Siderite and magnesite mineralizations in Palaeozoic strata of the Eastern Alps (Austria)

By

WALTER PROCHASKA

With 12 figures

Field Trip Guide

29th IAS Meeting of Sedimentology
Schladming, Austria

Address of the author:
University of Leoben
Department of Geological sciences and Geophysics, Geology and Economic Geology
Peter Tunner Strasse 5
8700 Leoben,
Austria
Email: walter.prochaska@unileoben.ac.at

Journal of Alpine Geology	54	S. 309-322	Wien 2012

Content

Abstract

The field trip focuses on the siderite and sparry magnesite mineralizations in Palaeozoic strata of the Eastern Alps. In both mineralizations, siderites as well as magnesites, metasomatic-epigenetic structures of lens-shaped orebodies with dolomitic alteration rims are dominant features. The basic chemical features of the ore forming fluids in these mineralizations are very similar indicating closely related ore forming processes. Both types of mineralizations were formed by the invasion of younger brines representing a unique type of secondary - diagenetically induced - sedimentary ore deposits. Fluid invasion and mineralization structure strictly depend on the original lithology of the host rocks, mainly carbonatic sedimentary rocks. In Late Triassic times, evaporitic brines were mobilized and their circulation led to siderite as well as magnesite formation.

1. Topics of the Field Trip

The field trip focuses on the siderite and sparry magnesite mineralizations in Palaeozoic strata of the Eastern Alps. Today slightly metamorphosed Palaeozoic rocks represent originally the sedimentary successions of the Variscan cycle. Opinions concerning the genesis of the siderite mineralizations in these rocks are inconsistent and discussions on this topic have a long-standing tradition. Early geoscientists favoured syngenetic models; at the turn of the century epigenetic models for the Erzberg type mineralization were proposed.

At present the impressive Steirischer Erzberg (‘Austrian pyramid’) siderite deposit near the town Eisenerz is the only operating iron mine in Austria and one of the largest siderite mines in the world. Currently the Austrian iron ore production of about 2 million t is exclusively produced from this giant open pit mine. The siderite body of the Erzberg is generally hosted in fine-grained limestones of Devonian age, similar to equivalent siderite deposits in the surroundings.

The sparry magnesite mineralizations occur exclusively in Carboniferous host rocks which belong to the same original sedimentary succession as the siderite deposits. The magnesite mineralizations occur very widespread in these Carboniferous rocks, and currently Austria is holding a prominent position in the world’s magnesite production.

In both mineralizations, siderites as well as magnesites, metasomatic-epigenetic structures of lens-shaped orebodies with dolomitic alteration rims are dominant features. The basic chemical features of the ore forming fluids in these mineralizations are very similar indicating closely related ore forming processes. Both types of mineralizations were formed by the invasion of younger brines representing a unique type of secondary - diagenetically induced - sedimentary ore deposits. Fluid invasion and mineralization structure strictly depend on the original lithology of the host rocks, mainly carbonatic sedimentary rocks.

According to their identical fluid characteristics the mineralizations were formed during the same minerogenetic event. Recent investigations and data suggest a Permo-Triassic origin of the mineralizing fluids; in the Neotethyan sedimentary cycle, starting in the Late Permian, huge masses of evaporites were deposited in the Late Permian and around the Early/Middle Triassic boundary. In Late Triassic times, evaporitic brines were mobilized and their circulation led to siderite as well as magnesite formation. Especially the diagenetic reactions under fluid overpressure conditions led to leaching of Fe from the surrounding carbonates.

The convection system caused the formation of irregular mineralizations, but large ore bodies were only formed in the carbonatic rocks of the original sedimentary sequence. We will see and discuss a complex mineralization history by ore forming fluids, which reveal characteristics of residual brines.

- Epigenetic models for the origin of these mineralizations will be discussed based on the investigations on the fluid chemistry and radiometric age dating.
- The ore forming fluids reveal characteristics of residual brines produced during evapo-concentration of seawater for the siderite occurrences, regardless their host rocks and stratigraphic position.
- Arguments and field evidence for a younger metasomatic formation of the mineralizations will be shown and discussed. E.g., we will see the metasomatic fluid front in Permian conglomerates.

2. Overview on the geology of the field trip area

The main tectonic feature of SE-Austria is the dipping of the Eastern Alps beneath the Tertiary Pannonian basin system. According to Tollmann (1977) the thrust belt of the Eastern Alps is zoned into the basal Penninic units overthrusted by the Lower, Middle and Upper Austroalpine nappe systems. Major parts of SE-Austria are occupied by Lower Austroalpine and Middle Austroalpine basement units. At the SE margin of the Eastern Alps the Penninic units form the tectonic window of Rechnitz (Fig. 1).

All Penninic and Austroalpine units consist of a metamorphosed pre-Alpine basement and Permomesozoic cover units. In the Upper Austroalpine within the Greywacke zone, the Graz Palaeozoic and the Gurktal Palaeozoic thrust systems the pre-Alpine metamorphic overprint is up to low grade metamorphic facies. This is in contrast to the medium to high grade Variscan metamorphosed basement of the Penninic, Lower Austroalpine and Middle Austroalpine units, which are frequently intruded by Variscan, mainly Carboniferous synorogenic granitoids. Penninic post-Variscan sediments include also Jurassic-Cretaceous oceanic formations. In the Austroalpine nappe system the Mesozoic sedimentary environments reflect the evolution of the former passive European continental margin.

The subduction of the Penninic oceanic realm below the Austroalpine continent caused Cretaceous nappe stacking and metamorphism in the Austroalpine units. This metamorphic overprint is increasing in the Austroalpine basement units to the south up to the amphibolite and locally even up to the eclogite facies. Relics of a Late Cretaceous to Early Tertiary high pressure subduction related metamorphism, followed by a Tertiary regional metamorphic event, are known from the Penninic units. Tertiary metamorphism is caused by the overriding of the Austroalpine nappe system above the Penninic units as a result of the indentation of the Apulian promontory.

The Permo-Mesozoic cover is preserved only fragmentarily in the Lower Austroalpine and Middle Austroalpine tectonic units. There the so-called “Central Alpine Mesozoic sediments“ are within the greenschist facies. In the Northern Calcareous Alps the Mesozoic is mostly unmetamorphosed. The unmetamorphosed Upper Cretaceous (Gosau) sediments of the Kainach and Krappfeld basins were deposited after the Mid-Cretaceous tectonothermal event on the Graz Palaeozoic or respective on the Gurktal Palaeozoic thrust.

During Tertiary an E-directed escape tectonic operated along sinistral wrench corridors of the Noric lineament and the Salzach/Enns valley-Puchberg line in the north. In the south there were dextral systems along the Lavant valley and the Periadriatic lineament zone. The extrusion of the Austroalpine crustal wedge east of the Tauern window was the result of the Apulian indentation which triggered also the “push up“ of the Penninic core. Today the Periadriatic lineament zone is the boundary zone between Eastern and Southern Alps. It is marked by some Oligocene tonalitic intrusions.

3. Metallogenetic processes and major metallogenetic districts of SE-Austria

A comprehensive overview on the mineral deposits and occurrences of SE-Austria is presented in the metallogenetic map of Austria, the explanatory text book to the map (Weber 1997) and the Interactive Raw Material Information System “IRIS“ (Weber et al. 2002). The section of the area of the excursion is given in Fig. 2. Note the different types of Fe-mineralizations (in red) and the magnesite deposits of the Greywacke Zone (in brown).

In contrast to the Alpine metallogenetic provinces in the Alpine-Balkan-Carpathian-Dinaride region, which are strongly influenced by Late Cretaceous and Neogene magmatism (Ebner et al. 2000, Ebner 2002, Neubauer 2002) the metallogenetic processes of SE-Austria are complex and controlled by the geodynamic settings and

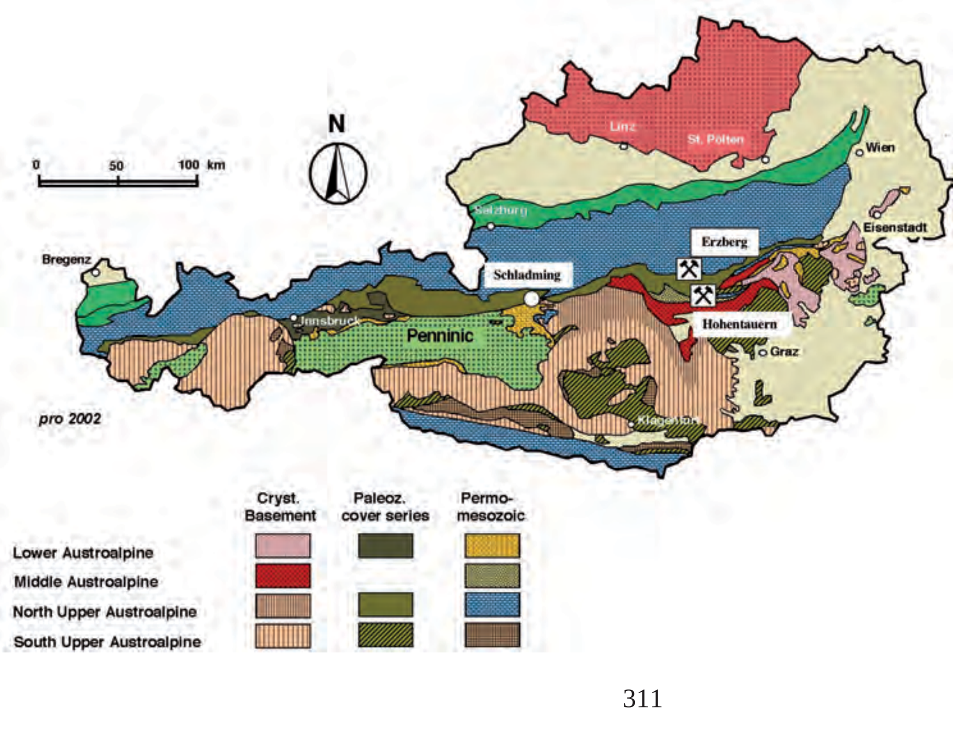

Fig. 1: Geologic map of the Eastern Alps (modified after Frank 1987) and the location of the excursion targets.

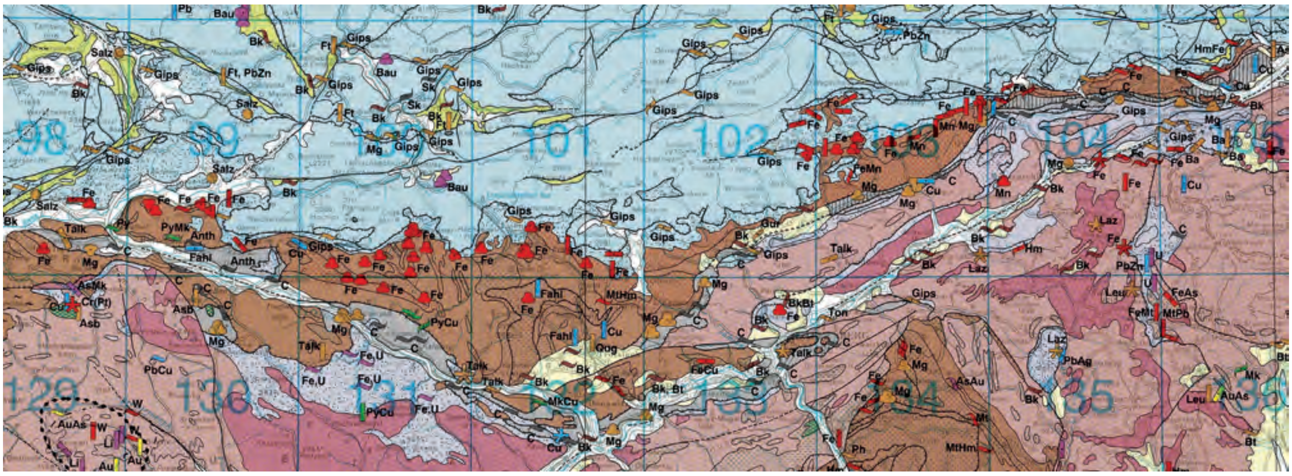

Fig. 2: Section of the Minerogenetic Map of Austria with the Fe- and magnesite mineralizations of the Greywacke Zone (WEBER et al. 2002).

intensive mobilizations during all major pre-Alpine and Alpine evolutionary stages. During the Palaeozoic the accreted Speik and Celtic terranes formed the basement of the Noric composite terrane. This includes all fossiliferous and low-grade metamorphic Palaeozoic units of the Eastern (Greywacke zone, Graz Paleozoic, Gurktal Palaeozoic) and Southern Alps as well as the Middle Austroalpine Micaschist-Marble Complex (NEUBAUER & FRISCH 1993). During Silurian/Lower Devonian this terrane split off Gondwana and drifted to the north. It collided finally during the Carboniferous with the European margin.

Extensional tectonics and alkaline basaltic intraplate volcanism were the most important facts controlling metallogensis in these units. SEDEX type deposits with Pb-Zn-Ag(Ba) mineralizations can be found in Graz Palaeozoic lead-zinc-barite district hosted by metasediments (carbonate, sericite, chlorite and graphite phyllite, marble) of the Late Silurian - Early Devonian age (WEBER 1997).

During the Devonian a passive continental margin with carbonate platforms evolved at the Noric composite terrane. In general the platform carbonate series of this event host the siderite mineralizations of “Erzberg-type“ in the Noric nappe of the Greywacke zone. Mostly the siderite hosted by Silurian/Devonian marbles („ore bearing limestone“) exhibits metasomatic features. However, siderite is also bound to quartz-ankerite-veins (Schendleck type) in siliciclastic and porphyroidic rocks. The debate on the siderite formation has a longstanding tradition and will be discussed during the excursion when visiting the outcrops in the open pit mine.

Post-orogenic molasse like marine sedimentation started within the Late Visean after deformation and metamorphism (“bretonic phase“) of the internal Variscan zones. During Alpine orogeny this zone, the Veitsch nappe, became the structural base of the Upper Austroalpine Greywacke zone. The marine shallow-water sediments of the Veitsch zone underwent exclusively Alpine (Cretaceous) deformation and greenschist facies metamorphism (RATSCHBACHER 1984, 1987). The Veitsch nappe hosts numerous deposits of sparry magnesite of the Veitsch type, talc and graphite. WEBER (1997) gathered these within two minerogenetic districts:

(1) the Veitsch nappe magnesite (talc) district and
(2) the Veitsch nappe graphite district.

The magnesite formation will be discussed later; the talc-formation is clearly related to late Alpine tectonic and metamorphogenic events (PROCHASKA 1999).

Post-Variscan sedimentation above the Lower Austroalpine and Middle Austroalpine crystalline complexes started with the Permian “Alpine Verrucano Fm.“ and Permo-Triassic quartzite formations (KRAINER 1993). These include strati-form U-mineralizations (Palten/Liesing valley and the Wechsel/Semmering U-ore districts; WEBER 1997).

Extensive rifting, Permian anorogenic intrusions of granite and gabbroic rocks and metamorphism marked the beginning of the Alpine cycle. In the Northern Calcareous Alps the evaporitic “Haselgebirge“ with economic halite and gypsum/anhydrite deposits was formed in rift-related basins. In these basins residual bittern brines were enriched during the evaporite precipitation. Crustal extension, opening pathways for the circulation of surface derived fluids, continued with less velocity until early Middle Triassic time and produced ht/lp metamorphism in some parts of the Austroalpine basement (SCHUSTER et al. 1998). It is striking that some evidently epigenetic mineralizations are hosted by Permo-Triassic sediments up to early Middle Triassic stratigraphic levels. This scenario is discussed by PROCHASKA (1999) as responsible for the formation of a variety of mineral deposits.

During the Cretaceous the subduction of the Penninic Ocean beneath the Austroalpine plate triggered thrusting within the Austroalpine and the expulsion of high salinity fluids from deeper tectonic units. Circulation of these fluids started after the peak of Cretaceous metamorphism around 90 Ma. They were focused along thrust/shear zones and along low angle normal faults above uprising metamorphic domes (BELOCKY 1992, POHL 1990, 1993, POHL & BELOCKY 1994, 1999, EBNER 2002). The formation of some talc and leucophyllite deposits (Lassing, Rabenwald, Kleinfeistritz) may be attributed to this period. The respective metamorphic P/T-conditions, the existence of Si-rich hydrothermal fluids, Mg-rich protoliths (dolomite, magnesite), and ductile shear and fracture zones were the prerequisites to form talc deposits of economic dimensions (Prochaska 1984).

The final Eocene-Oligocene continent-continent collision was the trigger of the extensive lateral extrusion of the Austroalpine crustal wedge east of the uplifting Tauern window. The formation and distribution of mineral deposits were controlled by this tectonics and by an increasing heat flow approaching the upliftig Penninic windows. The late orogenic Tertiary fluids are contrasting the Cretaceous synorogenic fluids. They are dominated by low to moderate salinities, significantly higher homogenization temperatures, appreciable contents of CO$_2$, and trapping of inclusions below 2 kb (Belocky 1992, Pohl 1993, Pohl & Belocky 1994, 1999).

Numerous Au-arsenopyrite vein-mineralizations are located in the Austroalpine basement along the Tertiary wrench corridors. Further mobilizations in the polymetallic (Fe-Pb-Zn-Ag-Ba) ore district of Oberzeiring and siderite/specularite mineralizations in the Hüttenberg/Waldenstein iron ore district may be related to this Tertiary metallogenetic event (Prochaska et al. 1995, Weber 1997, Ebner 2002).

3.1. The "Erzberg" Siderite deposit

On a world-wide scale the economic importance of siderite deposits is fairly limited compared to oxide iron ores and this mineral is hardly considered to be economic iron ore. Nevertheless, siderite is an important ore mineral and occurs in nearly all types of sedimentary iron ores and in many vein type mineralizations. In some European and Mediterranean countries siderite deposits are of national importance and are still in production.

Numerous siderite mineralizations are situated in the Noric nappe of the Greywacke zone; many of them were exploited in the past. Presently only the Erzberg siderite deposit is operated by VOEST-ALPINE Erzberg Ges.m.b.H. First iron production from Erzberg was recorded from 712 AD, but most probably the Romans had already worked this deposit. Currently the Austrian iron ore production of about 1.8 million t is exclusively produced from the Erzberg mine. Until now about some 245 million t of ore have been mined, and the current reserves are in the range of 150 million t.

The mined ore is siderite and siderite/ankerite intergrowths with an average geochemical composition of Fe 30-33 %, Mn 1.5-2 %, CaO 7 % and SiO$_2$ 3-4 %; the cut off grade is 22-28 % Fe. Ankerite, called as "Rohwand", with an average Fe-content of 15 % is not mined. It is mainly deposited in the waste dumps well visible from the parking slot. The ore concentrate has 32 % Fe and is used for steel production in Linz and Donawitz. In account of its carbonatic composition it is a good additive for Precambrian acid banded iron ores which were mainly smelted at the mentioned metallurgical plants.

The structure of the Erzberg deposit includes a tectonic (nappe) duplication of Palaeozoic rocks as proved by the unconformable superposition of the Präbichl and Werfen Formations by Variscan thrust tectonics, and a wide Alpine syncline which eastern part is faulted about 350 m along the "Christoph-Hauptverwurf" (Fig. 3). The deeper Variscan unit comprises the Late Ordovician Blasseneck porphyroid superposed by Silurian/Devonian limestones which were followed during the Visean after an erosional gap by thin limestones breccias with conodont mixed faunas and the pelitic Eisenerz Fm. Silurian/Devonian limestones are the constituents of the upper Variscan tectonic unit. Devonian stratigraphic ages of the limestones are proven by some makrofossils and conodonts (Schönlaub et. al. 1980). Gypsum is also included within the post-Variscan Permo-Triassic clastics. The metamorphic overprint of the whole pile is of Variscan and Alpine (Cretaceous) age and within the lower greenschist facies. The siderite deposits in the Greywacke zone are neither stratabound nor stratiform and exhibit different modes of occurrence. Host rock lithology strongly influences the

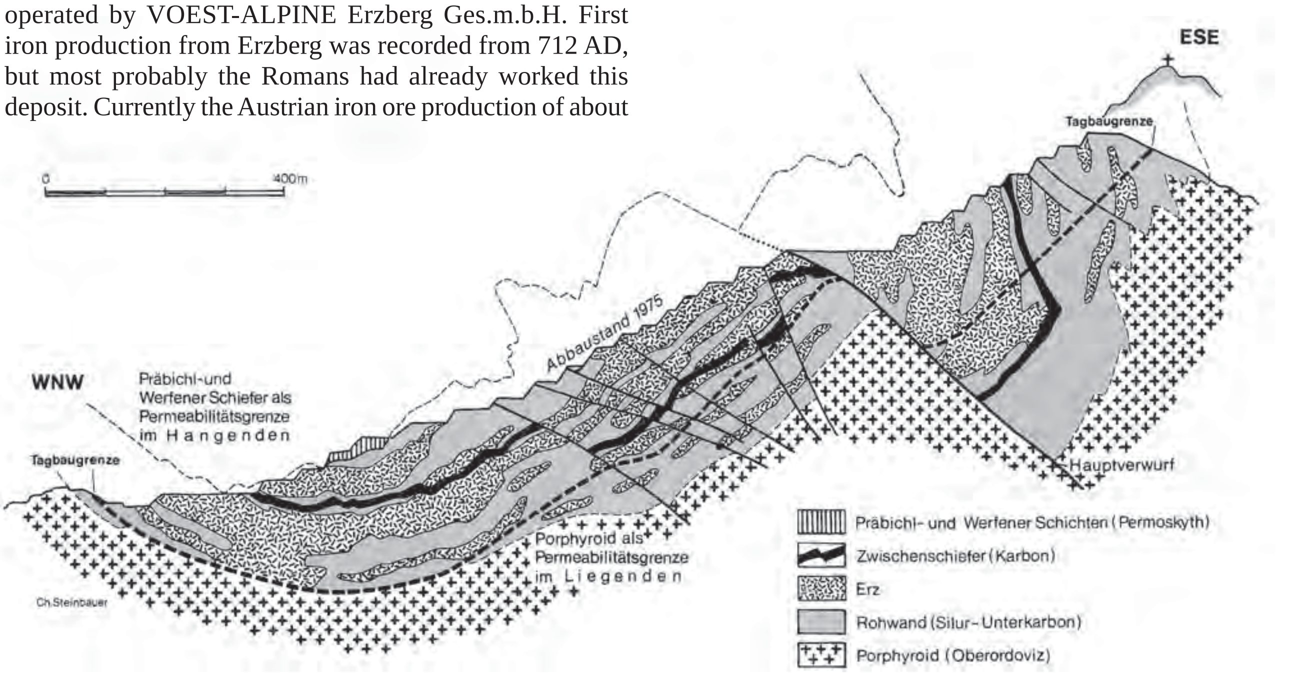

Fig. 3: Geological cross section through the Styrian Erzberg siderite deposit.

Fig. 4: Crosscutting contact of the siderite orebody to the Devonian limestone with concordant coarse-grained siderite veins grading into the hostrock limestones.

structure of the mineralizations. In acidic volcanic and clastic host rocks, Ordovician quartz porphyries or Palaeozoic metapelites and sandstones, vein type mineralization usually occurs, while Devonian carbonates and the Permian Präbichl conglomerates host metasomatic bodies and stocks of siderite.

In the Erzberg deposit irregular bodies of siderite mineralization occur within both Variscan tectonic units and within the post-Variscan Präbichl conglomerate. The siderite of the Erzberg deposit is generally hosted by fine-grained limestones of Devonian age. Metasomatic-epigenetic textures are dominant and usually coarse-grained siderite ore exhibits discordant contacts with the unmineralized limestones (Figs. 4, 5). In the nearby abandoned Radmer mine, the majority of the observed ore textures is the same, but very rarely banded ores occur. This lead to syngenetic interpretations of the primary genesis of these mineralizations (BERAN & THALMANN 1978). The Erzberg mineralizations and especially the ore textures were described by BERAN & THALMANN (1978) and SCHULZ et al. (1997). These authors focused on fine-grained, banded textures that have been interpreted as evidence for a primary syngenetic ore deposition.

Ore textures of the different siderite mineralizations of the Greywacke zone differ remarkably. As indicated above the mineralizations are usually siderite-(quartz-sulfide) veins in metapelitic or volcanic host rocks. In metapelites and the metamorphosed quartz porphyry series distinct alteration features and clearly epigenetic structures can be observed. Mineralizations in carbonate host rocks (Devonian limestones and Permian carbonate conglomerate) exhibit features of metasomatic bodies and siderite veins. The majority of the siderite ore bodies of the Erzberg mine belong to this type. Coarse-grained types of siderite (veins) as well as fine-grained metasomatic textures can be observed. In the latter case mimetic crystallization still exhibiting the textures of the sedimentary precursors can be found. Frequently idiomorphic quartz crystals occur indicating that no major metamorphic overprint after the formation of the siderite ore occurred (Fig. 6).

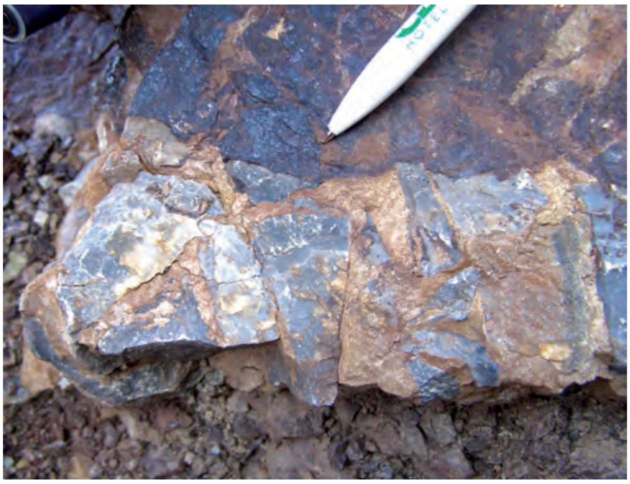

Fig. 5: Metasomatic siderite formation in the Permian carbonate conglomerate. Note that the metasomatic front and the boundary between the ore and the unmineralized conglomerate cut single carbonate components.

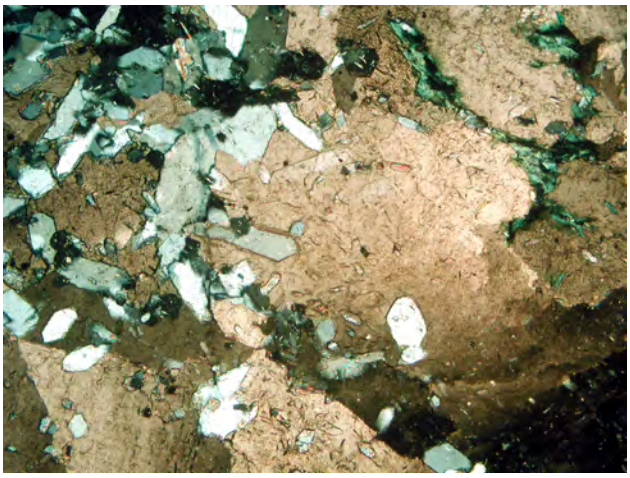

Fig. 6: Idiomorphic quartz crystals in the siderite ore prove the lack of a major postcrystalline overprint after ore-formation (length of image is 7 mm).

Chemistry of the ore-forming fluids

In order to characterize the nature of the ore-forming fluids the chemistry of the inclusion fluids of the siderites was investigated. On a Cl/Br and Na/Br molar ratio diagram (Fig. 7), the evolution of the fluids by fractionation of halite from seawater is demonstrated. Accordingly the composition of an evaporitic brine is shifting along the "evaporation trend" when halite starts to precipitate at an evaporation index of about 10. On the other hand fluids percolating through the crust acquiring salinity by dissolution of halite, plot towards higher Cl/Br and Na/Br molar ratios and their composition is close to the „halite dissolution trend".

In the Cl/Br and Na/Br molar ratio diagram (Fig. 7) the inclusion chemistry of none of the investigated samples from the mineralization matches the seawater composition. The molar ratios are characterized by low Na/Br (55-499) and low Cl/Br (78-530) numbers. Fig. 7 shows that all samples from the different localities are situated on the "evaporation trend" thus indicating an origin of the fluids from subaerial evapo-concentration of seawater.

Timing of the mineralizing event

The knowledge of the timing of the mineralization is crucial to establish a genetic model within the geodynamic frame of the Alpine or Prealpine orogenic cycles. The fact that the mineralized structures and the mineralizations cut Permo-Mesozoic strata excludes a syngenetic Devonian formation for these deposits. However, the Eoalpine metamorphic event is believed to be responsible by some authors for modification and remobilization of early syngenetic mineralizations finally producing epigenetic vein type deposits. No indication of two fundamentally different sets of fluid compositions (e.g. marine-sedimentary and Alpine hydrothermal) were found. In some localities, the mineralized Devonian limestones can be found in close vicinity of Carboniferous limestones of the tectonically deeper Veitsch nappe which completely lack siderite mineralizations. This observation is a sound proof for 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 (Prochaska et al. 1996). A plateau age (Ar-Ar) of approximately 160 Ma for the Schendleck deposit was found. 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 due to the opening of the South-Penninic Ocean. Furthermore a prominent rejuvenation due to the Cretaceous metamorphic event (~90 Ma) can be observed by the Ar-Ar investigations.

A breakthrough for the discussion of the genetic models of the Erzberg siderite mineralizations was the direct age determination of the ores and the alteration zones (Prochaska & Henjes-Kunst 2009). Sm-Nd investigations (Fig. 8) yielded an isochrone of 208 ±22 Ma. It is remarkable that recent age determinations on sparry magnesite mineralizations (Prochaska & Henjes-Kunst 2009) and ongoing investigations on the Bleiberg Pb/Zn deposit reveal similar Upper Triassic ages.

Consequently, from a geologic point of view and from radiometric age determination, the siderite forming hydrothermal activity is not older than Permo-Scythian and predates the Eoalpine tectono-metamorphic event. Sm-Nd dating yielded an Upper Triassic age for the mineralizing event.

3.2. The Hohentauern/Sunk Magnesite deposit

Magnesite in Styria/SE Austria

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, Redlich 1907) were published. Beginning with the 1950-ies a general trend towards syngenetic and early diagenetic models can be

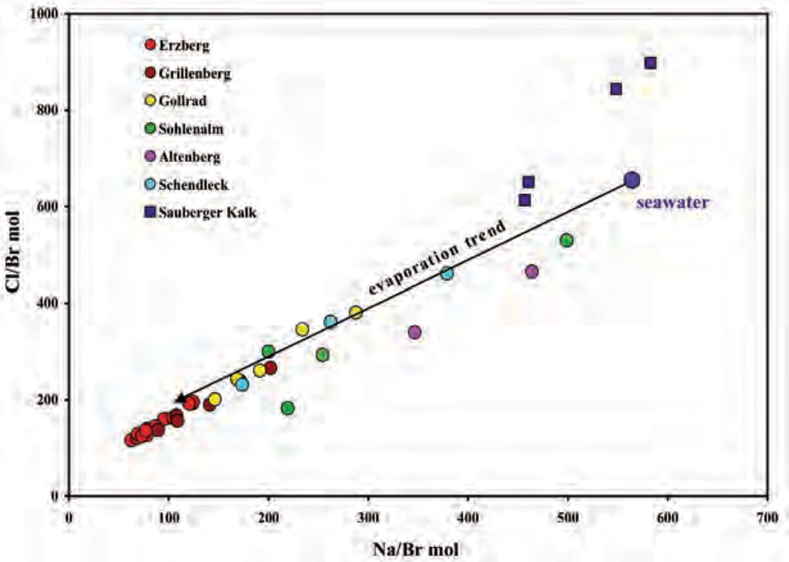

Fig. 7: Na-Cl-Br ratios of the siderite mineralizations of the Eastern Greywacke Zone. The fluid composition clearly plots on the seawater evaporation trend and exhibits different degrees of evaporation.

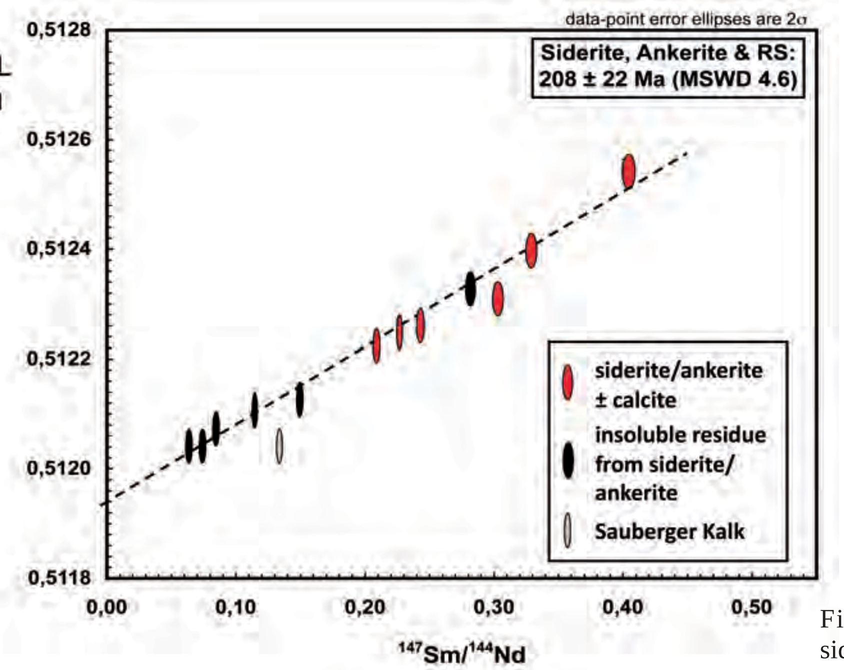

Fig. 8: Sm-Nd isochrone of the siderites of the Erzberg.

observed (DE LLARENA 1953, LEITMEIER & SIEGL 1954). NIEDERMAYR et al. (1989) argued for synsedimentary or early diagenetic genesis for magnesite mineralization in Permian sediments of the Eastern Alps and extended this model to the sparry magnesites of the Eastern Alps. There is no consensus so far about a genetic model and not even about the principal mechanisms for the magnesite mineralization. POHL & SIEGL presented an extensive overview on 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“.

Earlier workers (e.g., REDLICH 1907, 1909, PETRASCHECK 1932) already mentioned a consanguineous origin of the Alpine sparry magnesite mineralizations and the siderite deposits. In general they argued for hydrothermal fluids of different origin like magmatic or metamorphic fluids of Alpine age. Nevertheless these concepts never gained general acceptance. The model of a Permo-Triassic magnesite formation by the influence of residual bittern brines contemporaneous with the siderite formation (PROCHASKA 1999) was outlined in the previous chapter.

Deposits of the Veitsch type are hosted in Palaeozoic carbonatic rocks. In the Veitsch nappe of the Greywacke zone today only the deposits of Oberdorf/Laming and Wald/Schoberpass are in operation (Styromagnesit Company). After World War II additionally some other deposits were mined (year of closing): Lassing (1964), Veitsch (1968), Hohentauern/Sunk (1991). Another magnesite mine in operation is the Breitenau deposit situated in Silurian/Lower Devonian sediments at the northern margin of the Graz Paleozoic. In 2009 the annual production of sparry magnesite in Styria was some 540.000 t.

Long before the discovery of the sparry magnesite as a refractory commodity it was used also as decoration stone, e.g. for steps and window cornices in the Benedictine monastery of Admont which are made of sparry magnesite from Hohentauern. The decorative black and white pinolitic texture and the good polishing properties are the main quality criteria of this decorative rock.

Sparry magnesite and talc deposits are especially concentrated in the Veitsch Nappe of the Greywacke zone. In the metallogenetic map of Austria 1: 500.000 (WEBER 1997) all magnesite/talc deposits of the Veitsch nappe were gathered within the Veitsch nappe magnesite /talc district.

Characteristic features for Veitsch type magnesite are (WEBER 1997):

- Late Viséan shallow marine, fossiliferous carbonatic host rocks.
- Stratiform (layers, lenses) and irregular magnesite bodies.
- Coarse-grained banded and pinolitic texture. The matrix of the pinolite is black, fine-grained and rich in dispersed organic (graphitic) matter (Fig. 10).
- Seams of dolomite are mostly surrounding the magnesite.
- Magnesite is followed by several generations of dolomite. Large idiomorphic crystals of dolomite in the magnesite are frequent.
- Chlorite/leuchtenbergite and talc are bound to tectonized zones and marginal parts of the magnesite bodies. Temporarily this talc was also mined.
- Sulfide vein mineralizations with tetrahedrite, chalcopyrite, pyrite and gold belong to a younger metallogenic event.
- The regional metamorphic overprint of the host rocks is of Cretaceous age and within the greenschist metamorphic facies.

Up to now there is no consensus about a genetic model and the principal mechanisms for magnesite mineralization. Different genetic models, including a synsedimentary origin or an Eoalpine metamorphic vein-type or metasomatic mineralization, were proposed in the past.

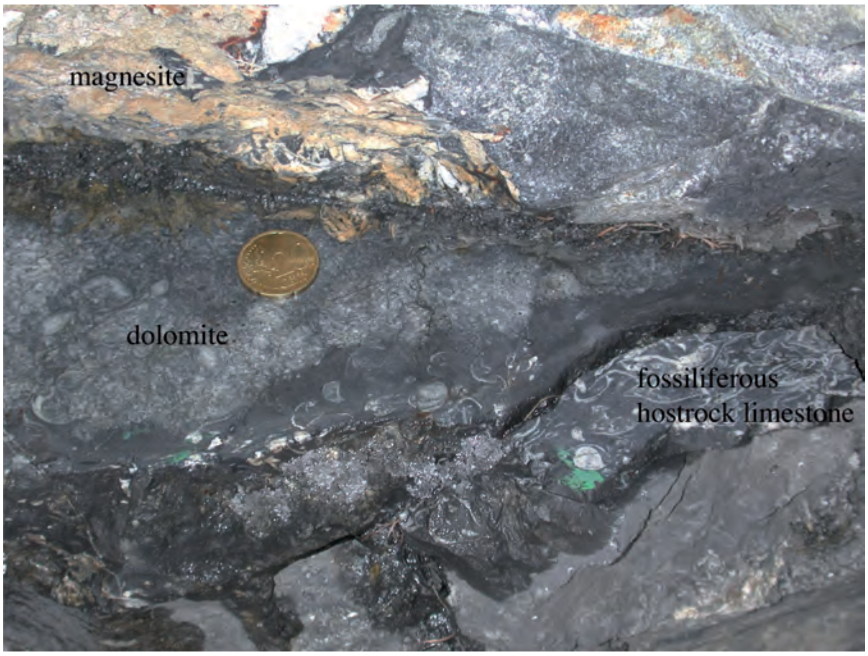

Fig. 9: Transition from the host rock-limestones to a dolomitic alteration zone and finally to the sparry magnesites in the Trieben/Sunk deposit.

The Hohentauern/Sunk deposit is one of the important magnesite deposits in the Veitsch nappe magnesite district. It was mined from 1907-1991 in underground and in open pit operations. In total the production was about some 5.5 million t of magnesite ore and a reserve of >10 million t is still in the deposit. A computer model based on the data of the abandoned mine operation exhibits an initial volume about some 10 x 106 m^3 of the deposit which can be followed along >750 m (Walter 2001).

Geological situation

The general geological situation of the deposit and its surroundings was described by Redlich (1935), Metz (1938, 1940), Meixner & Clar (1953), and Ratschbacher (1984, 1987); recently the deposit was investigated by Azimzadeh (2009). The location of the deposit is in the Veitsch nappe of the Greywacke zone in a very close position to the Tertiary Pöls line. The up to 650 m thick sequence of the Veitsch nappe comprises three lithostratigraphic formations. Their stratigraphic range from the Late Visean to Westfalian is proven by fossils.

The deposit is hosted by the Steilbachgraben Fm., which forms the stratigraphic base of the Veitsch nappe. This formation comprises silty/sandy shales, often rich in organic/graphitic materials, calcareous shale, dark limestones and dolomite. The magnesite occurs as lens-shaped, layered and irregular bodies in three levels, the “footwall“, the “middle“ and the “hanging wall layer“. Usually an envelope of dolomite of highly variable extension occurs at the transition of the massive magnesite bodies and the host rocks (Fig. 9). A layer of orbicular dolomite is another remarkable intercalation (Haditsch 1968, Siegl & Felser 1973).

The sedimentary sequence of the Veitsch nappe is a continuous one. It resembles to the evolution of a shallow shelf, sometimes interfingering with hypersalinar lagoons and lensoid bioherms, to a regressive shore line with distributary bay deposits and river dominated delta deposits (Ratschbacher 1984, 1987, Krainer 1993). The tectonofacies of the Veitsch nappe is interpreted as a marine molasse after the first tectonothermal peak (bretonic phase) of the Variscan orogeny (Fügel 1977, Schönlaub 1979, Neubauer & Vozarova 1990, Ebner 1992, Neubauer & Handler 2000). The heavy mineral spectra, dominated by turmaline, rutile, apatite and zircon derived from a hinterland dominated by anatectic granitoids (Ratschbacher & Nievoll 1984, Ratschbacher 1987). Devonian ages of detrital micas can be related to a pre-Carboniferous metamorphic source area (Neubauer & Handler 2000).

The boundary of the deposit in the N and NE to the Triebenstein Fm. is partly an E-W striking fault. The rocks of the deposit are deformed due to their different competences. Layers/lenses of the rigid magnesite are embedded in strongly folded calcareous/graphitic schists. The carbonates are often deformed to boudins by the NW stretching.

The regional metamorphic overprint is Cretaceous and within the greenschist facies (Ratschbacher & Klima 1985). Neither major Variscan internal deformation nor metamorphism was identified for the Veitsch nappe. The tectonothermal overprint is exclusively Alpine (Cretaceous) (Ratschbacher 1984, 1987, Ratschbacher & Klima 1985). On the basis of Raman investigation the temperature of metamorphism can be estimated between 400 °C and 500 °C, indicating the maximum temperature of this segment. This temperature is similar to thermometric data from Kaisersberg, another graphite deposit in the Veitsch nappe. There, temperatures between 360-410 °C and 2 kbar for a minimum of pressure were calculated (Raith & Vali 1998, Raith & Postl 2000).

The magnesite of the Hohentauern deposit is known for its attractive pinolitic texture (Fig. 10) which is characterized by big, oval shaped, usually white crystals without any orientation in a fine-grained black matrix rich in organic matter. Earlier workers interpreted these textures

Fig. 10: “Pinolitic“ texture of the magnesite from the Hohentauern deposit

as syn/diagenetic as well as epignetic/metasomatic features (Rumpf 1867, 1873, Petrascheck 1932, Friedrich 1951, Siegl & Felser 1973).

The orbicular dolomite is an up to 1 m thick intercalation in the “hanging wall magnesite“ which is parallel to the sedimentary bedding. The dolomite is composed of light grey coloured aggregates of dolomite spheres with a diameter up to 5 cm within a black-dark grey fine-grained dolomitic matrix. The orbicular aggregates have angular cores of fine-grained black dolomite or pinolite magnesite fragments. These cores are rimmed by some mm-thick, concentric seams of light radially orientated dolomite crystals. The spaces between the dolomite spheres are cemented by dolomite. Fluid chemistry of the matrix dolomite resembles marine composition. Therefore we consider these orbicular dolomites to be late veins or fillings of fractures after lithification of the magnesites.

The Hohentauern deposit is well known for its rich mineral paragensis (Meixner & Clar 1953). It includes graphite, chalcopyrite, sphalerite, millerite, pyrite, galena, marcasite, pyrrhotite, pentlandite, gersdorffite, boulangerite, fluorite, quartz (amethyst), hematite, rutile, magnesite, dolomite, calcite, aragonite, baryte, anhydrite, gypsum, pickeringite, slavikite, apatite, albite, muskovite, fuchsite, talc, chlorite (leuchtenbergite), uranylsilikate.

Geochemistry

The average geochemistry of the mined magnesite was MgO 43,3 %, CaO 2,5 %, SiO_2 2,0 % und Fe_2O_3 2,4 % and LOI 49,8 %. There are relatively higher contents in SiO_2 and Al_2O_3 in the “footwall layer“ of the open pit then within the “middle layer“. The “hanging wall layer“ is characterized by higher CaO contents and a decrease of pinolitic textures. An SiO_2 content >2 % was the limiting factor for mining.

Some geochemical investigations on the stable isotope geochemistry (C, O), Sr, the trace elements (REE) and the composition of the mineralizing fluids were carried out to investigate the magnesite formation and the origin of the mineralizing fluids. A summary of the data is given by Schroll (1997), Schroll et al. (1986), and Ebner & Prochaska (2003).

δ^{13}C(PDB) and δ^{18}O(PDB) from magnesite of the Hohentauern deposit were published by Guillou & Letolle (1986). The δ^{3}C value is 0 ‰, the δ^{18}O values are scattering in a small range between -15,4 and -13,3 ‰ and are in agreement with those of other sparry magnesites of the Veitsch nappe (Schroll 1997).

Petrascheck (1978) published δ^{34}S values of anhydrite (+17.2 ± 0.2 ‰) and gypsum from the Hohentauern magnesite deposit (+17,6 ± 0,2 ‰) and proposed Carboniferous age identical with the stratigraphic age of the host rock.

^{87}Sr/^{86}Sr values of the magnesite are between 0.7087-0.7103; those of dolomitic and calcitic host rocks between 0.7083-0.7085 (Frimmel 1988). All these values are close to or above Carboniferous seawater (0.7076-0.7081).

Fluid characteristics

The analysis of the mineralizing fluids by the crush-leach method allows the investigation of the fluid evolution and the determination of the primary nature of the hydrothermal solutions. Thus it seems to be a key to elucidate genetic problems of the siderite and magnesite mineralization in the Greywacke zone. A first and obvious result is the identity of the chemical composition trends of the fluids of all investigated siderite mineralizations of the Greywacke zone and the sparry magnesite mineralizations regardless of their host rock lithologies. This strongly suggests a consanguineous origin for the siderite as well as the magnesite deposits.

Very important questions to be solved within this context are the origin of the fluids, and the source of fluid salinity and the metals (Fe, Mg, Ba, etc.). Microthermometric data available so far (Belocky 1992, Spindler 1992) report high salinity values for the Erzberg and the Schendleck fluids. There are several possibilities to generate highly saline brines:

a) Surficial evapo-concentration of seawater.
b) Dissolution of evaporite minerals.
c) Metamorphic fluids and concentrating retrograde reactions generated by the Cretaceous event.

For recognition of the original fluid characteristics, conservative elements which are not buffered or changed by mineral reactions in the alteration zones, have to be considered. Thus chloride-bromide, and to some extent sodium systematics are more suitable for providing clues as to the source of the salinity of the fluids than other element ratios which can be changed by wallrock alterations.

In Fig. 11 the Na-Cl-Br ratios of the extracted fluids are presented (Prochaska 2000, Prochaska & Henjes-Kunst 2008). The fractionation trend of the halogen elements demonstrates that the magnesite forming fluids plot on the end of the evaporation trend, while the dolomitic transition zones still are buffered to some extent by the seawater ratios of the host rock limestones. This clearly proves the origin of the fluids and their high salinities from evaporitic brines and excludes the dissolution of evaporites by fluids migrating through the crust. If dissolution of evaporites would have had occurred the opposite trend (towards high Na/Br and Cl/Br molar ratios) would result. This fractionation trend contradicts models favouring Alpine metamorphogenic fluids that gained their salinities by dissolving Permo-Mesozoic evaporites (Belocky 1992, Pohl 1993). Additionally, the observation that residual brines from extensive evaporitic series were the mineralizing fluids, restricts the timing of the formation of the fluids to the Late Permian - Early Triassic where extensive evaporitic systems occurred. The timing of the mineralizing event not necessarily coincides with the formation of the mineralization (see below).

Microthermometric studies of inclusion fluids from the Hohentauern deposit were carried out by Weninger (1981) and Azimzadeh (2009). Nevertheless, the position of the investigated quartz is unclear and it is questionable if the fluid trapped in the quartz is in a genetic relation to the magnesite formation. According to Azimzadeh (2009) the magnesite fluids are highly saline with tH clustering between 170-190 °C and final ice melting temperatures between -15 and -20 °C. The NaCl-dominated fluids are interpreted as saline brines with an overall salinity of 22,4 eq. mass % NaCl. The application of the Na-K geothermometer yielded a fluid temperature of 247 °C.

4. A model for epigenetic siderite and magnesite formation by evaporitic residual brines during a Permo-Triassic rifting stage

Opinions concerning the genesis of the Greywacke zone siderite and magnesite mineralizations are inconsistent (cum. cit. Tollmann 1977) and discussion about this topic is longstanding tradition. Different genetic models, including a synsedimentary origin or an Alpine (Cretaceous) vein type or metasomatic mineralization, were proposed in the past. Early workers on this topic favored syngenetic models, and at the turn of the century, epigenetic models for the Erzberg type mineralization were proposed. More recent research focused on the investigation of structural and geochemical features. In the 1970‘s syngenetic models were favored mainly because of the findings of minor banded ore structures that were interpreted as primary sedimentary ore bands (Beran & Thalmann 1978 cum lit.). Following these arguments Schulz et al. (1997) described ore textures of the Erzberg deposit and postulated a marine-synsedimentary origin for the mineralization. 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, Pohl & Belocky 1994, Laube et al. 1995). A detailed overview on sediment hosted magnesite deposits was given by Pohl & Siegl in 1986. Möller (1989) published a monograph containing different aspects of magnesite deposits of the Eastern Alps.

Based on the above mentioned geologic observations and on crush leach fluid analyses on siderite and magnesite deposits in the Eastern Alps a genetic model for the formation of siderite and sparry magnesite can be proposed. This model is based on the following observations:

1. The nature of the mineralizations is hydrothermal-metasomatic. No indications of a synsedimentary concentration of Fe or Mg can be observed.
2. In general the magnesite as well as the siderite mineralizations are neither stratabound nor stratiform.
3. The immediate transition in the fluid composition and the sharp contact between marine host rock carbonates and the mineralizations characterized by evaporitic fluids is not compatible with a simple marine-sedimentary model.
4. The mineralizing event is post-Variscan and pre-Cretaceous because of mineralized Variscan basal conglomerates on one hand and the termination of hydrothermal mineralizing features at Alpine nappe boundaries. Furthermore Sm-Nd age determination

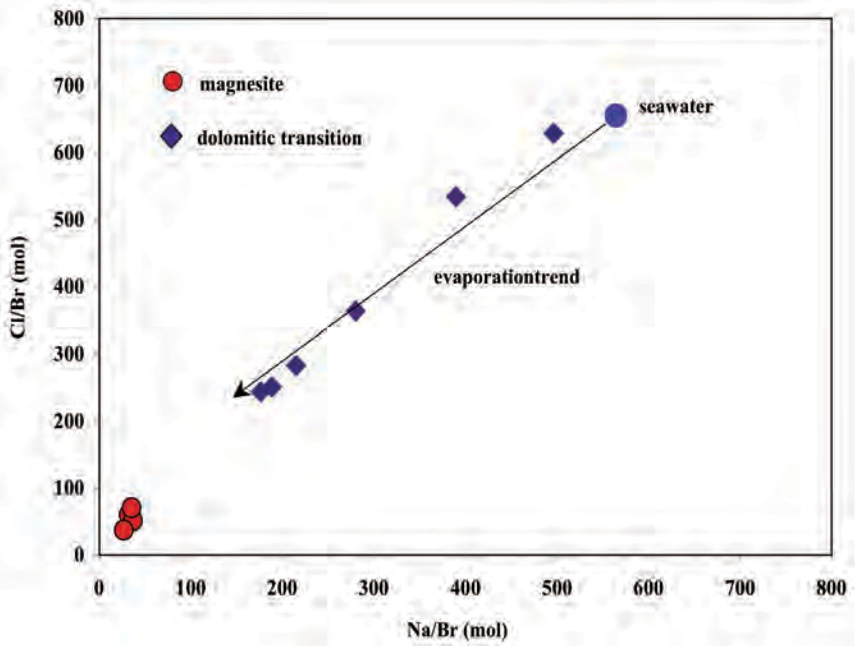

Fig. 11: Na-Cl-Br ratios of the Hohentauern sparry magnesites. The magnesite forming fluid composition plots on the extreme end of the seawater evaporation trend thus clearly exhibiting similarities to the siderite fluids.

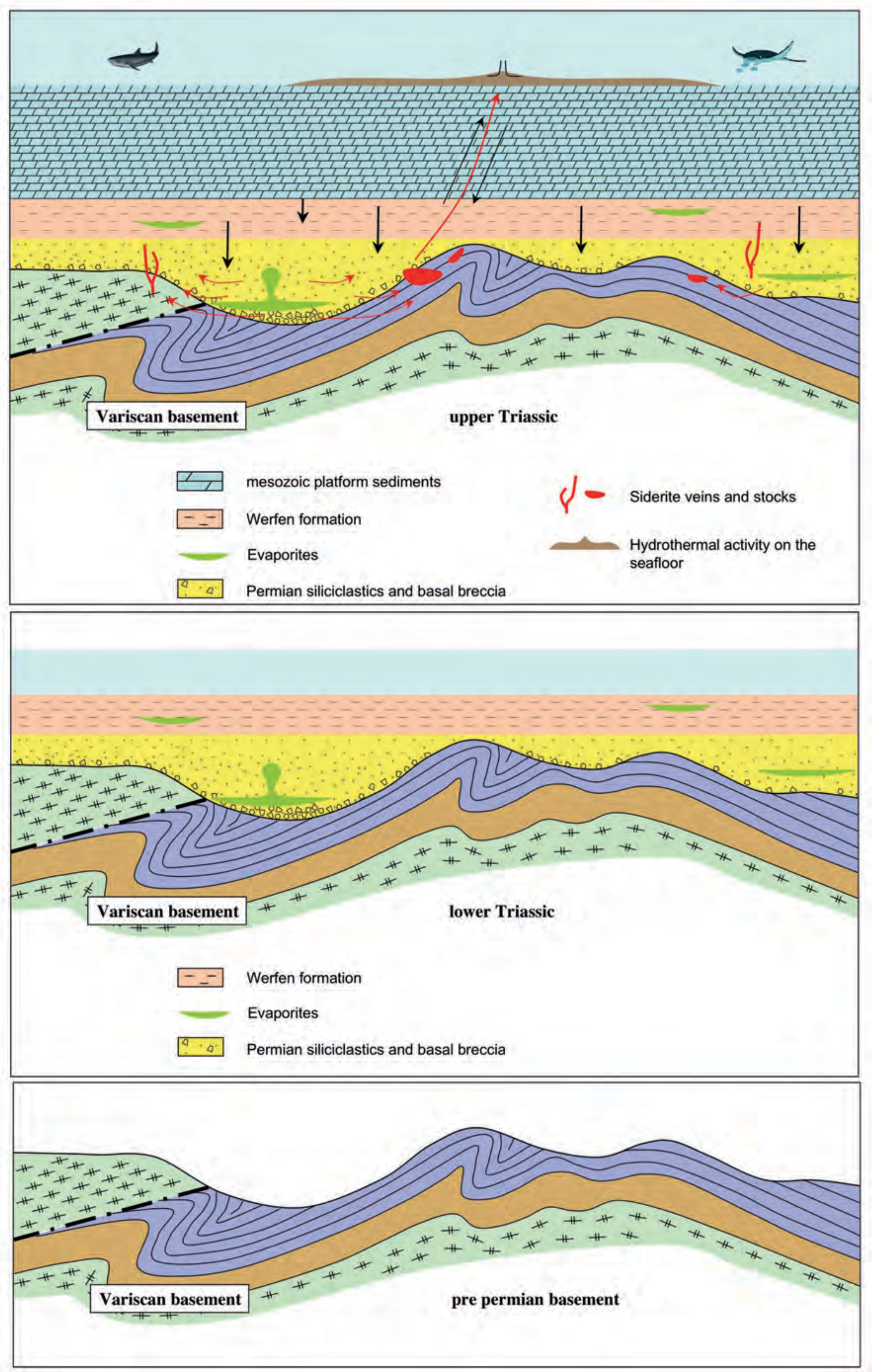

Fig. 12: Genetic model for siderite formation by diagenetic mobilization of buried evaporitic brines (Upper Permian/ Lower Triassic) mobilized in the Upper Triassic by diagenetic processes.

indicates an Upper Triassic age for the metasomatic event.

5. The high salinity of the fluids and especially the chemical composition of the fluids indicate that the mineralizing fluids were originally oxidized evaporitic, bittern brines with high Mg/Fe-ratios leading to magnesite formation. Low fluid rock interaction results in the formation of magnesite. During migration and fluid-rock interaction these originally oxidizing fluids are modified by wallrock alteration (hot reducing fluids) with the capacity of leaching iron and the formation of the different types of siderite mineralizations.
6. The Upper Triassic age of the mineralizations can be explained with diagenetic mobilization of buried residual bittern brines from Permo-Mesozoic series.

In Permian (to Lower Triassic) times evaporitic basins are ubiquitous in the Austroalpine realm. Deposition of thick series of evaporites is widespread in the Permo-Scythian strata of the Upper Austroalpine unit. High degrees of evaporation (evaporation index 20-90) produced residual „bitterns“ with high salinities and high concentrations of Br, Mg, K, SO_4 in the fluids. Diagenetic reactions and host rock alterations (crustal thinning and high heat-flow) changed these brines into acid and reducing fluids with the capacity of leaching Fe from the host rocks. Lithification and diagenesis due to the sedimentation of the Mesozoic formation finally expelled the originally buried bittern brines and formation waters and induced hydrothermal systems. Vein type siderite-hematite-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 lead earlier researchers to postulate syngenetic models. A graphic sketch of the formation of the siderite mineralizations is given in Fig. 12. Similar mechanisms are considered for the formation of the magnesite mineralizations. As magnesite forming fluids have to be totally free from Fe, these fluid could not have undergone an intensive interaction with the host rocks because in this case the fluids would easily loose their capability of producing magnesites.

This model is consistent with features as the overall high salinity of the fluids, the uniform and special fluid chemistry and the Sr- and stable isotope ratios which can neither be explained by sedimentary scenarios nor by Alpine remobilization models. It is worth to note that the advances in the investigations by applying inclusion fluid analysis and radiometric dating, uncovers crucial similarities between the siderite and magnesite mineralizations. These observations again put the model of a consanguineous origin of the deposits in perspective.

References

Azimzadeh, A. (2009): The genetic model of the Hohentauern/Sunk sparry magnesite deposit (Eastern Alps/Austria). - Unpublished thesis, University of Leoben.

Beran, A. & Thalmann, F. (1978): Der Bergbau Radmer-Buchegg - ein Beitrag zur Genese alpiner Sideritlagerstätten. - TMPM, **25**: 287-303.

Belocky, R. (1992): Regional vergleichende Untersuchung lagerstättenbildender Fluide in den Ostalpen als Hinweis auf eine mögliche metamorphe Ableitung. - PhD Thesis Univ. Braunschweig, 1-103.

De Llarena, J.G. (1953): Über die sedimentäre Entstehung des ostalpinen Magnesits „Typus Veitsch“. - Montan-Zeitung, **69**: 55-62.

Ebner, F. (1992): Correlation of marine Carboniferous sedimentary units of Slovakia, Hungary and Austria. - Spec. Vol. IGCP Project No. 276, 37-47, Dionyz Stur Inst., Bratislava.

Ebner, F., Cerny, I., Eichhorn, R., Götzinger, M., Paar, W., Prochaska, W. & Weber, L. (2000): Mineral resources in the Eastern Alps and Adjoining Areas. - Mitt. Österr. Geol. Ges., **92**: 157-184.

Ebner, F. (2002): Alpidische Stoffmobilisation und Lagerstättenbildung in den Ostalpen. - BHM, **12**: 397-402.

Ebner, F. & Prochaska, W. (2003): Die Magnesitlagerstätte Sunk/Hohentauern und ihr geologischer Rahmen. - Joannea, Geol. Paläont., **3**: 63-103.

Flügel, H.W. (1977): Paläogeographie und Tektonik des alpinen Variszikums. - N. Jb. Geol. Paläont. Mh., **1977**: 659-674, Stuttgart.

Frank, W. (1987): Evolution of Austroalpine Elements in the Cretaceous. - (In: Flügel, H.W. & Faupl; P. (Eds.): Geodynamics of the Eastern Alps), 379-407, (Deuticke) Vienna.

Friedrich, O.M. (1951): Zur Genese ostalpiner Spatmagnesit- und Talklagerstätten. - Radex-Rundschau, **1951**: 281-298.

Friedrich, O.M. (1969): Beiträge über das Gefüge von Spatlagerstätten. - Radex-Rundschau, **1**: 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.

Haditsch, J.G. (1968): Beiträge über das Gefüge von Spatlagerstätten (Bemerkungen zur Genese des Kokardendolomites der Magnesitlagerstätte Sunk bei Trieben. - Radex-Rundschau, **3**: 188-193.

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

Krainer, K. (1993): Late- and Post-Variscan Sediments of the Eastern and Southern Alps. - (In: J.F. Raumer & F. Neubauer (Eds.): Pre-Mesozoic Geology in the Alps), 537-564, (Springer) Berlin.

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.

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.

Meixner, H. & Clar, E. (1953): Die Magnesitlagerstätte im Sunk bei Trieben (Obersteiermark). - Miner. Mitt.-Bl-., Landesmus. Joanneum, **1**: 1-6.

Metz, K. (1938): Über die tektonische Stellung der Magnesit- und Erzlagerstätten in der steirischen Grauwackenzone. - BHM, **86**: 105-113.

Metz, K. (1940): Die Geologie der Grauwackenzone von Mautern bis Trieben. - Mitt. Reichsst. Bodenforsch. Zweigst. Wien, **1**: 161-220.

Möller, P. (1989): Magnesite - Geology, Mineralogy, Geochemistry, Formation of Mg-Carbonates. - Monograph Series on Mineral Deposits, 300 p., Berlin.

Neubauer, F. (2002): Contrasting Late Cretaceous with Neogene ore provinces in the Alpine-Balkan-Carpathian-Dinaride collision belt. - (In: Blundell, D.J., Neubauer, F. & von Quadt, A. (Eds.): The Timing and Location of Major Ore Deposits in an Evolving Orogen), Geol. Soc. London, Spec. Publ., **204**: 81-102.

Neubauer, F. & Vozarova, A. (1990): The Nötsch-Veitsch North Generic Zone of the Alps and Carpathians; Correlation, paleogeography and significance for Variscan orogeny. - Festive Volume: Thirty years of geol. Cooperation between Austria and Czechoslovakia, Ústr. Ústav geologický, Praha, 167-170, Praha.

Neubauer, F. & Frisch, W.(1993): The Austro-Alpine Metamorphic Basement E of the Tauern Window. - (In: J.F. Raumer & F. Neubauer (Eds.): Pre-Mesozoic Geology in the Alps), 515-536, Springer, Berlin.

Neubauer, F. & Handler, R. (2000): Variscan orogeny in the eastern Alps and Bohemian Massif: How do these units correlate. - Mitt. Österr. Geol. Ges., **92**: 35-59.

Niedermayr, G., Beran, A. & Brandstätter, F. (1989): Diagenetic type magnesites in the Permo-Scythian rocks of the Eastern Alps, Austria. - Monograph Series on Mineral Deposits, **28**: 35 - 60.

Petrascheck, W. (1932): Die Magnesite und Siderite der Alpen. - Sitz.-Ber. Akad. Wiss., math.-naturwiss. Kl. Abt. 1, **141**: 195-242.

Petrascheck, W.E. (1978): Zur Altersbestimmung einiger ostalpiner Erzlagerstätten. - Mitt. Österr. Geol. Ges., **68**: 79-87.

Pohl, W. (1990): Genesis of magnesite deposits - models and trends. - Geol. Rdsch., **79**: 291-299.

Pohl, W. (1993): Metamorphogene Lagerstätten in den Ostalpen. - Geowissenschaften, 11: 86-91.

Pohl, W. & Belocky, R. (1994): Alpidic metamorphic fluids and metallogenesis in the Eastern Alps. - Mitt. Österr. Geol. Ges., **86**: 141-152.

Pohl, W. & Belocky, R. (1999): Metamorphism and metallogeny in the Eastern Alps. - Mineralium Deposita, **24**: 614-629.

Pohl, W. & Siegl, W. (1986): Sediment-hosted magnesite deposits. - (In: Wolf, K.H. (Ed.): Handbook of strata-bound and stratiform deposits), **14**: 223-310, (Elsevier) Amsterdam.

Prochaska, W. (1984): Neue geochemische Aspekte zur Genese der Talklagerstätte Rabenwald, Stmk. - BHM, **129**: 457-462.

Prochaska, W. (1991): Beispiele für alpidisch-hydrothermale Lagerstättenbildung in den Ostalpen. - Mitt. naturwiss. Ver. Steiermark, **121**: 129-148.

Prochaska, W. (1999): Die Bedeutung der chemischen Zusammensetzung von Einschlußfluiden und laugbaren Salzen für die Genese von hydrothermalen und sedimentären Karbonatgesteinen der Ostalpen. - Mitt. Österr. Geol. Ges., **90**: 175-183.

Prochaska, W. (2000): Magnesite and talc deposits in Austria. - Mineralia Slovaca, 32: 543-548.

Prochaska, W., Pohl, W., Belocky, R. & Kucha, H. (1995): Tertiary metallogenesis in the Eastern Alps - the Waldenstein hematite deposit. - Geol. Rundschau, **84**, 831-842.

Prochaska, W., Frank, W. & Bechtel, A. (1996): Pretertiary siderite mineralization in the Greywacke Zone of the Eastern Alps. - (In: Grecula, P. (Ed.): Variscan metallogeny in the Alpine orogenic belt), Mineralia Slovaca-Monography, 165-174, Bratislava.

Prochaska W. & Henjes-Kunst, F. (2008): Inclusion fluid chemistry of sparry magnesite mineralizations in the Eastern Alps. - From Sea to Sky - Goldschmidt 2008, Goldschmidt Conference Abstracts, A 763.

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.

Raith, J.G. & Vali, H. (1998): Fibrous chlorite and muscovite from the Kaisersberg graphite mine, Styria, Austria. - The Canadian Mineralogist, **36**: 741-754.

Raith, J. & Postl, W. (2000): „Asbest“ aus der Graphitlagerstätte Kaisersberg und vom Leimsgraben bei Mautern, Steiermark, Österreich. - Joannea Min., **1**: 65-86.

Ratschbacher, L. (1984): Beitrag zur Neugliederung der Veitscher Decke (Grauwacken-zone) in ihrem Westabschnitt (Obersteiermark, Österreich). - Jb. Geol. B.-A., **127**: 423-453.

Ratschbacher, L. (1987): Stratigraphy, tectonics and paleogeography of the Veitsch nappe /Graywacke zone, Eastern Alps, Austria): A rearrangement. - Mineralia Slovaca, Monogr., 407-414.

Ratschbacher, L. & Klima K. (1985): Übersicht über Gesteinsbestand und Metamorphose in einem Querprofil vom Altkristallin zur Kalkalpenbasis (Obersteiermark - Österreich). - Jb. Geol. B.-A., **128**: 151-173.

Ratschbacher, L. & Nievoll, J. (1984): Die Aussagekraft von Schwermineraldaten aus der Veitscher Decke (Steiermark, Österreich). - Jb. Geol. B.-A., **127**: 455-469.

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.

Redlich, K.A. (1935): Über einige wenig bekannte Magnesitlagerstätten Österreichs. - Jb. Geol.B.-A., **85**: 101-133.

Rumpf, J. (1867): Über steirische Magnesite. - Mitt. naturwiss. Ver. Steiermark, **13**: 91-96.

Rumpf, J. (1873): Über krystallisierte Magnesite aus den nordöstlichen Alpen. - Min. Petr. Mitt., 263-272.

Schönlaub, H.P. (1979): Das Paläozoikum in Österreich. Verbreitung, Stratigraphie, Korrelation, Entwicklung und Paläogeographie nichtmetamorpher und metamorpher Abfolgen. - Abh. Geol. B.-A., **33**: 5-124.

Schönlaub, H.P., Flajs, G. & Thalmann, F. (1980): Conodontenstratigraphie am Steirischen Erzberg (Nördliche Grauwackenzone). - Jb. Geol. B.-A., **123**: 169-229.

Schroll, E. (1997): Geochemische und geochronologische Daten und Erläuterungen. - (In: L. Weber (Ed.): Metallogenetische Karte von Österreich (1: 500.000) und Handbuch der Lagerstätten der Erze, Industrieminerale und Energierohstoffe Österreichs). - Arch. Lagerst. forsch. Geol. B.-A., **19**: 395-538.

Schroll, E., Dolezel, P. & Papesch, W. (1986): Beitrag der C- und O- Isotopenanalyse zur Genese ostalpiner Sideritvorkommen. - Mitteilungen. Österr. Geol. Ges., **78**: 181-191.

Schulz, O., Vavtar, F. & Dieber, K. (1997): Die Siderit-Erzlagerstätte Steirischer Erzberg: eine geowissenschaftliche Studie mit wirtschaftlicher und geschichtlicher Betrachtung. - Arch. Lagerst. Forsch. Geol. B.-A., **19**: 65-178.

Schuster, R., Scharbert, S. & Abart, R. (1998): Permo-Triassic high temperature/low pressure metamorphism in the Austroalpine Basement Units (Eastern Alps). - Mitt. Österr. Miner. Ges., **143**: 383-385.

Siegl, W. & Felser, K.O. (1973): Der Kokardendolomit und seine Stellung im Magnesit von Hohentauern (Sunk bei Trieben). - BHM, **118**: 251-256.

Spindler, P. (1992): Neue Untersuchungen zur Mineralogie und Geochemie der Basisbreccie des Steirischen Erzberges, Österreich. - Österr. Akad. Wiss., math.-naturwiss. Kl., 1-25.

Tollmann, A. (1977): Die Geologie von Österreich, Bd. 1, Die Zentralalpen. - 1-765, (Deuticke) Wien.

Walter, S.H.G. (2001): 3D-Modellierung der Magnesitlagerstätte Hohentauern. - Diplomarbeit, FU Berlin, Inst. Geologie, Geophysik und Geoinformatik, 1-57, Berlin.

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.

Weber, L., Ebner, F. & Hausberger, G. (2002): The Interactiv Raw Material Information System („IRIS“) of Austria - the computer based Metallogenetic Map of Austria. - Slovak. Geol. Mag., **8**: 89-99, Bratislava.

Weninger, H.P. (1981): Kraubath/Steiermark: Der Ultrabasit von Kraubath und seine Mineralien. - Lapis, **6/10**: 27-33.