Veitsch and the siderite mine «Steirischer Erzberg», Austria.– Acta Mineralogica Petrographica, Field guide series, 4, 1–16.
PROCHASKA, W. (1991): Beispiele für alpidisch-hydrothermale Lagerstättenbildung in den Ostalpen.– Mitt. naturwiss. Ver. Steiermark, 121, 129–148.
PROCHASKA, W. (1997): Formation of different siderite provinces during the Alpine tectono-metamorphic event in the Eastern Alps of Austria.– In: Mineral Deposits Research and Exploration. Where do they meet? Proceedings of the 4th Biennial SGA Meeting Turku 1997, Balkema, Rotterdam, 1997, 845–848.
PROCHASKA, W. (2000): Magnesite and talc deposits in Austria.– Mineralia Slovaca, 32, 543–548.
PROCHASKA, W. (2001): Magnesite Mineralizations of the Eastern Alps and the Carpathians.– In: PIESTRZYNSKI et al. (eds.): Mineral Deposits at the Begining of the 21 st Century, Swets & Zeitlinger Publishers Lisse, 2001, 1017–1019.
PROCHASKA, W. (2012): Siderite and magnesite mineralizations in Palaeozoic strata of the Eastern Alps (Austria).– Field Trip Guide, 29th IAS Meeting of sedimentology, Schladming, Austria, Journal of Alpine Geology, 54, 309–322.
PROCHASKA, W., FRANK, W. & BECHTEL, A. (1996): Pretertiary Siderite Minerali-zation in the Greywacke Zone of the Eastern Alps.– Mineralia Slovaca-Monography, Bratislava, 165–174.
PROCHASKA, W. & HENJES-KUNST, F. (2007): The origin of sparry magnesite in the Eastern Alps (Austria): evidence from inclusion fluid and Sr-Nd isotope chemistry.– In: Proceedings of the 9th Biennial Meeting of the Society for Geology Applied to Mineral Deposits Dublin, IAEG, 2007, 2, 823–826.
PROCHASKA, W. & HENJES-KUNST, F. (2009): Genese der Siderit-Vererzungen der östlichen Grauwackenzone - aktueller Stand der Forschung.– Arbeitstagung Geol. B.-A., 2009, Blatt 101 Eisenerz, 153–169.
REDLICH, K.A. (1907): Die Genesis der Pinolitmagnesite, Siderite und Ankerite der Ostalpen.– TMPM, 26, 499–505.
REDLICH, K.A. (1909): Die Typen der Magnesitlagerstätten.– Z. Prakt. Geologie, 17, 300–310.
RUMPF, J. (1873): Über krystallisierte Magnesite aus den nordöstlichen Alpen.– Min. Petr. Mitt., 263–272.
SCHÖNLAUB, H.P. (1982): Die Grauwackenzone in den Eisenerzer Alpen (Österreich).– Jahrb. Geol. B.-A., 124, 361–423.
SCHOUPPE, A. (1854): Geognostische Bemerkungen über den Erzberg bei Eisenerz.– Jahrb. Geol. Reichsanstalt, 5, 396–405.
SCHULZ, O., VAVTAR, F. & DIEBER, K. (1997): Die Siderit-Erzlagerstätte Steirischer Erzberg: Eine geowissenschaftliche Studie, mit wirtschaftlicher und geschichtlicher Betrachtung.– Arch. F. Lagerst.forsch. Geol. B.-A., 20, 65–178.
SIEGL, W. (1969): Entwurf zu einer salinar-sedimentären Entstehung der Magnesite vom Typ Entachen (Salzbrg).– Mineralium Deposita, 4, 225–233.
SPINDLER, P. (1992): Neue Untersuchungen zur Mineralogie und Geochemie der Basisbreccie des Steirischen Erzberges, Österreich.– Österr. Akad. Wiss., Math.-Naturwiss. Kl., 1–25.
THALMANN, F. (1979): Zur Eisenspatvererzung in der nördlichen Grauwackenzone am Beispiel des Erzberges bei Eisenerz und Radmer/Bucheck.– Verh. Geol. B.-A., 479–489.
THÖNI, M. (2002): Sm-Nd isotope systematics in garnet from different lithologies (Eastern Alps): age results, and an evaluation of potential problems for garnet Sm–Nd chronometry.– Chem. Geol., 185, 255–281. doi: 10.1016/S0009-2541(01)00410-7
TOLLMANN, A. (1977): Geologie von Österreich. Band I Die Zentralalpen. Franz Deuticke, Wien, 766 p.
TUFAR, W., GIEB, J., SCHMIDT, R., MÖLLER, P., POHL, W., RIEDLER, H. & OLSACHER, A. (1989): Formation of magnesite in the Radenthein type locality (Carinthia, Austria).– In: MÖLLER, P. (ed.): Magnesite – Geology, Mineralogy, Geochemistry, Formation of Mg-Carbonates.– Monograph Series on Mineral Deposits, Berlin, 28, 135–171.
VACEK, M. (1903): Der steirische Erzberg.– Exk. Führer 9. Int. Geol. Kongreß, 27, Wien, 27 p.
VIETS, J.G. & LEACH, D.L. (1990): Genetic implications of regional and temporal trends in ore fluid geochemistry of Mississippi Valley-type deposits in the Ozark region.– Economic Geology, 85, 842–861. doi: 10.2113/gsecongeo.85.4.842
WEBER, L. (1997): Metallogenetische Karte von Österreich (1: 500.000) und Handbuch der Lagerstätten der Erze, Industrieminerale und Energierohstoffe Österreichs.– Arch. Lagerst.forsch. Geol. B.-A., 19, 1–607.