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Mineral Resources in the Eastern Alps and Adjoining Areas

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1 Figure and 20 Box-Figures

Abstract

In the Eastern Alps, Western Carpathians and the northern part of the Pannonian Basin mineralizations are closely related to the particular geodynamic settings and remobilizations during all major (pre-Variscan, Variscan and Alpine) geodynamic stages. Within the frame of this evolution the formation of mineral resources is explained. Some mineral deposits/occurrences of the Eastern Alps are described in special boxes to demonstrate characteristic features of this particular minerogenetic province.

General situation

The geology of Austria mainly comprises parts of the Variscan Bohemian Massif in the north, as a part of the Paleozoic Central European Variscan orogen and domains of the younger Cretaceous to Tertiary Alpine orogen in the south (Eastern and Southern Alps). Together with the Western Carpathians and the pre-Neogene basement units of the Pannonian Basin the Alps form a particular minerogenetic province.

We view the Alpine-Carpathian domain as a polycyclic minerogenetic province, which is controlled by the particular geodynamic settings and remobilizations of pre-existing mineral concentrations during all major (pre-Variscan, Variscan and Alpine) evolutionary stages (WEBER, 1997b; EBNER, 1998a, b). This polystage geodynamic evolution reflects a continuous progression in the cratonization of the crust, in which a pre-Alpine minerogenetic epoch can be clearly subdivided from an Alpine one.

The metallogenetic map of Austria, which also includes industrial minerals and mineral fuels (WEBER, 1997a), is based on the analysis of about 3000 mineral deposits and occurrences, which have been grouped into 150 minerogenetic districts. Most of these are small by international standards. Nevertheless, they gave rise to intense research for more than 150 years and some controversial metallogenetic theories.

Formerly the basic genetic concept of the mineral deposits and occurrences was a hypothetical magmatic source beneath the central Eastern Alps (W. PETRASCHECK, 1926). Later this model was succeeded by another concept, in which a large part of the mineralizations were attributed to fluids derived from distinct centres of Alpine regional metamorphism (CLAR, 1953; FRIEDRICH, 1968; W. E. PETRASCHECK, 1963; POHL, 1993; POHL and BELOCKY, 1994, 1999). Beside these models, a considerable number of mineralizations were considered to be strata-bound from Paleozoic and Mesozoic times. From the 1970's onwards, the metallogeny of the Eastern Alps was combined with global tectonics (W. E. PETRASCHECK, 1976, 1986).

Detailed information on the geodynamic history and mineral formation of the Eastern Alps with exhaustive references is provided by: EBNER (1998a, b), FRISCH and NEUBAUER (1989), FRISCH and LOESCHKE (1993), KÖPPEL et al. (1993), NEUBAUER (1994), NEUBAUER et al. (1998), POHL (1984, 1993), POHL and BELOCKY (1994, 1999), RATSCHBACHER et al. (1991), V. RAUMER and NEUBAUER (1993), V. RAUMER (1998), WEBER (1997a, b). The situation with regard to the Slovakian Western Carpathians is summarized by VOZÁROVÁ and VOZÁR (1996), CHOVAN et al. (1994) and GRECULA et al. (1995, 1997), and respectively by KOVÁCS et al. (1998) and MÓRVAI (1982) for the Hungarian Pannonian basement units. Some selected mineral deposits or groups of mineralizations are described in much more detail in the inserted boxes. These "spotlights" should document particular minerogenetic or geodynamic events of the Eastern Alps. Locations mentioned in the text are shown in Fig. 1. (In all references to Fig. 1 the additional remarks loc. 1-54 indicate locations and geological units mentioned in the text.)

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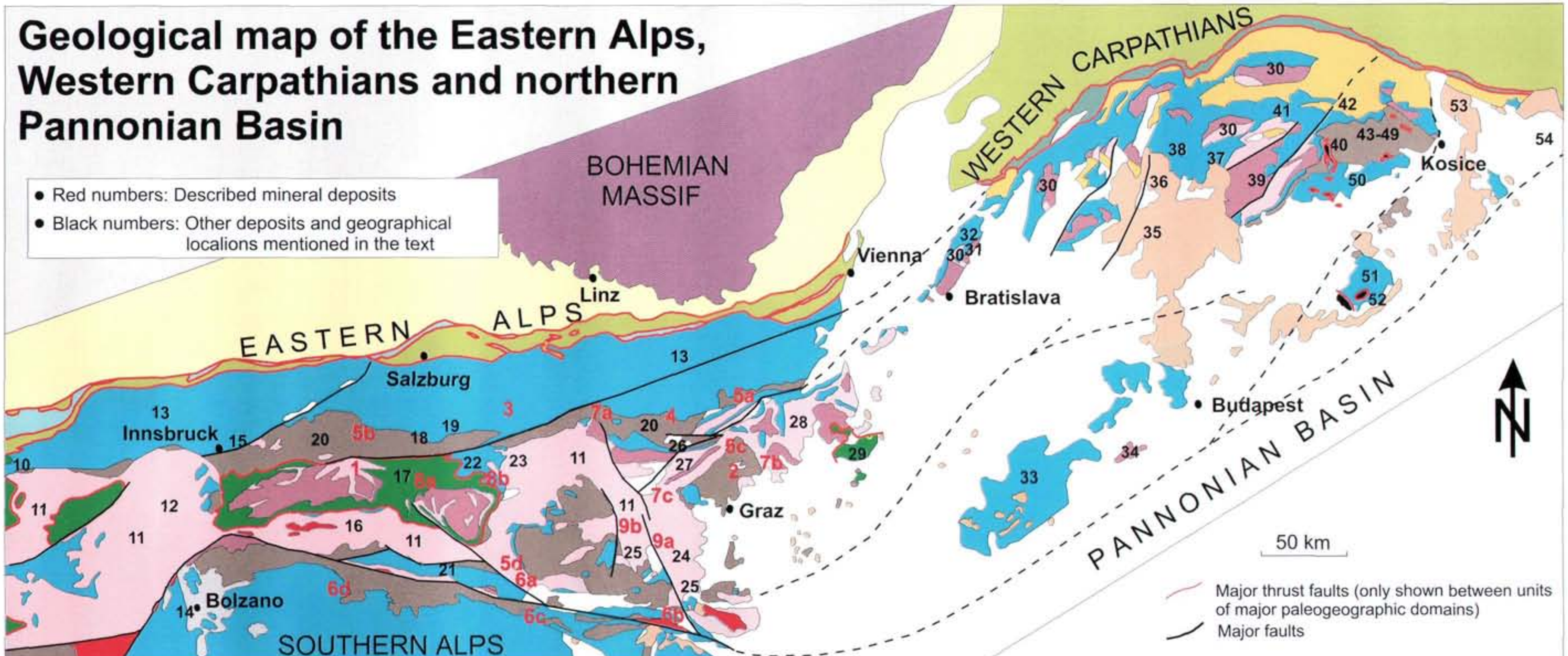


Legend

Central European Variscan belt

- Metamorphic rocks and granitoids

Alpine Carpathian belt

- Alpine-Carpathian Tertiary peripheral foreland basins
- Intramontane Tertiary basins, Paleogene/Neogene
- Periadriatic intrusive rocks (Oligocene)
- Tertiary volcanic rocks
- Helvetic units (Jurassic-Paleogene)
- Alpine/Carpathian flysch (Cretaceous-Paleogene)
- Carpathian Klippen belt (Mesozoic-Paleogene)
- Mesozoic oceanic environments (incl. pre-oceanic Permomesozoic and marginal Mesozoic sediments) Meliata ocean (Triassic/Jurassic)/Penninic ocean (Jurassic-Paleogene)
- Permomesozoic (locally up to Paleogene) sediments
- Quartz-porphyry (Permian)
- Granitoids (Late Paleozoic)
- Paleozoic volcano-sedimentary units (locally including Carboniferous post-Variscan sediments)
- Medium- to high-grade pre-Mesozoic metamorphic basement

Historical and current mining in Austria

Mining has a long history and old tradition in Austria. Graphite was used for neolithic ceramics, and the production of copper by Celtic and Illyric miners was considerable. Between 1800 and 100 B.C. the total output of "black" copper is estimated at ca. 50,000 t. Rock salt has been mined in the Northern Calcareous Alps since the Hallstatt period (800-400 B.C.). The Roman province Noricum was famous for its "Norian iron" produced from manganese-rich ores from Hüttenberg/Carinthia (Fig. 1, loc. 9). Production of iron ore was recorded in 712 A.D. from the Styrian "Erzberg" (Fig. 1, loc. 4), but most probably the Romans had already worked the deposit. Since Roman times precious metals have also been mined at numerous locations in the Eastern Alps. These activities culminated during the Middle Ages between 1480-1560 when the mines of Tyrol and Styria were the leading producers of silver in Europe. The state of the art of Austrian mining during this period was excellently documented in the Schwaz code of mining ("Schwazer Bergbuch") dated at ca. 1556-1561 (HOLZER, 1986).

Nowadays, though there are a large number of quarries producing construction materials (limestone, dolomite, magmatic hard rock, marl, clay, sand, gravel), only a few mines are in operation (production data of 1998; ÖSTERREICHISCHES MONTANHANDBUCH, 1999):

iron ore	1,792,000 t
tungsten ore	362,565 t
gypsum	872,468 t
anhydrite	88,932 t
graphite	10,738 t
talc	137,114 t
kaolin	298,110 t
magnesite	722,876 t
trass	4,037 t
rock salt	1,343 t
salt brine	2,447,083 m^3

← Fig. 1
Simplified geological map of the Eastern Alps, Western Carpathians and northern part of the Pannonian Basin with locations of mineral deposits and occurrences, geographic sites and tectonic units mentioned in the text.

Red numbers: deposits/occurrences described in the boxes:

1 Felbertal	6c Raibl
2 Paleozoic of Graz	6d Salafossa
3 Salzkammergut	7a Lassing
4 Erzberg	7b Rabenwald
5a Veitsch nappe	7c Weißkirchen
5b Hochfilzen	8a Gastein and Rauris valley
5c Breitenau	8b Rotgülden
5d Radenthein	9a Waldenstein
6a Bleiberg/Kreuth	9b Hüttenberg
6b Mesica	

Black numbers: deposits, occurrences and geographic locations mentioned in the text:

10 Montafon	32 Malé Karpaty
11 Middle Austroalpine basement	33 Transdanubian Central Mts.
12 Ötztal	34 Velence Mts.
13 Northern Calcareous Alps	35 Banská Štiavnica
14 South Tyrol	36 Kremnica
15 Hall/Tyrol	37 Lubietová
16 Kreuzeck	38 Špania dolina
17 Tauern window	39 Veporic unit
18 Mitterberg	40 Nižná Slaná/Mano
19 Sulzau/Werfen	41 Nízké Tatry
20 Greywacke zone	42 Kišovce/Švábovce
21 Drau Range	43 Novoveská huta
22 Forstau	44 Rudňany
23 Schladming	45 Bystrý potok
24 Koriden unit	46 Čučma
25 Plankogel terrane	47 Mníšek
26 Kaisersberg	48 Smolník
27 Speik terrane	49 Gemeric unit
28 Lower Austroalpine basement units	50 Silica unit
	51 Bükk Mts.
29 Rechnitz window	52 Rudabanya
30 Tatric unit	53 Zlatá Baňa
31 Pezinok	54 Zemplín Mts.

Genesis of mineral deposits in the Eastern Alps, Western Carpathians and Pannonian Basin

The geological make-up of the Eastern Alps, Western Carpathians and the basement units of the Pannonian Basin, together with all Tertiary volcanic phenomena of the inner Carpathian volcanic arc, are the result of the Mesozoic-Tertiary Alpine orogeny. Nevertheless, this area also includes numerous pre-Alpine structural elements. During the last decade the geodynamic and minerogenetic significance of all these features has become well known (EBNER, 1998 a, b, FRISCH and NEUBAUER, 1989, FRISCH and LOESCHKE, 1993, KÖPPEL et al., 1993, NEUBAUER, 1994, NEUBAUER et al., 1998, POHL, 1984, 1993; POHL and BELOCKY, 1994, 1999; RATSCHBACHER et al., 1991; V. RAUMER and NEUBAUER, 1993; V. RAUMER, 1998; VOZÁROVÁ and VOZÁR, 1996; CHOVAN et al., 1994; GRECULA et al., 1995, 1997; KOVÁCS et al., 1998; MÓRVAI, 1982).

A distinct break in the geodynamic evolution followed the Variscan orogeny, when the basement units of the area in consideration became part of Pangea. During the Paleozoic their incorporation into this megacontinent occurred step by step by terrane accretion at an active continental margin, followed by Carboniferous continent-continent collision and intrusion of granitoids. All units derived from a volcanic arc/suture zone situated at the northern margin of Gondwana, from which they split off during the Cambrian-Ordovician and Silurian. Cambrian (?) rifting at the active Gondwana margin was interrupted by a short-lived Orodovician orogenic event. After terrane drifting to the north, the final Variscan collision started in the internal zones during the Devonian-Early Carboniferous. This was followed by granitoid intrusion and by nappe stacking in the future Upper Austroalpine and South Alpine domains during Visean-Namurian times. These stages reflect a continuous progression in the cratonization of the crust with distinct metallogenetic/minerogenetic epochs: (1) pre-Late Ordovican (pre-Variscan), (2) Late Ordovician to Early Carboniferous (Variscan) and (3) Carboniferous-Permian late- to post-Variscan.

Pre-Alpine (Pre-Variscan and Variscan) metallogeny

The pre-Upper Ordovician (pre-Variscan) metallogenetic epoch is characterized by the formation of oceanic crust, island (magmatic) arcs and deposition of volcanosedimentary rocks in arc-related basins. Approximately 450 Ma old granitic intrusions are widespread and often pre-dated by a high pressure metamorphic event. These meta-granites are virtually devoid of any mineralizations and they terminated the first period of crustal formation.

In the Eastern Alps significant W-Au-Cu-Pb mineralizations of this period were formed in island arc systems now exposed in the Habach Group of the Tauern window (Fig. 1, loc. 17). In the Austroalpine domain some amphibolite-gneiss complexes [Ötztal (Fig. 1, loc. 12), Kreuzeck mountains (Fig. 1, loc. 16), Schladming (Fig. 1: loc. 23)] contain stratiform polymetallic (Fe-Cu-Zn-Pb) mineralizations, which were most probably formed in back arc settings (KÖPPEL et al., 1993). The Speik terrane (Fig. 1: loc. 27) is a highly dismembered back arc ophiolite with subeconomic Cr and PGE mineralizations. Isotope signatures of the mineralizations hosted in the island arc systems of the Tauern window point to a mixture of lead derived from a depleted mantle and from crustal sources. In contrast, the lead from Pb/Zn-mineralizations in Austroalpine units bears a continental signature (KÖPPEL et al., 1993).

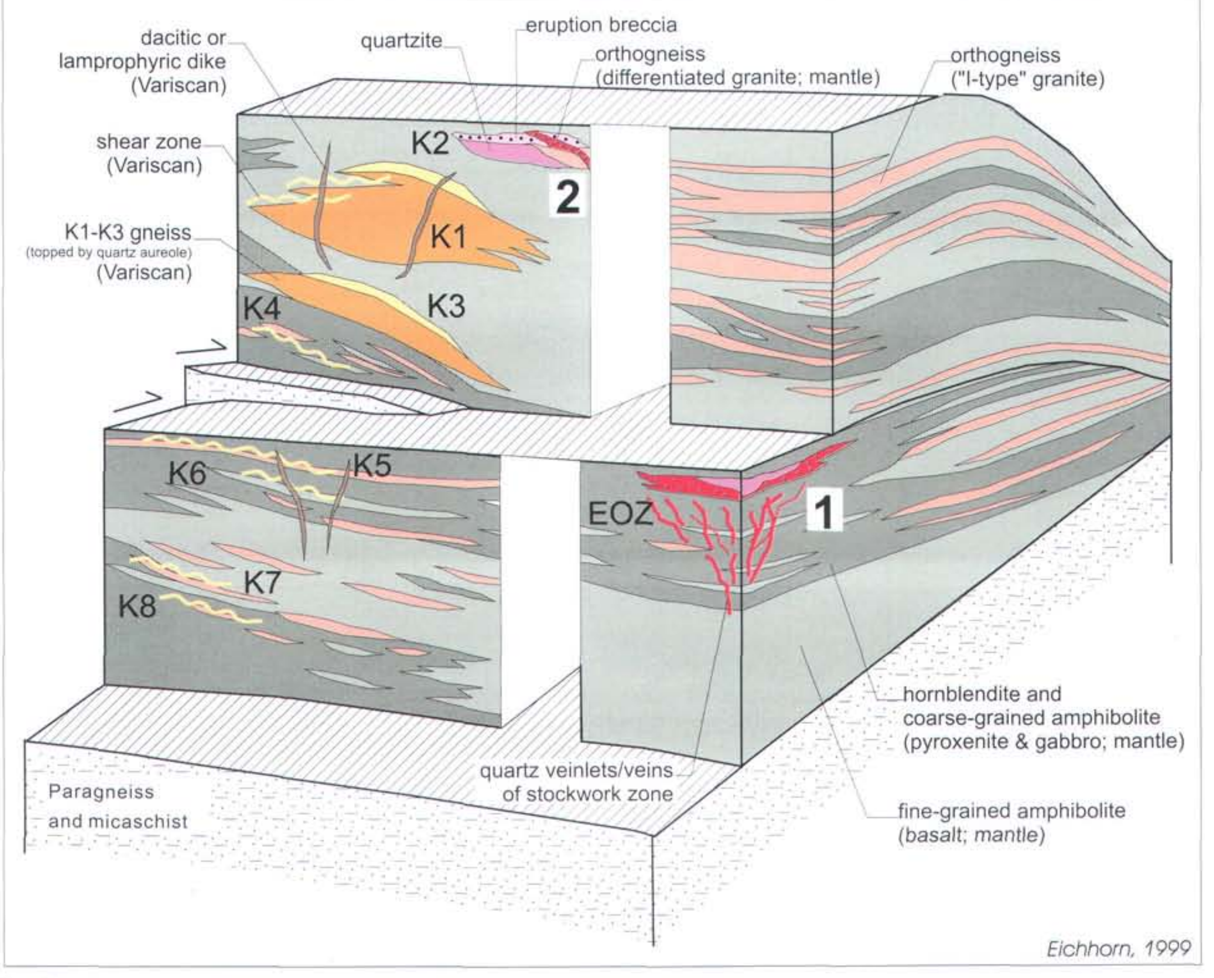
In the Western Carpathians pre-Variscan mineralization is of little significance. Only the stratiform, low to high-grade metamorphosed pyrite and pyrrhotite mineralizations in the Malé Karpaty mountains (e.g. Pezinok; Fig. 1, loc. 31, 32) and Nízke Tatry mountains (Fig. 1, loc. 41), as well as stratiform scheelite occurrences within the Veporic crystalline unit (Fig. 1, loc. 39) should be mentioned (CHOVAN et. al., 1994).

Box 1

The Felbertal tungsten deposit in the Tauern Window *(Fig. 1, loc. 1)*

R. EICHHORN

The Felbertal scheelite deposit in the northern part of the central Tauern Window was discovered in 1967. Mining occurred from 1975 to 1993, and was resumed in 1995. The deposit has produced some 7 mill. t of ore and produces 400,000 t/year ore at a grade of 0.5% WO_3. It is located 9 km south of the town of Mittersill and consists of two ore fields within an up to 400 m thick rock pile, considered to represent stacked nappes. The ore



Box-Fig. 1-1

Schematic block diagram of the Felbertal scheelite deposit. Arrows indicate relative nappe movements. Note that red and green colors denote Pre-Variscan, orange and yellow colors denote Variscan features.

deposit belongs to the Magmatic Rock Formation, which is tectonically squeezed between the Habach Phyllite Formation and the Basal Schist Formation (all formations of the Habach Group).

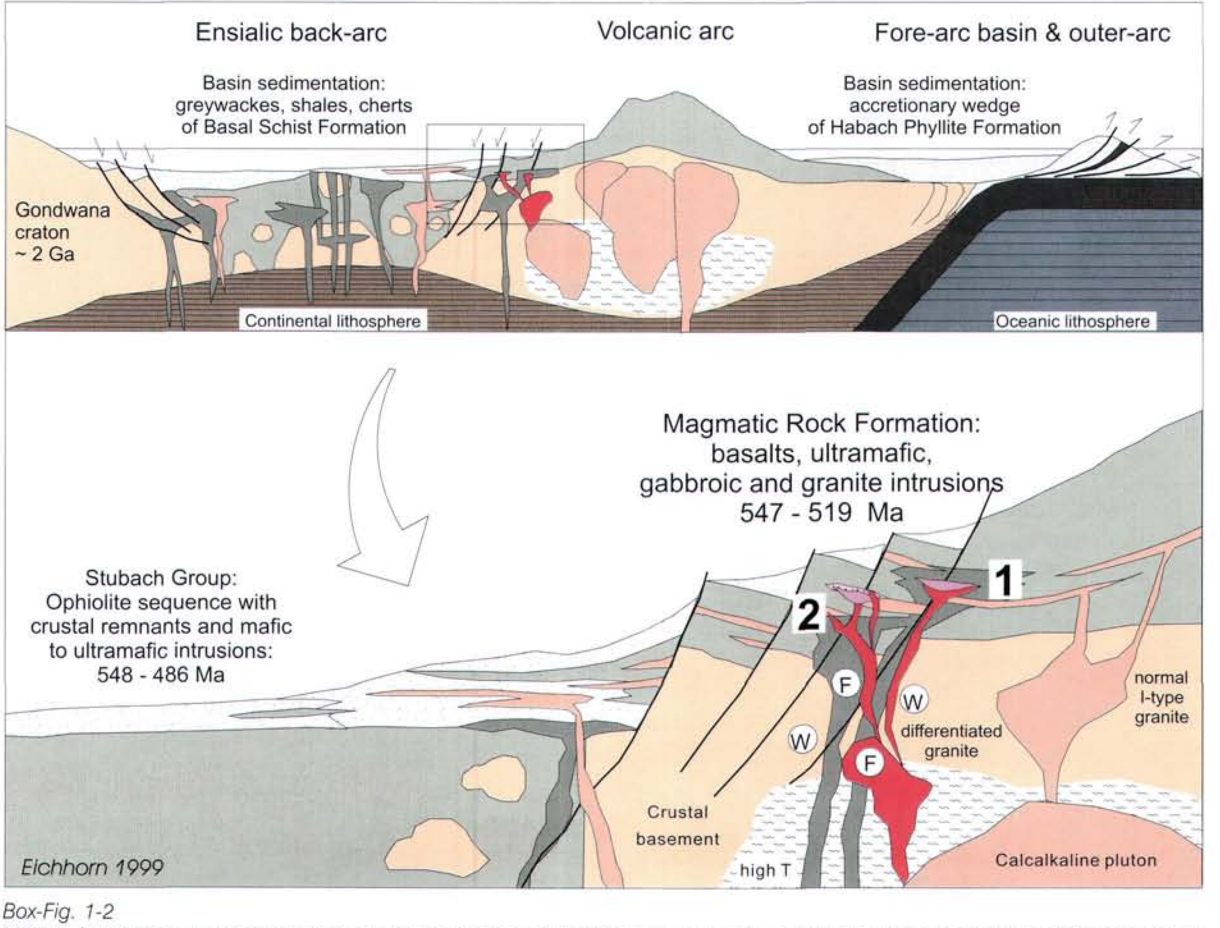
The eastern ore field is an elongate, 2500 m long and 200 m wide ore zone (EOZ= eastern ore zone), and comprises scheelite-rich quartzite with ~2% WO_3 evolving into a differentiated EOZ gneiss at deeper structural levels, and numerous scheelite-bearing quartz veins beneath the quartzite-gneiss lens. The western orefield comprises two ore-bearing wedges separated by a barren wedge of predominant paragneiss and micaschist. Several distinct ore bodies (K1 to K8) are still being mined underground. A major ore body is associated with the Variscan K1-K3 granitoid intrusion. Further scheelite enrichments are bound to small Variscan shear zones. However, voluminous rock masses have mostly subeconomic or low-grade ores due to scheelite in cross-cutting quartz veins and along the principal (Variscan) schistosity (Box-Fig. 1-1).

Since its discovery, the origin of the Felbertal scheelite deposit has been a matter of debate. The genetic models proposed can essentially be divided into two main groups: The first group advocates a pre-Variscan (Early Paleozoic) subduction-related origin for the first scheelite formation, the second a Variscan (Late Paleozoic) granite-related origin.

HÖLL (1975) was among the first to interpret the ore deposit in terms of an Early Paleozoic submarine-exhalative deposition within small-scale basins. He and his co-workers compared the scheelite-rich quartzites of the EOZ and the K2 ore body with sinter masses generated by exhalative processes in a geothermal field.

The wealth of new geochronological and geochemical data now allow the evolution of the Felbertal scheelite deposit to be reconstructed (EICHHORN et al., 1999; HÖLL and EICHHORN, 2000):

(1) A volcanic arc is formed at ca. 550 Ma by the emplacement of volcanic-arc basalts. This arc may have been close to a continental margin, possibly near the northern rim of Gondwana. More or less coeval crustal thinning occurred in an ensialic back-arc region, accompanied by the emplacement of tholeiitic basalts and the intrusion of minor diorites (Box-Fig. 1-2). Subsequently, gabbroic and ultramafic melts intruded into the arc and back-arc region followed by normal, "I-type" granitoid



Box-Fig. 1-2
Model of a possible pre-Variscan scenario for the Felbertal scheelite deposit and its vicinity. Note that normal faults of an extensional tectonic regime behind the main arc are the pathways for both the gabbroic and ultramafic magmas (heralding back-arc rifting), as well as the normal "I-type" and differentiated granitic melts. The latter supposedly caused the (primary) tungsten mineralization in the eastern ("1") and western ("2") ore fields of the Felbertal scheelite deposit. Legend as in Box-Fig. 1-1.

melts with mantle signature until 530 Ma. Then increasingly differentiated, yet still mantle-dominated granitic melts intruded between 530 Ma (EOZ) and 520 Ma (K2) locally in the Felbertal ore deposit and caused the primary tungsten mineralization. Such differentiated granitic melts may already be tungsten-enriched due to the high incompatibility of W. They may become more enriched in W if they are fluorine-rich.

In the eastern ore field the hydrothermal activity resulted in an elongate ore zone with scheelite mineralization in the stockwork zone and the scheelite-rich quartzite lens. These mineralizing fluids were characterized by crustal isotopic compositions, derived from deeper sections of a thick continental crust beneath the arc, where crustal anatexis is prominent.

In the western ore field the scheelite mineralization starts in the K2 ore body, together with a bowl-shaped quartz deposition and is followed by the formation of a strongly mineralized breccia lens. It ends with the intrusion of the poorly scheelite-bearing younger K2 granite.

(2) Further episodic magmatism occurred during Variscan time. One of these intrusions (the K1-K3 gneiss protolith at ca. 340 Ma) may be responsible for a second tungsten input (yellowish-fluorescent scheelite mineralization in K1-K3 gneiss and its aureole). Subsequent ductile deformation obviously remobilized the scheelite and formed further (yellowish-flurorescent stage 2 scheelite) porphyroblasts in shear zones and along the main schistosity before a dacitic dike crosscut the rock pile some 340 Ma ago.

(3) Ongoing medium-grade Variscan metamorphism till 282±2 Ma induced scheelite remobilization under reducing conditions (bluish-fluorescent stage 3 scheelite).

(4) Finally, Alpine lower amphibolite to upper greenschist facies metamorphic conditions at ca. 30 Ma led to a further scheelite remobilization, predominantly along some faults and quartz veins (sparse, but large, whitish-bluish-fluorescent crystals; stage 4 scheelite).

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Cu, Fe, Pb, Zn mineralizations of the Upper Orodovician – Early Carboniferous metallogenic epoch are controlled by the paleogeographic position of their host rocks. According to the terrane reconstruction of FRISCH and NEUBAUER (1989), the polymetamorphic tectonostratigraphic units of the Lower Austroalpine unit (TOLLMANN, 1977; Fig. 1, loc. 28) were situated at the southern, active continental margin of the Ligerian plate. Their ore mineralizations are strongly deformed and polymetamorphically overprinted to conditions above those of the Alpine metamorphism (TUFAR, 1963; NEUBAUER and FRISCH, 1993).

An accretionary wedge was formed south of this zone, which was metamorphosed to high-grade gneisses (Koriden unit; Fig. 1, loc. 24). Part of the accreted terranes (Plankogel terrane; Fig. 1, loc. 25) derived from the ocean situated between Europe and Gondwana, whereas others – the Noric Composite and the Habach terrane – had a primary position along the northern margin of Gondwana.

The Noric Composite terrane (including all low- to very low grade Paleozoic units of the Eastern Alps) split off from Gondwana by Silurian to Lower Devonian rifting and drifted northward until it collided with the European margin during the Carboniferous. Ore formation is controlled by extensional tectonics, alkaline basaltic intraplate volcanism and euxinic environments. Mineralizations are predominantly of syngenetic Sedex-, VMS-, Meggen-, and Lahn Dill-types and include Fe-Cu(Pb/Zn) and Pb-Zn-Ag(Ba) associations (WEBER, 1997a). Generally, the lead isotope compositions of these ores indicate crustal origin (KÖPPEL et al., 1993). Linked to the black shales there are small-sized but ubiquitous tungsten-mineralizations and sometimes magnesite.

During the drift stage passive continental margins with carbonate platforms evolved. In the Greywacke Zone (Fig. 1, loc. 20) they host a great number of siderite, magnesite, fahlore and baryte mineralizations, the genesis of which is partly under debate.

Box 2

Ag-rich Pb-Zn (SEDEX) Deposits in the Paleozoic of Graz *(Fig. 1, loc. 2)*

L. WEBER

In the Eastern Alps a considerable number of stratiform Pb-Zn mineralizations of volcano-sedimentary origin are widely distributed within Silurian-Devonian (meta)sediments of the Noric Composite terrane.

In the Paleozoic of Graz (Styria) these stratiform mineralizations with galena, sphalerite, and barite (Box-Fig. 2-1) have been summarized as a metallogenetic district (WEBER, 1990). Mining commenced in the Middle Ages and ceased in 1927 (WEBER, 1990, and references therein). The main abandoned mining sites are located both east and west of the river Mur north of Graz, the provincial capital of Styria. Between 1973 and 1983 an extensive prospection- and exploration campaign proved the existence of additional Pb-Zn mineralizations in parts of the Graz Paleozoic. Yet, the low metal price did not allow any new mining to begin.

Box-Fig. 2-1
Stratiform barite-galena mineralization in the "Mariahilf" adit Arzberg, Styria.

The Pb-Zn mineralizations of the Paleozoic of Graz are developed only in rocks of a basinal environment ("Schöckel facies"). Mineralization is linked to the Schönberg Formation (Late Silurian to Early Devonian) of the Peggau Group. Typical rocks are various chlorite schists (tuff, tuffite, metabasalt), sericitic schists, carbonate-bearing phyllite, black phyllite and marble (Box-Fig. 2-2).

Within the basinal environment the mineralizations are strictly linked to small-scale sub-basins, with a length of some hundred, and a width of some ten meters. The thickness of these mineralizations ranges from a maximum of several meters down to thin layers. The mineralization consists of galena, containing significant amounts of Ag (average 300 g/t), Fe-rich sphalerite, and Sr-poor barite. The mineralization is poor in chalcopyrite. Other silver-bearing minerals include freibergite and polybasite. The sphalerite is known to contain traces of Hg and Ga. The ore minerals are fine-grained and highly intergrown.

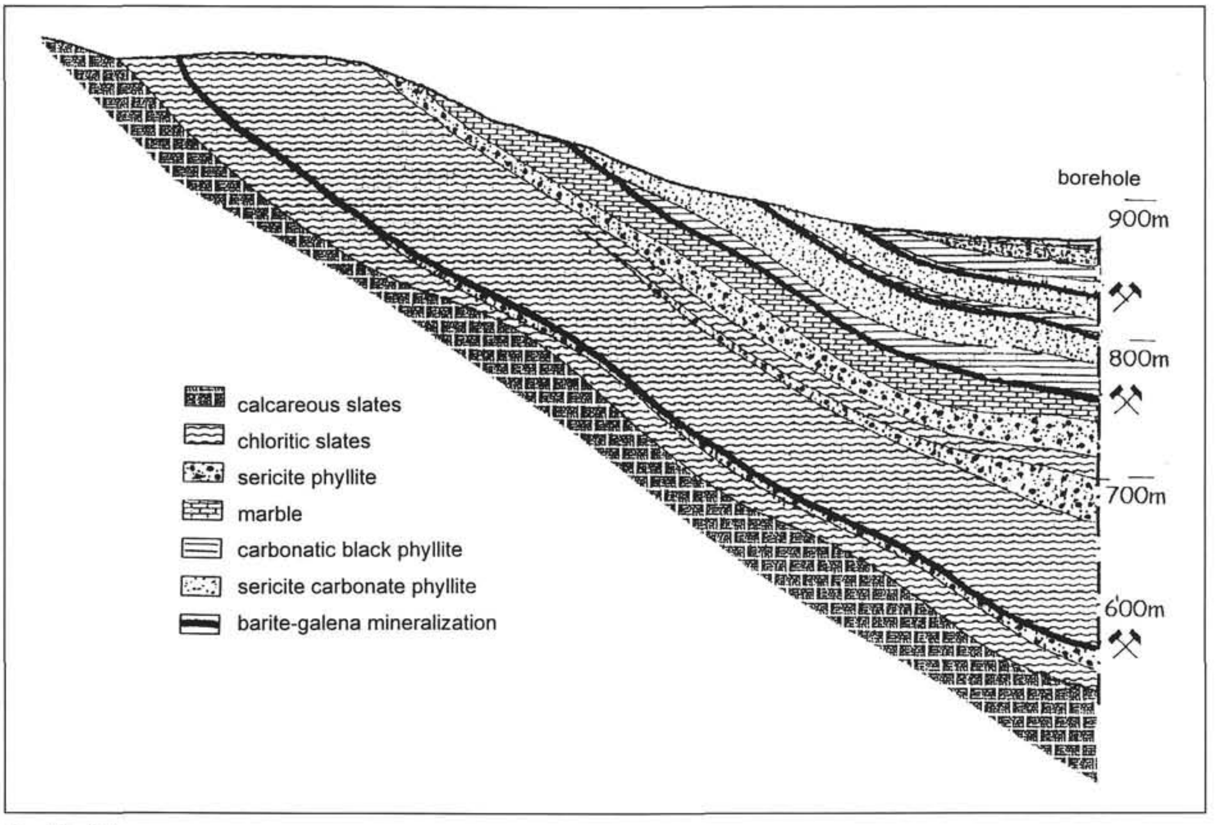
There are at least three different levels of mineralization: the lowermost mineralization mainly contains barite in chlorite schists as host rocks. The main mineralization is linked to marble beds containing barite, sphalerite and galena. The uppermost mineralization, which is developed mainly in black phyllites, exclusively contains sulphides (galena and sphalerite) and no barite (Box-Fig. 2-2).

There is strong evidence for submarine sedimentary genesis of the mineralization. Hydrothermal solutions were expulsed from the depth to the submarine surface in basins. Sulfides precipitated in the basin environment due to the reducing physicochemical conditions. In outer zones there were optimal conditions for the precipitation of barite, as the oxygen concentration in the ocean was significantly higher. Feeder-zones are not yet known. The host rocks next to the mineralizations show alterations such as silicification and albitization, both typical for that type of mineralization.

Primary fluid inclusions are two-phase saline solutions with homogenization temperatures between 195 °C and 250 °C and an average temperature near 230 °C.

The hydrothermal activity followed alkalibasaltic submarine volcanism between Late Silurian to Early Devonian, as a result of a rifting process. The composition of immobile elements in the metabasaltic rocks indicates the "within-plate" character as a consequence of crustal extensional processes.

The mineralizations were formed by hydrothermal solutions, which were expelled from depth to the seafloor. This hydrothermal activity was the main cause of warming of sea-water in isolated submarine basins, resulting in death of organisms. In addition, the poor exchange of seawater within these restricted basins caused a sapropelitic environment. The sudden cooling of the hydrothermal solutions to sea-water temperature was one of



Box-Fig. 2-2
Geological cross-section of Pb-Zn and baryte-bearing Silurian-Devonian volcanosedimentary sequences in the Paleozoic of Graz (WEBER, 1990).

the main reasons for the formation of muds, rich in heavy metals, which were transformed to sulfides under reducing conditions. In the oxidizing environment which surrounded the basins, sulfates (barites) were formed instead of sulfides, such that the existence of barite indicates the outer zones of these mineralizations.

During the Alpine orogenic cycle the mineralizations and their host rocks were deformed to flat-lying folds and overprinted by low-grade metamorphism. Thus, the mineralized horizons are exposed in different tectonic units.

Key reference

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The Variscan orogeny was accompanied by extensive metamorphism and syn- to late orogenic granitoid intrusions. In the Eastern Alps they are devoid of any important ore mineralization due to their present erosional levels. Pegmatites with spodumene and locally Sn, Be, Nb and Ta concentrations are widely distributed within the Middle Austroalpine polymetamorphic crystalline units (Fig. 1, loc. 11).

The Variscan metallogenic epoch in the Western Carpathians is well established. In the Tatric unit the stratiform Sb replacement mineralization of Pezinok (Fig. 1, loc. 31) was formed by metamorphic hydrothermal fluids. In the less metamorphosed flysch-like South Gemeric unit (Cambrian – ? Early Carboniferous) volcanic activity formed massive sulfide-type mineralizations in Smolník (Cu, Fe; Fig. 1, loc. 48), Pb/Zn deposits in Mníšěk (Fig. 1, loc. 47) and Bystry potok (Fig. 1, loc. 45), as well as Fe oxide and Mn deposits in Čučma (Fig. 1, loc. 46). The metamorphic overprint of the Gemeric unit is up to lower amphibolite facies in the central and to greenschist facies in the marginal parts. The latter area hosts a great number of siderite-sulfide veins (e.g. Rudňany; Fig. 1, loc. 44). In the southern parts of the higher grade central area there is a distinct belt of quartz-Au-Sb veins. All these mineralizations were formed by Variscan (and/or Paleo-Alpine) metamorphic fluids as hydrothermal veins or metasomatic replacement ores (e.g. Nižná Slaná/Mano; Fig. 1, loc. 40) (GRECULA et al., 1995).

Furthermore, the Slovakian Gemeric units (Fig. 1, loc. 49) are intruded by some late Variscan granites with small-scale greisen Sn-W mineralizations. Some vein mineralizations in the Malé Karpaty (Sb-Au; Fig. 1, loc. 32), Nízké Tatry (Sb-Au; Pb/Zn; Fig. 1, loc. 41), and polymetallic Au-W-bearing mineralizations in the South-Veporic shear zones (Fig. 1, loc. 39) may be attributed to hydrothermal fluid activity linked to granitoid magmatism (GRECULA et al., 1997). In Hungary hydrothermal polymetallic (Mo-Pb-Zn-Cu) vein mineralizations were formed at the end of Late Carboniferous granitic intrusions in the Velence mountains (Fig. 1, loc. 34).

Carboniferous-Permian late- to post Variscan minerogenetic epoch

Post-orogenic shallow marine, carbonatic/clastic molasse sedimentation started in the Eastern Alps within the Early Carboniferous. These rocks now form the Veitsch nappe of the Greywacke Zone (Fig. 1, loc. 5a), which hosts some mines of Veitsch-type sparry magnesite (Fig. 1, loc. 5a), graphite (Kaisersberg; Fig. 1, loc. 26) and talc (Lassing; Fig. 1, loc. 7a). Continental molasse sediments (with anthracitic seams) were deposited in some other areas of the Upper Austroalpine unit within the Late Carboniferous. In the Western Carpathians post-Variscan sedimentation also started in the late Early Carboniferous and continued within lagoonal/continental environments until the Permian. Some lens shaped deposits of sparry magnesite and talc are linked to the Carboniferous rocks. Because they were metamorphosed during the Alpine cycle to greenschist-facies conditions, the same controversy surrounds their origin as well as that of the deposits in the Eastern Alps. Anthracite, bound to Late Carboniferous (lagoonal) molasse sediments, is found only in the Zemplin mountains (Fig. 1, loc. 54).

During the Permian, continental/arid, and in some areas shallow marine and partly evaporitic sedimentary conditions prevailed all over the Alpine-Carpathian-Pannonian area. Acidic (rhyolitic) volcanism is restricted to the upper levels of the Early Permian. Disseminated mineralizations linked to rhyolitic volcanism are known from Montafon (Cu-Au: Eastern Alps; Fig. 1, loc. 10) and Slovakia (Cu: Lubietová, Fig. 1, loc. 37; Špania dolina, Fig. 1, loc. 38). In Slovenia (Sava folds) polymetallic vein mineralization (Pb-Zn, Fe, Cu, Hg, Ba) in Carboniferous/Permian clastics is also most probably linked to Early Permian magmatism. However, in the Bolzano/Trentino area of the Southern Alps (Fig. 1, loc. 14), Late Carboniferous – Permian calc-alkaline volcanics, formed in an Andean-type subduction or post-collisional slab breakoff magmatic environment, gave rise to a great variety of F-Ba-Pb-Zn-Cu-Fe-As-Sb-Ag-Au vein mineralizations.

Clastic sedimentary complexes contain U mineralizations, sometimes associated with Cu, Pb-Zn and other metals. They are known from several locations of the Late Permian Gröden Formation (sandstones) in the Southern Alps (South Tyrol, Fig. 1, loc. 14; Slovenia/Žirovski Vrh), as well as the Permo-Triassic quartzitic formations (e.g. Forstau, Fig. 1, loc. 22) of the Eastern Alps.

Alpine formation of mineral deposits

Troughout the area Late Permian rifting indicates the beginning of the Alpine cycle. This is indicated by bimodal tholeiitic/rhyolitic volcanism, the intrusion of anorogenic magmatic rocks, and less known Permian metamorphism in the Eastern Alps. The U-Mo-Cu deposit of Novoveská huta in Slovakia (Fig. 1, loc. 43) was formed in this extensional regime by the circulation of brines and meteoric water (GRECULA et al., 1997). However, the best evidence of crustal extension at the beginning of the Alpine cycle is the Late Permian evaporitic "Haselgebirge" with remarkable rock salt (halite) and gypsum/anhydrite deposits, which were formed in (?) rift-related transtensional basins of the later Northern Calcareous Alps.

In Slovakia and NE Hungary evaporation reached only the sulfate stage. Locally, evaporites are in contact with ultrabasic and basic magmatic rocks. This is an additional argument for Permoskythian rifting. Rifting and circulation of brine-derived fluids have been proposed for the formation of some Austroalpine epigenetic metasomatic siderite and magnesite deposits.

Box 3

***Late Permian "Haselgebirge" at the initiation of the Alpine cycle** (Fig. 1, loc. 3)*

M. A. GÖTZINGER

Late Permian evaporites are situated along main thrust faults within and at the base of the Northern Calcareous Alps. Their role as detachment surfaces during tectonic transport of nappes was important. The term "Haselgebirge" denotes a rock mixture of gypsum, salt and clay-breccias.

In the Northern Calcareous Alps the following Permian evaporite deposits are found from W to E: the former salt deposit at Hall in Tyrol (Fig. 1, loc. 15), the evaporite-(phosphate) district of Sulzau-Werfen (Fig. 1, loc. 19), the evaporite district of the "Salzkammergut" (Fig. 1, loc. 3) and the evaporite district of the eastern Northern Calcareous Alps (Fig. 1, loc. 17).

The Permian evaporites of the Northern Calcareous Alps are stratigraphically located between grey-green quartzites (Permian) and the Werfen Formation (Skythian) in the hanging wall. Their form is strongly tectonized and similar to diapirs and stocks. A comprehensive description of salt deposits in Austria was given by SCHAUBERGER (1986), who discerned four main types of salt rocks:

Rotsalzgebirge (Box-Fig. 3-1): red banded salt with anhydrite, polyhalite, glauberite and Na-Mg-sulfates; black and red salt-clay as clastic components with pyrite and talc.

Grüntongebirge: white streaked salt with anhydrite; green salt-clay and grey-green salt-sandstone as clastic components.

Bunttongebirge: honey-coloured salt-matrix of "Haselgebirge", black, green and greysalt-clay, basic volcanic rocks (tuffites), hematite.

Grausalzgebirge: grey-white salt with anhydrite, dolomite; grey salt-clay, magnesite.

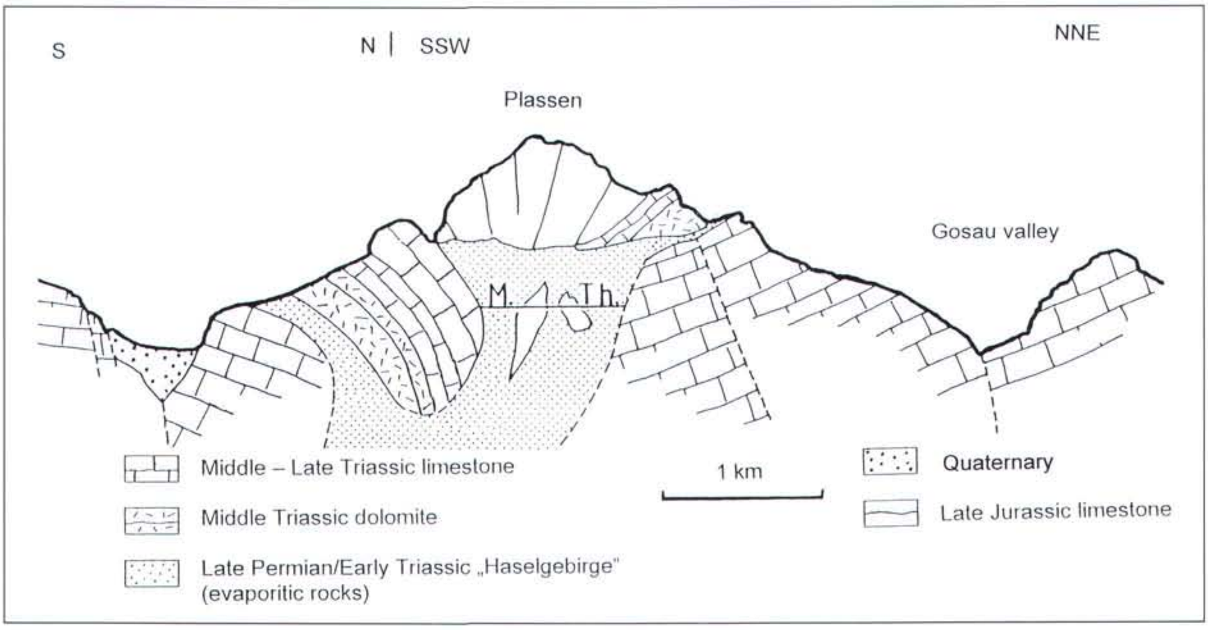
The main minerals of the salt deposits are halite, gypsum and anhydrite, polyhalite. Mirabilite, kieserite, epsomite, glauberite, astrakanite (bloedite, simonyite), loeweite, langbeinite, schoenite; pyrite, chalcopyrite are rare and only locally enriched. The most variety of minerals occur in the banded Rotsalzgebirge. It is notable that the main accessory salts are sulfates of Na, Mg and Ca.

The significant ^{34}S values (in ‰, CDT) are around +10 to +12 $^{87}Sr/^{86}Sr$ ratios of sulfate evaporites range widely

Box-Fig. 3-1
"Rotsalzgebirge" (red rock-salt) in the Hallstatt salt deposit.

from 0.7070 to 0.7098 and indicate Late Permian seawater values (SPÖTL and PAK, 1996).

The area of the "Salzkammergut" extends into the three federal states of Upper Austria, Styria and Salzburg and contains the four main salt deposits in Austria: Dürrnberg-Hallein (Salzburg), Bad Ischl and Hallstatt (Upper Austria), Altaussee (Styria). Hallstatt and Hallein have a very long salt mining tradition (from the late Bronze Age –



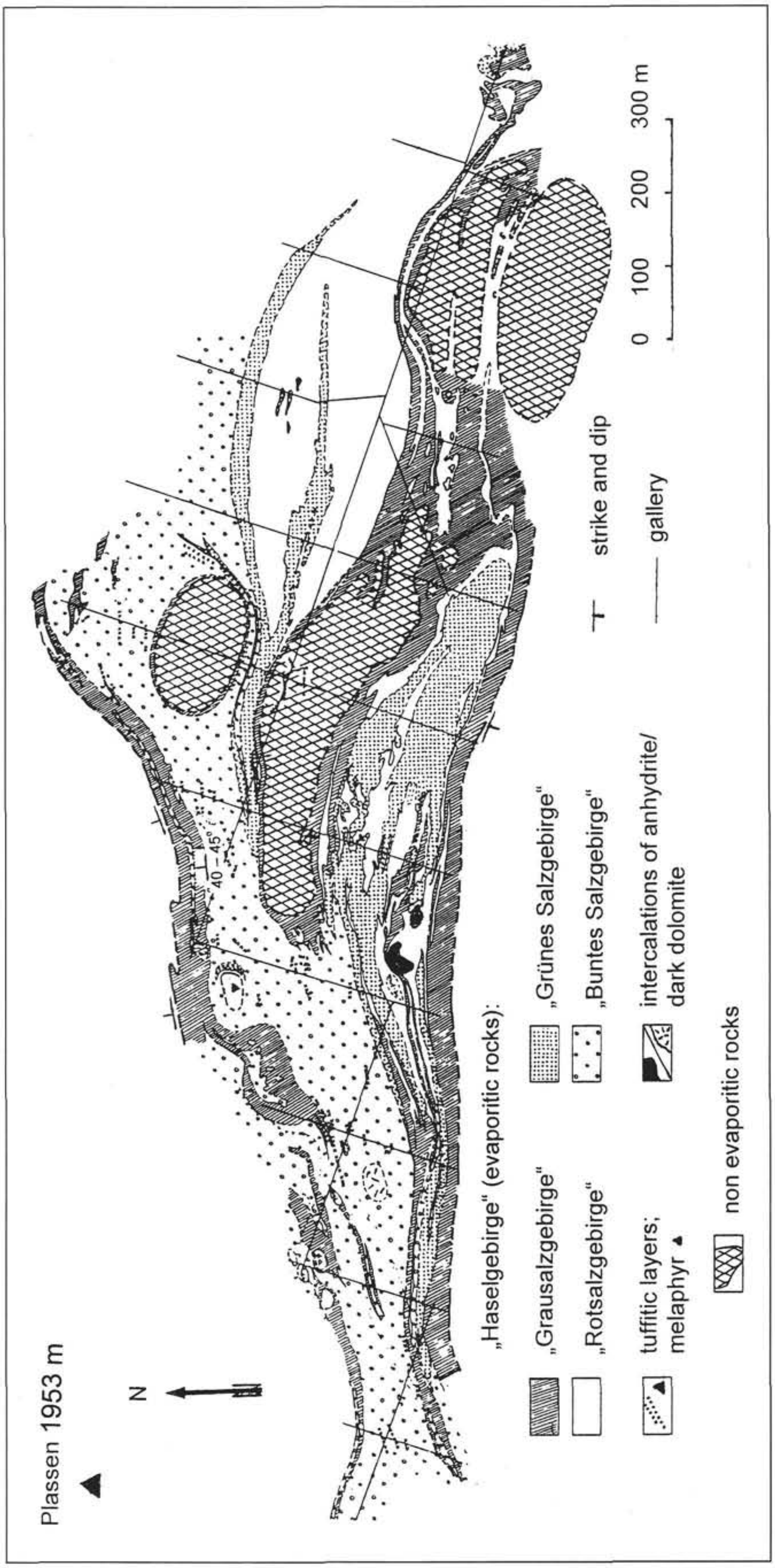
Box-Fig. 3-2 (above)
Geological cross-section of Plassen mountain with the Hallstatt salt deposit. The "M.-Th." level (Empress Maria Theresia adit) indicates the position of the mine.

1000 B.C.: Hallstatt culture, and from the early Iron Age – 800 B.C., respectively).

Many worked gypsum deposits are within this district (e.g. Abtenau, Grubach-Moosegg near Golling, Rigaus-Webing), which are all connected to tectonic boundaries of the nappes. Gypsum was deposited from the marine environment and was transformed to anhydrite by anchizonal metamorphism. A main retransformation to gypsum began after the excavation and alteration by meteoric water: the deposits contain a mantle of gypsum around a core of anhydrite (which is also mined for the cement industry). Some basic intrusives cut the evaporites with relatively sharp boundaries, causing small mineralizations of Fe and Cu (+ Pb, Zn and As).

The Austrian salt deposits Bad Ischl, Hallstatt (Box-Fig. 3-2, 3-3) and Altaussee are currently mined and are also situated within the geographic area of the "Salzkammergut". The deposit of Bad Ischl is characterized by the Rotsalzgebirge salt type, with famous clusters of anhydrite crystals (locally named "Muriazit").

Hallstatt represents the most complex salt types and the most varied salt minerals in different clastic sequences of the "Haselgebirge". The village Hallstatt is a UNESCO "world heritage" location because of its history of nearly three



Box-Fig. 3-3 (below)
Geological map of the Hallstatt salt deposit at the "M.-Th." level (modified after SCHAUBERGER, 1955).

thousand years of mining and because of its situation between the Plassen mountain (1953 m) and the deep lake of Hallstatt.

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Box 4

Siderite and magnesite mineralizations formed during initial rifting of the Alpine cycle

W. PROCHASKA

Siderite *(Fig. 1, loc. 4)*

Numerous siderite mineralizations of various sizes can be found in the Eastern Alps. Today only one siderite mine, Erzberg (Fig. 1, loc. 4), situated in the province of Styria, is operating, with an iron ore production of about 1.4 mil. t/year.

The Erzberg deposit (Box-Fig. 4-1, 4-2) and most of the siderite mineralizations belong to the Greywacke zone where they are situated exclusively in the highest thrust sheet (Noric nappe). The rock series range from the Ordovician to the Carboniferous comprising carbonates, metapelites, acid and mafic volcanic rocks. The grade of metamorphism is generally of lower greenschist facies from both the Variscan and the eo-Alpine, Cretaceous, orogenic events. 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 the transgressive Lower Triassic sedimentary cover of the Northern Calcareous Alps.

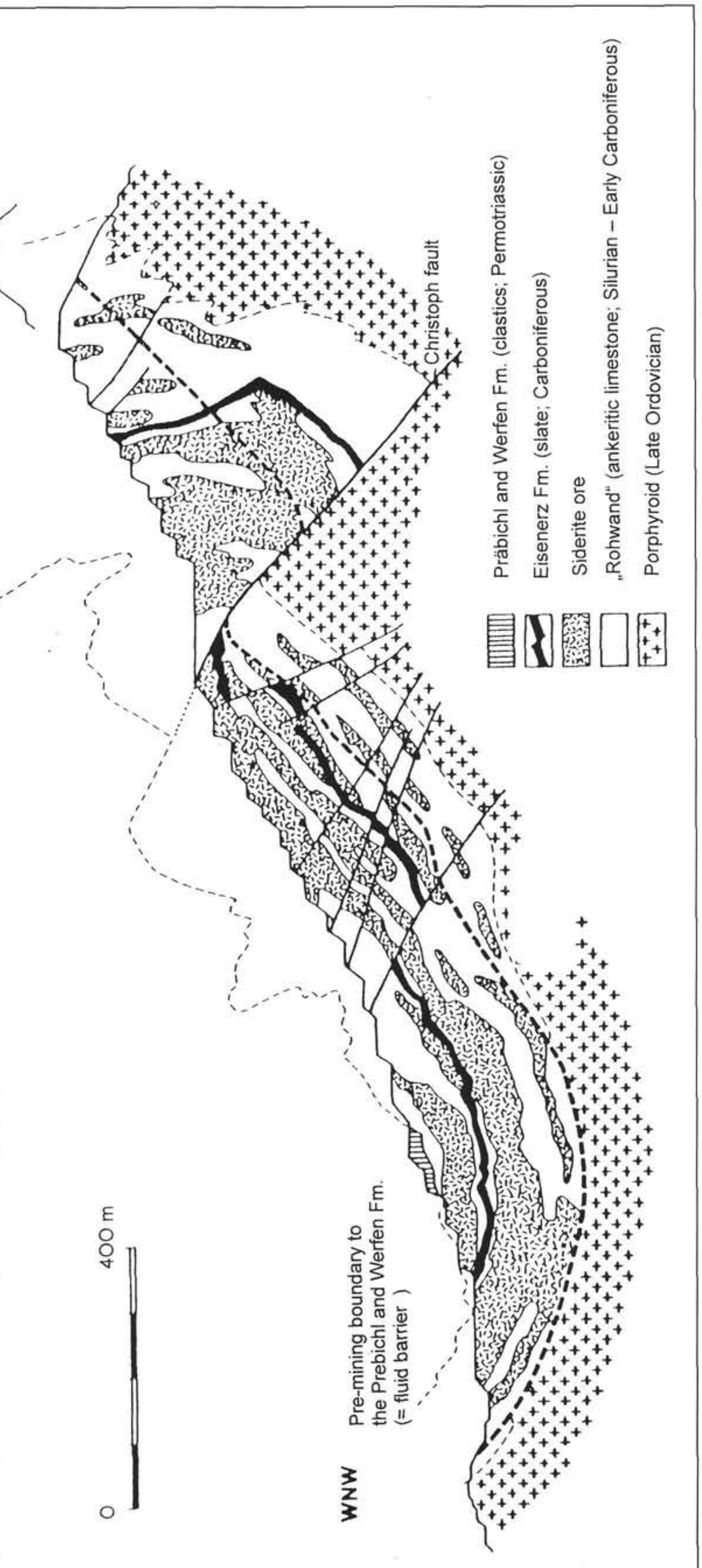
The shape of the ore bodies is strongly controlled by the host lithology. In competent (siliceous) host rocks (Ordovician quartz porphyries, Paleozoic metapelites and sandstones), vein-type mineralization usually occurs, while Devonian limestones and Permoskythian carbonate conglomerates host metasomatic bodies and stocks of siderite.

Box-Fig. 4-1
The Erzberg siderite deposit hosted in Paleozoic limestones of the Greywacke Zone – symbol of mining in Austria.

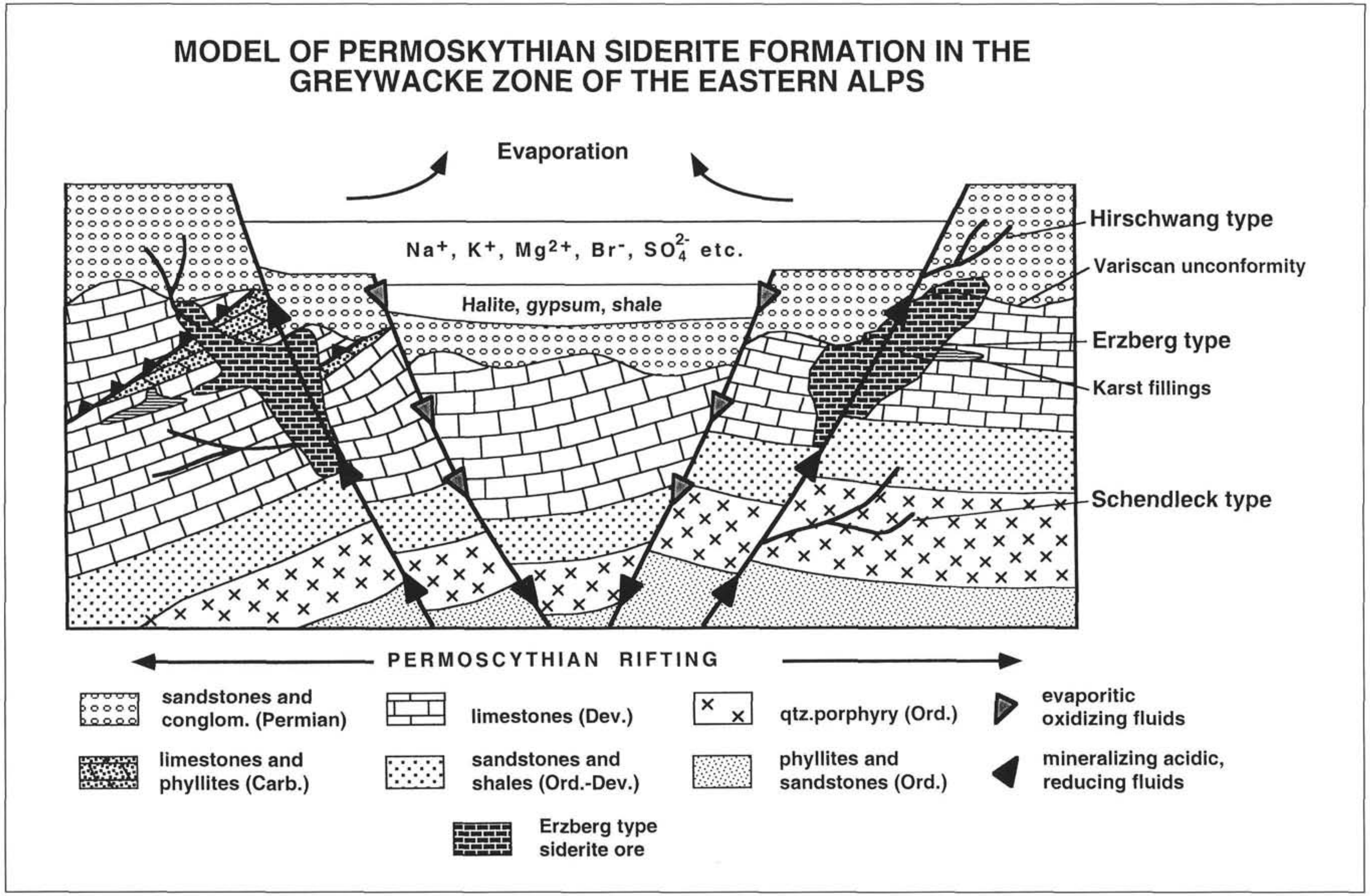
Opinions concerning the genesis of these siderite mineralizations are inconsistent. Various genetic models, including a synsedimentary origin or an eo-Alpine vein-type or metasomatic mineralization, have been proposed in the past. More recent research concentrated on the investigation of structural and 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 and THALMANN, 1978). Following these arguments, SCHULZ et al. (1997) described ore textures of the Erzberg deposit and postulated a marine-synsedimentary origin. LAUBE et al. (1995) reintroduced an epigenetic genesis for siderite mineralization in the Greywacke zone on the basis of microthermometric, geochemical and isotope data.

The model proposed below is an attempt to demonstrate that siderite and magnesite mineralizations were formed during a Permoskythian rifting period by the migration of evaporitic brines in the crust (Box-Fig. 4-3). The arguments are mainly based on field observations and investigations of the chemistry of fluid inclusions that allow the ore-forming fluids to be characterized (PROCHASKA, 1997, 1999).

1. *The mineralizing event must be post-Variscan and pre-Cretaceous, because of mineralized post-Variscan, Permian conglomerates are mineralized and because the hydrothermal features terminate at Alpine nappe boundaries.*
2. *The high salinity and chemical composition of fluid inclusions in siderites and magnesites indicate*



Box-Fig. 4-2
Geological cross-section of the Erzberg siderite deposit.



Box-Fig. 4-3
Model of Permo-Triassic rifting and siderite formation in the Greywacke zone.

that the mineralizing fluids were originally oxidized evaporitic, bittern brines which were modified (reduced) by water-rock reactions (uptake of Fe) while percolating through the crust.

3. The sharp transition in fluid composition between the marine host rock carbonates and the mineralizations characterized by evaporitic fluids is not compatible with a simple marine-sedimentary model.
4. The structure of the mineralizations is hydrothermal-metasomatic. No indications of a synsedimentary concentration of Mg or Fe and stratabound/stratiform mineralizations can be observed.

In Permian (to Early Triassic) times, evaporitic basins were ubiquitous in the Austroalpine realm. High degrees of evaporation produced residual bitterns with high salinities and high concentrations of Br, Mg, K, and SO_4. The peculiar composition (e.g. high Br/Na and Br/Cl ratios) of fluid inclusions in the siderites and magnesites is in itself a strong argument for the Permo-Triassic timing of the mineralization.

High heat flow in the rift environment induced hydrothermal convection systems connected with marine residual evaporitic brines. In higher, more oxidizing levels Mg-enriched brines lead to the formation of magnesites. Diagenetic reactions and hostrock alterations changed these brines at deeper levels into acid and reducing fluids with the capacity to leach Fe from the country rocks. Vein-type siderite-hematite-sulfide mineralizations were formed in the metapelitic and metavolcanic hostrocks in a reducing environment. Metasomatic siderite bodies were formed within the Devonian platform carbonates. Metasomatism and mimetic crystallization of the marine hostrock carbonates often preserved primary sedimentary textures very well, which led earlier researchers to postulate syngenetic models.

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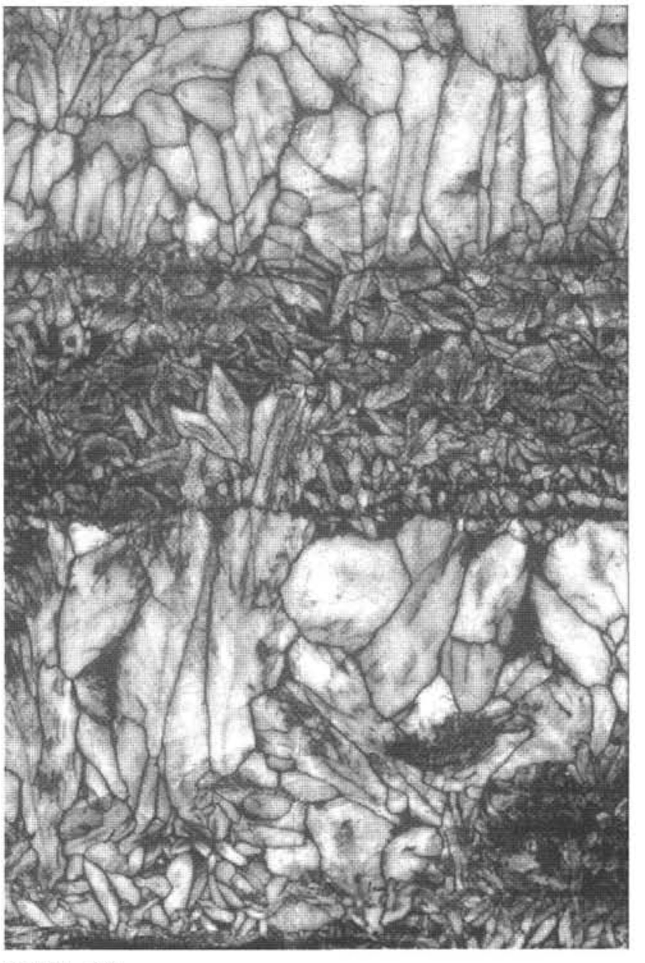
Magnesite (Fig. 1, loc. 5)

Several magnesite mineralizations can be found in the Eastern Alps, some of them being of considerable economic importance (POHL & SIEGL, 1986). Austria's well-developed magnesite industry is of worldwide importance and is, to a large extent, still based on the Austrian mines. The magnesite production of Austria is approximately 800,000 t/year and is mined in 5 deposits (in Hochfilzen, Salzburg, Fig. 1, loc. 5b; in Oberdorf, Wald, Styria Fig. 1, loc. 5a; in Breitenau, Styria, Fig. 1, loc. 5c, and in Radenthein, Carinthia, Fig. 1, loc. 5d).

In the Eastern Greywacke Zone carbonate hosted sparry magnesite (Box-Fig. 4-4) mineralization occurs in Carboniferous strata of the Veitsch nappe (Fig. 1, loc. 5a), which is affected only by low-grade Alpine metamorphism. A set of lens-shaped magnesite bodies of various size can be found in a sequence of sericite phyllite, metagreywackes, metaconglomerates and metatuffs. The rocks hosting the magnesite bodies are of Late Visèan-Namurian age and exhibit a marine, shallow- water environment. In some cases the orebodies are enveloped by mottled, hydrothermal dolomite, but frequently sharp contacts to the hostrock limestones occur. The



Box-Fig. 4-4
Sparry magnesite from the abandoned mine at Hohentauern, Styria, situated in the Noric nappe of the Greywacke Zone.

most prominent example is the abandoned Veitsch mine, which is the type locality of carbonate-hosted sparry magnesite deposits. In the Western Greywacke zone magnesite can be found most frequently in Lower to Middle Devonian dolomites (Hochfilzen deposit; Fig. 1, loc. 5b), but also Silurian black dolomites contain magnesite occurrences.

In the Paleozoic of Graz the Breitenau magnesite deposit (Fig. 1, loc. 5c) is located in a sequence of Silurian-Devonian deep-water sediments. The tectonic position of the highly metamorphosed Radenthein deposit (Fig. 1, loc. 5d) is unclear. Some authors consider it to be a tectonic wedge of Upper Austroalpine Paleozoic rocks imbricated with the tectonically deeper Middle Austroalpine basement during the Alpine orogen, while others regard it as a primary formation of the Middle Austroalpine basement.

There is no consensus about the genetic model and not even about the principal mechanisms for the magnesite mineralization. Starting soon after the discovery of the world's first magnesite deposits in the Eastern Alps after 1850, syngenetic models and epigenetic models were published. In the 1950's a general trend towards syngenetic and early diagenetic models can be observed. Earlier workers mentioned a consanguineous origin of the Alpine sparry magnesite and siderite mineralizations. In general they argued for hydrothermal fluids of different origin, such as magmatic or metamorphic fluids of Alpine (Tertiary) age. Nevertheless, these concepts never gained general acceptance.

Recently, the investigation of fluid inclusions in the magnesites and of geological constraints indicate that the formation of magnesite and siderite in the Greywacke zone is related. As demonstrated above, the hydrothermal event took place under oxidizing conditions (PROCHASKA, 1999).

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During the Triassic the Alpine-Carpathian domain was part of the European shelf. However, according to palinspastic models, the units have to be shifted to the E-SE by a few hundred kilometers before Cretaceous nappe stacking occurred. After initial Permo-Triassic rifting the Alpine (Mesozoic-Cenozoic) history can be subdivided into the following geodynamic stages of metallogenetic relevance:

- Opening and closing of the Meliata ocean (Middle Triassic – Late Jurassic).
- Opening and closing of the Penninic ocean (Jurassic – Early Tertiary).
- Nappe stacking in the upper plate combined with metamorphic overprinting of deeper structural units, after and during subduction of oceanic domains.
- Early Tertiary collision with the European continent.
- Tertiary thrusting to the foreland, uplift, gravitative orogenic collapse, and escape tectonics directed to the east.
- Tertiary magmatism in response to slab breakoff.
- Formation of Tertiary foreland and intramontane molasse basins.

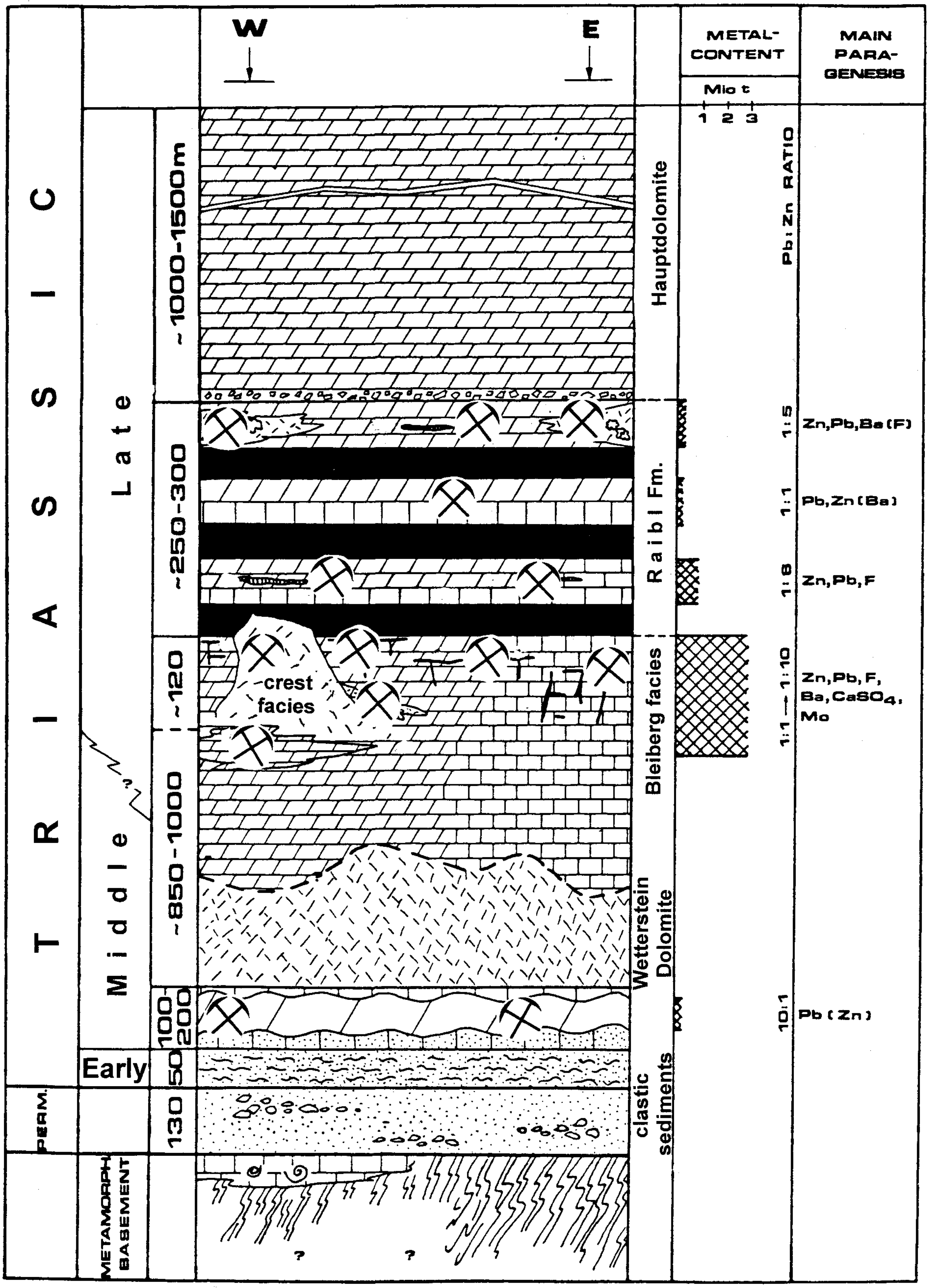
Within the Triassic a large number of carbonate-hosted Pb-Zn deposits, stratabound to Anisian and Carnian levels, is characteristic for the Eastern (Northern Calcareous Alps, Fig. 1, loc. 13; Drau Range, Fig. 1, loc. 21; Bleiberg/Kreuth, Fig. 1, loc. 6a; Mesica, Fig. 1, loc. 6b) and Southern Alps (Raibl, Fig. 1, loc. 6c; Salafossa, Fig. 1, loc. 6d). Their origin is controversial. There is general agreement on their formation in the Eastern Alps by low temperature fluids, but the timing (syngenetic, diagenetic or epigenetic) is still under discussion. The lead model ages of the Bleiberg deposit are significantly older than the host rock and may be derived from Paleozoic sediments (KÖPPEL and SCHROLL, 1988). Nevertheless, during host rock sedimentation, rifting thinned the Austroalpine crust, massive alkaline volcanism occurred in the South Alpine domain and the Meliata ocean was opened. The cinnabar deposit of Idrija was also formed along Middle Triassic extensional systems by ore-bearing hydrothermal fluids before the culmination of Middle Triassic magmatic activity. In Hungary the iron ore district of Rudabanya (Fig. 1, loc. 52) is also situated in Middle Triassic carbonatic rocks. The ore, sometimes associated with barite and sulfides (Pb/Zn, Cu), is of hydrothermal metasomatic origin and a link to Middle Triassic volcanism seems possible. Finally in the Bükk mountains (Szarvaskö, Fig. 1, loc. 51) bodies of titanomagnetite with Cu-Ni sulfide parageneses situated in Middle Triassic gabbroic and peridotitic magmatic rocks represent remnants of the Meliata ocean crust.

Box 5

***Triassic carbonate-hosted Pb-Zn deposits in the Alps** (Fig. 1, loc. 6)*

I. CERNY

The Pb-Zn deposits of Bleiberg-Kreuth (Austria; Fig. 1, loc. 6a), Mesica (Slovenia; Fig. 1, loc. 6b) and Raibl (Fig. 1, loc. 6c) and Salafossa (Italy, Fig. 1, loc. 6d) form part of a Middle Triassic metallogenetic province that is situated on both sides of the Periadriatic lineament (CERNY, 1989). These deposits were all of economic



Box-Fig. 5-1
Stratigraphic sequence of the Bleiberg Pb-Zn deposit. Note the position of the ore- bearing horizons.

5-2a 5-2b 5-2c

Box-Fig. 5-2
Types of Pb-Zn ores of the Bleiberg deposit. 5-2a: resedimented ore (sphalerite-fluorite) within the Wetterstein Fm. (polished section, 7×8 cm), 5-2b: breccia ore (massive sphalerite with grey dolomite clasts); Josefischolle (outcrop 3×2 m); 5-2c: stratabound Pb-Zn ore; Carditascholle (outcrop 3×2 m).

significance and have so far provided more than 10 mil. t of Pb-Zn metal. Mineralizations are generally stratabound in very pure carbonates of the Ladinian and Carnian stages. Usually they are combined under the term "Bleiberg type" and have often been compared with the Mississippi Valley type deposits. The ores are free of silver and copper. Zn-ores, especially at Raibl and Bleiberg-Kreuth, carry significant Ge-contents. The ores are accompanied by fluorite and rarely by barite. In the oxidation zones of Bleiberg and Mesica, Mo-mineralization containing wulfenite and jordesite also occurs.

In addition to these deposits, more than 200 similar Pb-Zn occurrences are known in the Eastern Alps. They are situated in the Drau Range (Fig. 1, loc. 21) and in the Northern Calcareous Alps (Fig. 1, loc. 13).

The Drau Range includes thick Triassic carbonate rocks predominantly of platfom and lagoonal facies with transitions to basinal facies (Box-Fig. 5-1). In the lower part of this sequence mineralization is bound to dolomitic intercalations at the top of the Middle Triassic (Anisian) Alpine Muschelkalk Formation. It gradually changes into dolomitic rocks of the Wetterstein Formation of the Ladinian and Carnian stage. Its lower portion is only locally mineralized with stratabound ores. Separated by some intermediate layers the Bleiberg facies follows with the major ore-bearing limestone.

Within the uppermost 120 m of the Bleiberg facies there are nine very pronounced reference strata, resulting from cyclic sedimentation within a shallow marine depositional area with temporary horizons of emersion. Evaporites are widespread. It has been known for some time that there is a distinct connection between mineralization and these horizons (Box Fig. 5-2a, b).

Separated by a discontinuity, the Raibl Formation (Cardita Formation) follows. It includes three shale horizons within 30-70 m thick carbonatic levels, occasionally rich in stratabound ores (Box-Fig. 5-2c). At the top the very thick Norian Hauptdolomite Formation does not bear any ore.

The Anisian mineralizations are strictly stratabound. They are small and uneconomic. The ores are finegrained, laminated and partly rich in Zn. The mineralizations show a broader variation of paragenesis (Ag, Cu, Fe, F but without Ba).

The shapes of the Carnian ore bodies connected to the Wetterstein carbonate platform are manifold (Box-Fig. 5-2a, b). In addition to stratabound and pipe-shaped orebodies, which continue for 400 to 800 m along strike, there are also vein and fissure-linked parts of the deposit as well as breccias that contain bodies from 0.5 to 1 mil. m^3 of ore. Large stock-shaped ore bodies (crest-type) are marginal to the lagoonal facies. They are interpreted as a product of mobilization during late diagenetic dolomitization and differ significantly from other ore types by their massive and extremely frequent ore formations.

Mineralization in the Cardita Dolomite is controlled by the paleomorphology of the Bleiberg facies. Reduced dolomites above the crest facies contain massive stratabound mineralizations contrasting with the dolomites above the lagoonal facies, which are only locally mineralized.

A pronounced paleogeographic relief at the southern margin of the deposit and intra-Triassic fault tectonics caused extensive rock slides and slumpings to the southern basinal areas. The rock slides comprise several 100 mil. t of brecciated and mineralized rocks derived from the crest facies and the Cardita Formation.

The genesis of the Bleiberg- and of similar Pb-Zn deposits in the Eastern and Southern Alps has been interpreted in a variety of ways (SCHROLL, 1996). The derivation of metals and the concentration mechanisms of Pb-Zn metals for these deposits are not yet understood but possibilities under consideration include the hydrothermal supply of metals, metal derivation from the sediments as a consequence of diagenesis and dolomitization, the formation of residual sediments during intense evaporation phases and metal supply by weathering of former continental regions.

In spite of the variety of these possible mechanisms, it is clear that mineralization has been controlled by facies, and that there are distinct links between dolomitization, salinity, and mineralization. A wide spectrum of sedimentatry and diagenetic concentration is required to reach the ore grades that have been mined.

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The Late Triassic Carnian stage is also marked by a distinct regressive facies change to which evaporites (gypsum/anhydrite) and coal formation are bound in the Northern Calcareous Alps. Within the sedimentary cover of the Lower Austroalpine unit gypsum is known from sediments assigned as "Carpathian Keuper", which is also widely distributed in Slovakian Tatro-Veporic (Fig. 1, loc. 30, 39) cover sediments.

The separation of the Austroalpine domain from Europe and the Penninic area started during the Jurassic by the opening of the south Penninic ocean. In this oceanic domain small-scale stratiform VMS-deposits of base metals are linked to metavolcanics within the Tauern (Fig. 1, loc. 17) and Rechnitz window (Fig. 1, loc. 29).

During the Jurassic, marly deep-water sedimentation took place in parts of the Northern Calcareous Alps, Southern Alps, the Transdanubian Central mountains and the Carpathian Silica unit. Some carbonatic Mn-deposits were formed in areas of slow sedimentation there.

The Late Jurassic to Tertiary history is related to the closure of the oceanic domains, nappe stacking, continent collision, uplift of metamorphic core complexes, gravitative orogenic collapse, and escape tectonics along major strike-slip zones. Cretaceous magmatism, which was formerly regarded as a most important mineralizing factor, is totally missing in the Eastern Alps and is only of subordinate importance for the Western Carpathians.

The lack of magmatism in the Eastern Alps may be explained if Penninic subduction beneath the Austroalpine units was only at a low angle and did not reach the necessary depths to form magmatic arcs and related mineralizations (e.g. porphyry copper deposits). Some small-scale granitic intrusions are reported from the Western Carpathians (Veporic and Gemeric units). Those gave rise to a few subeconomic W-Mo porphyry/stockwork and disseminated Hg-mineralizations (GRECULA et al., 1997).

Metamorphism in deeper structural units in the Eastern Alps and the changing of the tectonic style from compression into extension were important for fluid production and fluid migration. Cretaceous synorogenic fluids of high salinity were formed by metamorphic devolatilization of subducted Penninic rocks or were expulsed from deeper Austroalpine tectonic units. These fluids were focussed along thrust and shear zones within the Austroalpine units (POHL, 1993; POHL and BELOCKY, 1994, 1999). Beside some ore mineralizations e.g. the Cu-vein deposit of Mitterberg (Fig. 1, loc. 18) they formed also some important deposits of talc and leucophyllite.

Box 6

Syn-orogenetic formation of talc and leucophyllite in shear zones and veins *(Fig. 1, loc. 7a-c)*

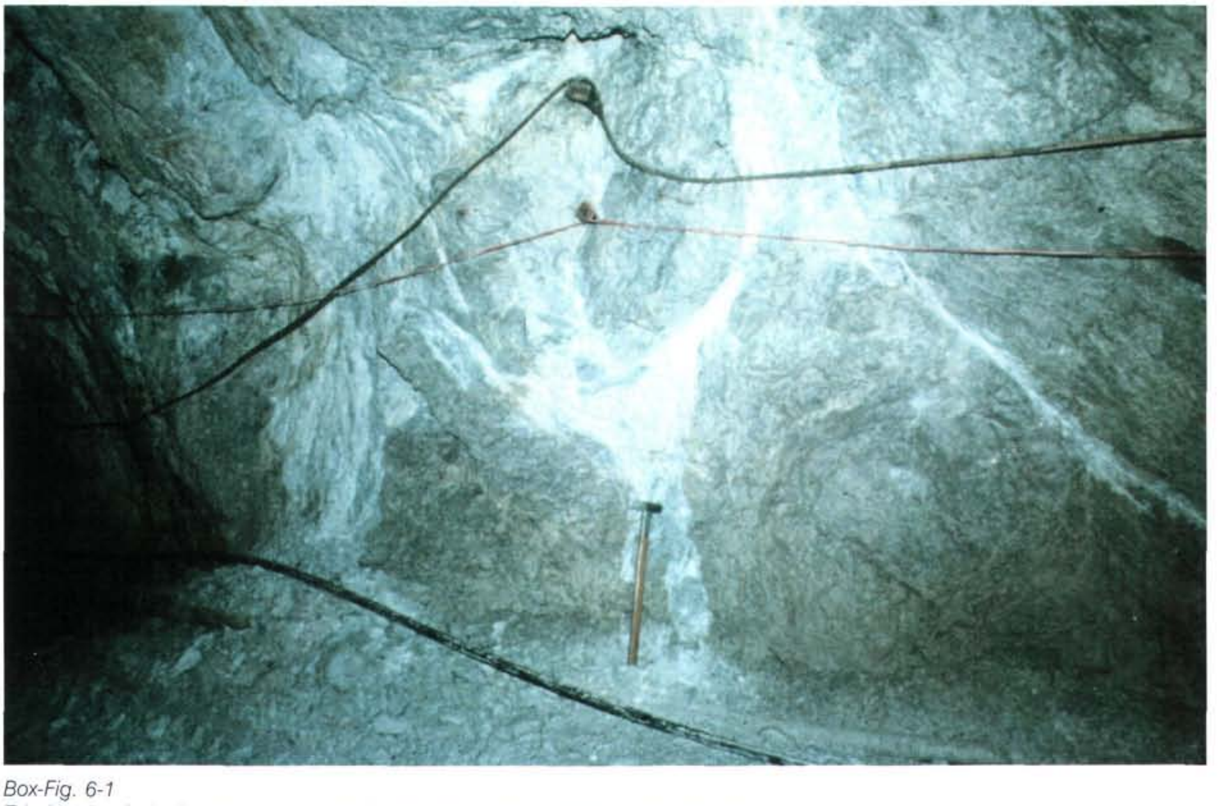
W. PROCHASKA

Several carbonate-hosted ***talc*** *deposits were formed in the Eastern Alps during the Cretaceous orogeny by wall-rock alteration by metamorphic fluids in shear and fault zones. The Rabenwald talc mine in Styria (Fig. 1, loc. 7b) is a big open-pit mine and the largest talc producer in Austria. It is situated in metamorphic rocks of the Lower Austroalpine unit. In Styria, also another accumulation of talc deposits can be found in the Greywacke zone. Most important is the Lassing talc deposit (Fig. 1, loc. 7a), where production ceased in July 1998 after a mine collapse.*

The talc deposit of ***Lassing*** *(Fig. 1, loc. 7a) is situated in Carboniferous rocks (Veitsch nappe) of the Greywacke zone. Its position is in the northern flank of an E-W striking anticline. The deposit is bordered to the north and south by secondary faults, which are part of the Liesing-Palten fault zone. Talc occurs only in dolomitic protoliths in the intensely tectonized block inbetween these two faults, and it is obvious that fractures in the fault zone acted as channelways for the ingress of hydrothermal solutions (Box-Fig. 6-1). In compact undisturbed carbonates, talc formation has not taken place.*

Evidently talc formation is due to the ingress of Si-bearing chloride solutions fluids reacting with dolomite. Talc formation includes removal of Ca according to the reaction:

$$3CaMg(CO_3)_2 + 4SiO_2(aq.) + H_2O \rightarrow Mg_3Si_4O_{10}(OH)_2 + 3CaCO_3(aq.) + 3CO_2(aq.).$$



Box-Fig. 6-1
Talc-bearing faults hosted by dolomite in deep levels of the Lassing talc deposit.

As a result of this hydrothermal reaction, only newly formed talc and residual (but recrystallized) dolomite can be found in the talc-bearing area.

Tectonic movement during these events compensated for the drastic decrease in volume as a consequence of the total removal of calcite. Talc formation ceased with the termination of hydrothermal activity and Si-supply; dolomite was not completely consumed by the reaction. Continuous availability of H_2O and removal of CO_2 from the system along fractures are basic requirements for talc formation of this type (PROCHASKA 1989).

The **Rabenwald talc deposit** *(Fig. 1, loc. 7b; Box-Fig. 6-2) is located in the Grobgneis complex of the Lower Austroalpine nappe complex, which is exposed in a large tectonic window. The deposit is linked in strike and dip to a distinct shear zone. A strongly altered rock (leucophyllite) typically envelopes the talc schists. Although similar leucophyllite-bearing faults are widespread in this region, no further talc occurrences are known.*

Metamorphism of the host rocks is of Variscan age. Retrograde metamorphic overprinting during the Upper Cretaceous is ubiquitous. Leucophyllite and talc formation are contemporaneous with this eo-Alpine, Cretaceous-age metamorphism.

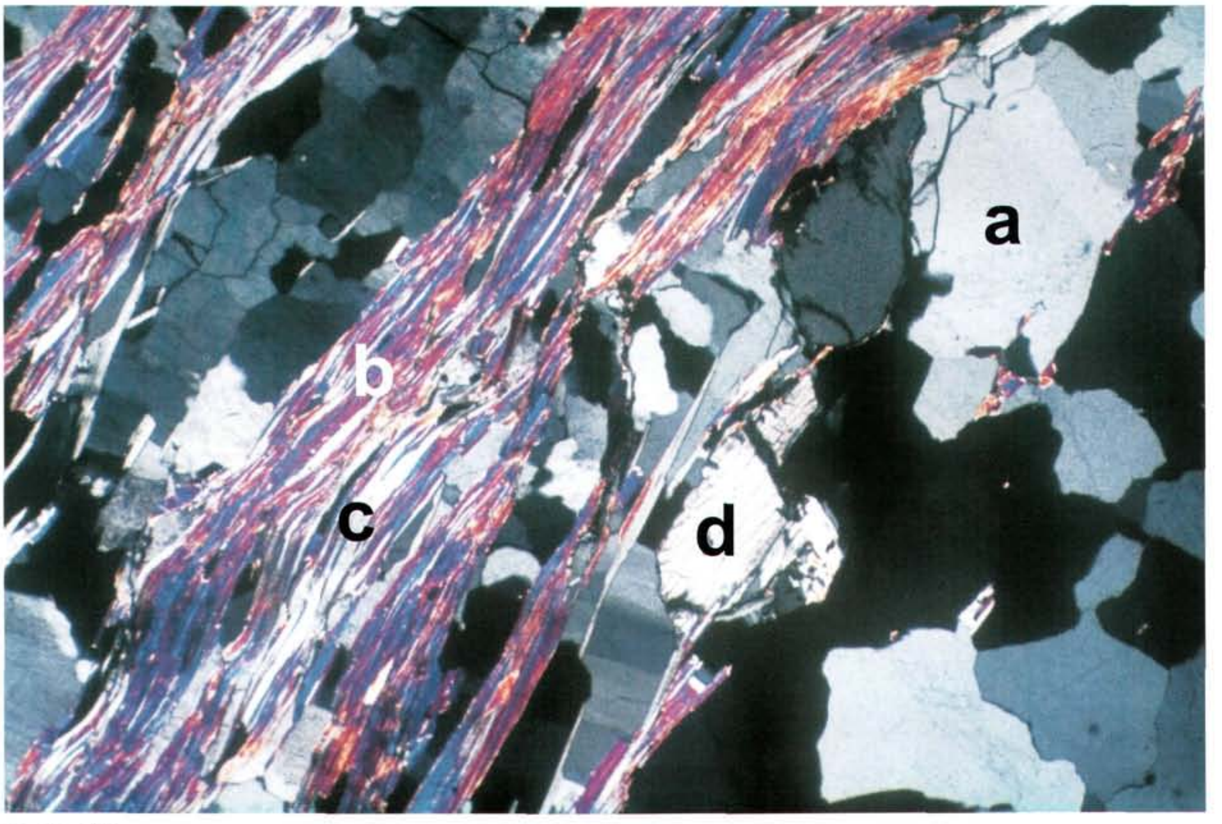
Former genetic models for the talc formation were based on deep-seated Penninic ultrabasic rocks as a Mg-source or the metamorphism of evaporites. However, new data do not support these models.

During the Cretaceous nappe stacking, magnesites from the Upper Austroalpine basement are thrust into the underlying Lower Austroalpine gneisses on account of the thinning of the Middle Austroalpine system in the Rabenwald area (magnesite bodies are known in the Upper Austroalpine units – Greywacke zone and Paleozoic of Graz). Hydrothermal fluids produced during the Alpine tectonometamorphic event mobilized Si from the adjacent host rocks during leucophyllite formation and the magnesite reacted in the shear zone with the Si component of the fluid. Mg was only locally transported into and along the fault, and not necessarily supplied from deep-seated ultramafic sources (PROCHASKA 1984).

A hydrothermal quartz-mica product with similar industrial applications as talc or kaolin products called **"leucophyllite"** *has been mined in Austria since 1850. Generally it is produced in two mines (Aspang/Lower Austria; Weißkirchen/Styria) under different trade marks ("Leukophyllit", "Kaolin", "Weißerde", etc.). They are bound to shear zones in Austroalpine metamorphic terrains.*

The term "leucophyllite" is used for white, micaceous, hydrothermally altered phyllonitic rocks (in most cases gneisses). Leukophyllites mainly consist of quartz, muscovite, variable amounts of Mg-chlorite and subordinate kyanite, apatite, zircon, rutile and ilmenite (Box-Fig. 6-3). The term should not be confused with the Mg-Al-celadonite "leuco-phyllite". The term "Weißschiefer" has also been used in the past to describe phyllonitic rocks in shear zones in granitic gneisses from the Eastern Alps.

Box-Fig. 6-2
The open-pit talc mine at Rabenwald, Styria.



Box-Fig. 6-3
Thin section of leucophyllite showing quartz (a), muscovite (b), leuchtenbergite (c) and kyanite (d) from the Weißkirchen deposit, Styria.

The "whiteschists" of high-grade metamorphic origin (talc-kyanite assemblage) are genetically quite different from the leucophyllites, which are usually formed under greenschist or amphibolite facies metamorphic grade and under allochemical conditions.

The origin of leucophyllite in the Eastern Alps is related to early Alpine (Cretaceous) compressional stages, accompanying metamorphism and subsequent exhumation. They had been formed by chemical alteration and hydrothermal activity linked to deep-seated shear zones, which are frequently found in the eastern parts of the Eastern Alps (PROCHASKA et al., 1992).

Temperatures of the leucophyllite formation were between 400 and 500 °C according to stable isotope equilibria between quartz, muscovite, chlorite and rutile. Heavy δD values (~ -20‰) indicate the influence of seawater (or formation water similar to seawater) expelled from deeper tectonic units after nappe stacking. The $^{87}Sr/^{86}Sr$-ratio of the leucophyllites is dominated by the gneiss host rocks and generally in the range of ca. 0.720. K-Ar cooling ages of the micas of the phyllonites are identical with the regional cooling ages and Ar/Ar ages (~ 90 Ma) and indicate complete recrystallization and rejuvenation of the mineral assemblage in these shear zones.

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After a short break in sedimentation and emersion the Alpine-Carpathian Cretaceous nappe pile was sealed by Late Cretaceous-Paleocene sediments. Hot and humid climate conditions produced several deposits of karst bauxites (the most important are north of Balaton Lake). Early Tertiary sediments are flysch-like and comprise some manganese deposits in the inner Carpathians (Kišovce, Švábovce; Fig. 1, loc. 42).

The Late Cretaceous/Early Tertiary collisional stage was succeeded by uplift of metamorphic core complexes and the indentation of the Apulian plate into the Eastern Alps. The result was an east-directed tectonic escape to the Slovakian and Pannonian Basin. Circulation of fluids characterized by an appreciable content of CO_2 and low to moderate salinities was concentrated to the area of fault zones within the extended and thinned crust. The character of the fluids is best explained by the circulation of surficial water in the brittle crust along fault systems and mixing with metamorphic water derived from the cooling metamorphic complexes (POHL, 1993; POHL and BELOCKY, 1994, 1999).

Best known there are the gold-veins of the Tauern window (Fig. 1, loc. 17). They were generated during the uplift and a late cooling stage of the Tauern metamorphic core complex. During this process decompression opened NE-SW to NNE-SSW trending veins in which the mineralizations were formed by the circulation of residual metamorphic fluids, which were mixed with supergene derived waters (PAAR, 1997).

Box 7

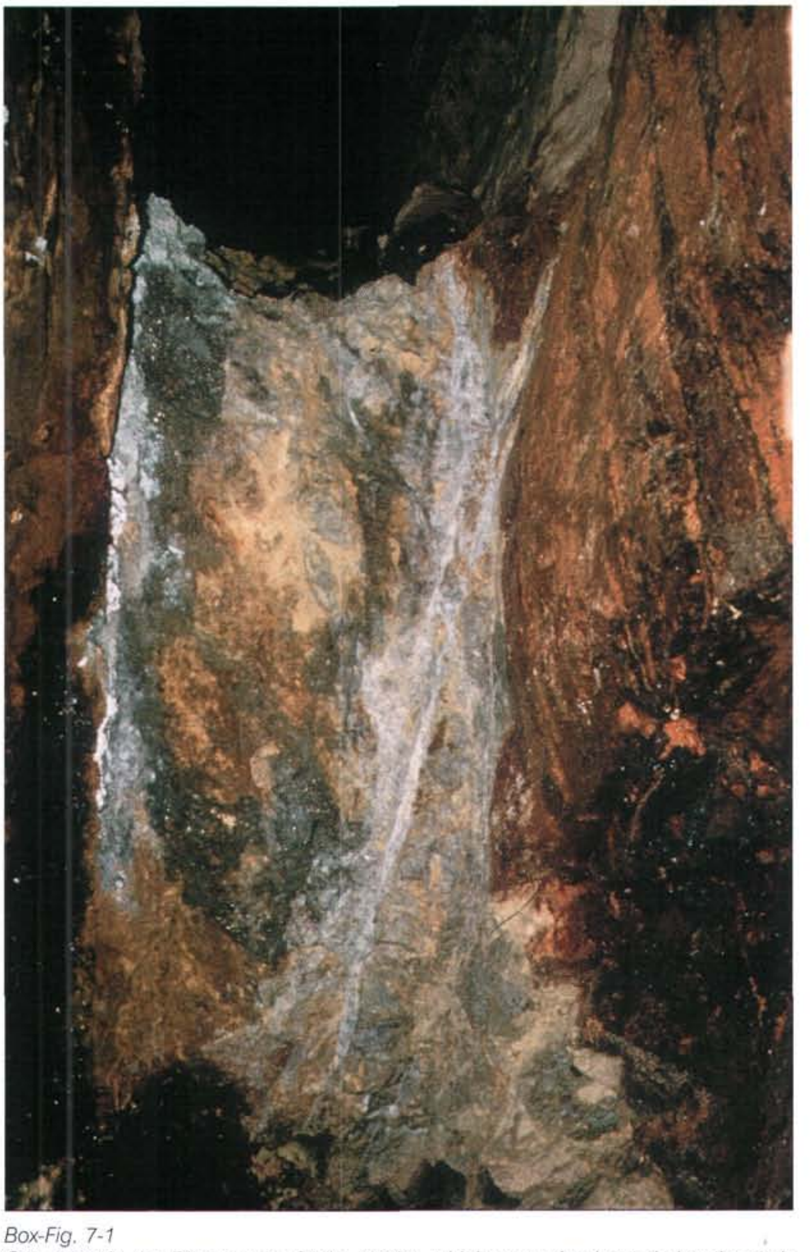
***Tauern gold veins** (Fig. 1, loc. 8)*

W. PAAR

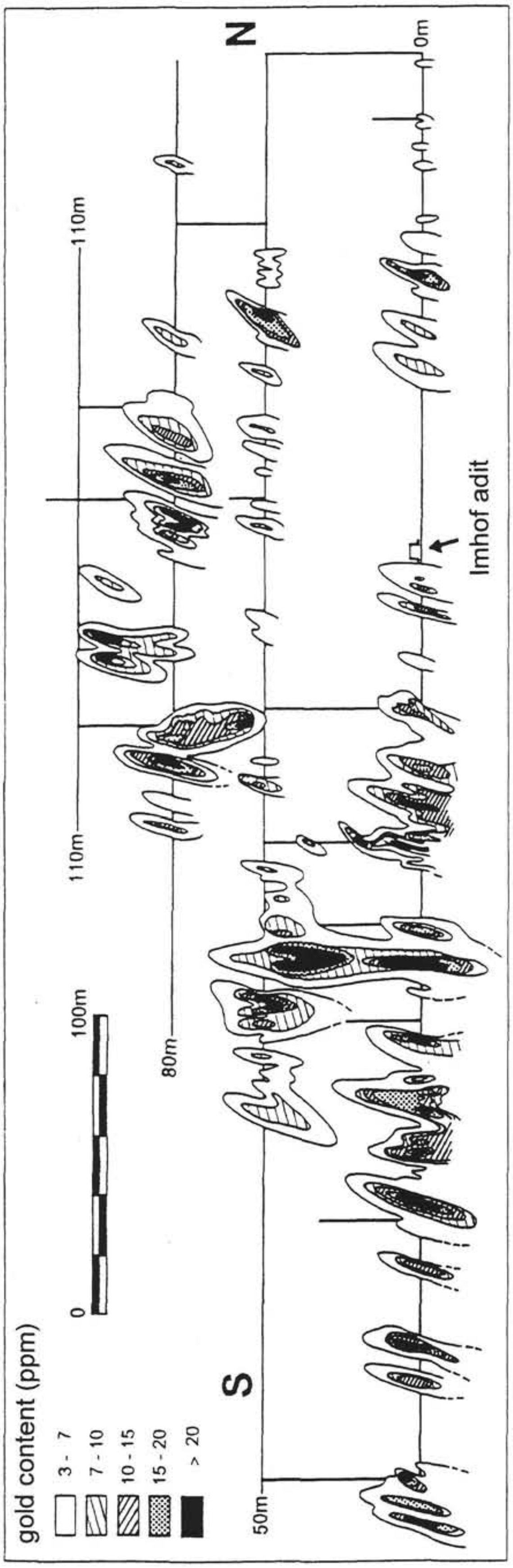
Epigenetic gold (and silver) mineralization, commonly known as "Tauerngoldgänge" (Tauern gold veins), is concentrated in only a few districts within the Tauern window (Fig. 1, loc. 17). The most obvious accumulations occur in the Rauris and Gastein valleys (Fig. 1, loc. 8a), where mineralized veins crosscut Variscan granitoids and penetrate into overlying Permomesozoic carbonate-bearing metasediments. Genetically related mineralization had been mined west of the Fuscher valley and the upper Mur valley (Rotgülden district; Fig. 1, loc. 8b), where metasediments are hosts of structurally controlled gold mineralizations. Bonanza-grade gold occurred as an exception in Mesozoic serpentinites and Late Precambrian magmatites of the Habach terrane.

The first documented records of mining for primary ore are from the 14th century. The most important period of exploitation was between the 14th and the beginning of the 17th centuries. Mining continued intermittently in different areas until 1944, when the last operations were shut down. During the last 50 years domestic companies and joint ventures with foreign companies started reconnaissance and – on a small scale – exploration for gold in the Tauern region. A preliminary evaluation points towards a possible economic potential in the Gastein valley, where a high density of mineralized veins with an average gold grade of 6-8 ppm can be assumed with certainty. The total production of gold from both alluvial and primary deposits in the Tauern window is estimated to be in the order of 60 t (1.8 million oz.).

In the most prominent mining districts in the Gastein and Rauris valleys the mineralized structures can be traced up to 7 km along strike and extend more than 1000 m along dip (FEITZINGER & PAAR, 1991). Pinch and swell structures are common. The economically mineable ore is only concentrated in the swells, which have quite irregular geometries and dimensions, and always a steeply plunging axis (Box-Fig. 7-1, 7-2).



Box-Fig. 7-1
Ore shoot in the Dionys vein, Siglitz district, which was mined out during the early 20th century. Remaining bonanza-grade ore (1 m thickness) above ground level is composed of free gold, arsenopyrite and pyrite in a matrix of quartz and altered host rock fragments.



Box-Fig. 7-2
Zonal distribution of gold (ppm) in ore shoots along a mineralized vein structure (Kupelwieser vein, Siglitz district). The indicated gold grades apply to the mining width of 1 m.

Hypogene alteration (phyllic, rarely propylitic; silicification, pyritization) is rather insignificant and can only be recognized for little more than 1 m into the wall rocks. K/Ar dating using sericite from the alteration halo at Siglitz revealed a crystallization age of 27 Ma.

Open-space filling of ore and gangues are supported by symmetrically and asymmetrically banded structures, crustification, comb and cockade structures and vugs, which are especially abundant in superficial levels of the veins.

The mineralization of the Rotgülden district (Fig. 1, loc. 8b) can be considered as a sub-type of the classical Tauern gold veins and shows different styles of tectonic control of the ore (HORNER et al., 1997). The highest gold and silver grades (up to 4 and 30 oz., respectively) occur in saddle-reef structures, whereas ore in tension gashes and extensional veins is less enriched. Metasomatic replacement bodies composed of gold-bearing arsenopyrite, pyrrhotite and pyrite are typical for this subtype.

The complex mineralogy of the Tauern gold veins is the result of polyphase events. Gold predominantly is associated with abundant arsenopyrite, pyrite, base metal sulfides and quartz plus minor carbonates as gangues. Native gold shows a wide range in chemical composition with electrum prevailing in the high-silver assemblages. It varies in grain size from less than a few µm up to more than 1 cm, averaging at 10-20 µm. High-grade gold mineralisation ("Glaserz") usually is associated with various Ag-Pb-Bi(Sb) sulfosalts and tellurides of Ag and Bi (PAAR, 1994).

A vertical mineral zonation is obvious: A silver-enriched base metal assemblage dominates in the upper levels of a vein system, whereas an increase of gold in association with arsenopyrite, pyrite and quartz can be observed below that. Secondary enrichment processes are limited to a few meters from the surface and characterized by coarse-grained silver-poor gold.

The temperatures of formation of the various mineral assemblages have been estimated using both fluid inclusion data and arsenopyrite geothermometry. A temperature range of 370-420 °C was determined for the gold-rich, and 200-260 °C for the silver-dominated, paragenesis. The ore minerals were precipitated from fluids with high contents of CO_2 and salinities ranging between 2-11 wt.% NaCl equiv.

The Tauern gold veins can be classified as metamorphogenic deposits, which were formed along deeply reaching structures and from fluids generated from hydrothermal convection cells during retrograde leaching of suitable host rocks (PAAR, 1997).

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In areas east of the Tauern window (Fig. 1, loc.17) hydrothermal fluid circulation along Tertiary fault zones was responsible for the formation of some Au-arsenopyrite vein mineralizations, the overprint of older polymetallic (Fe-Pb-Zn-Ag-Ba) ore districts and the formation of siderite and specularite mineralizations.

Box 8

Tertiary vein type mineralization as a consequence of escape tectonics *(Fig. 1, loc. 9)*

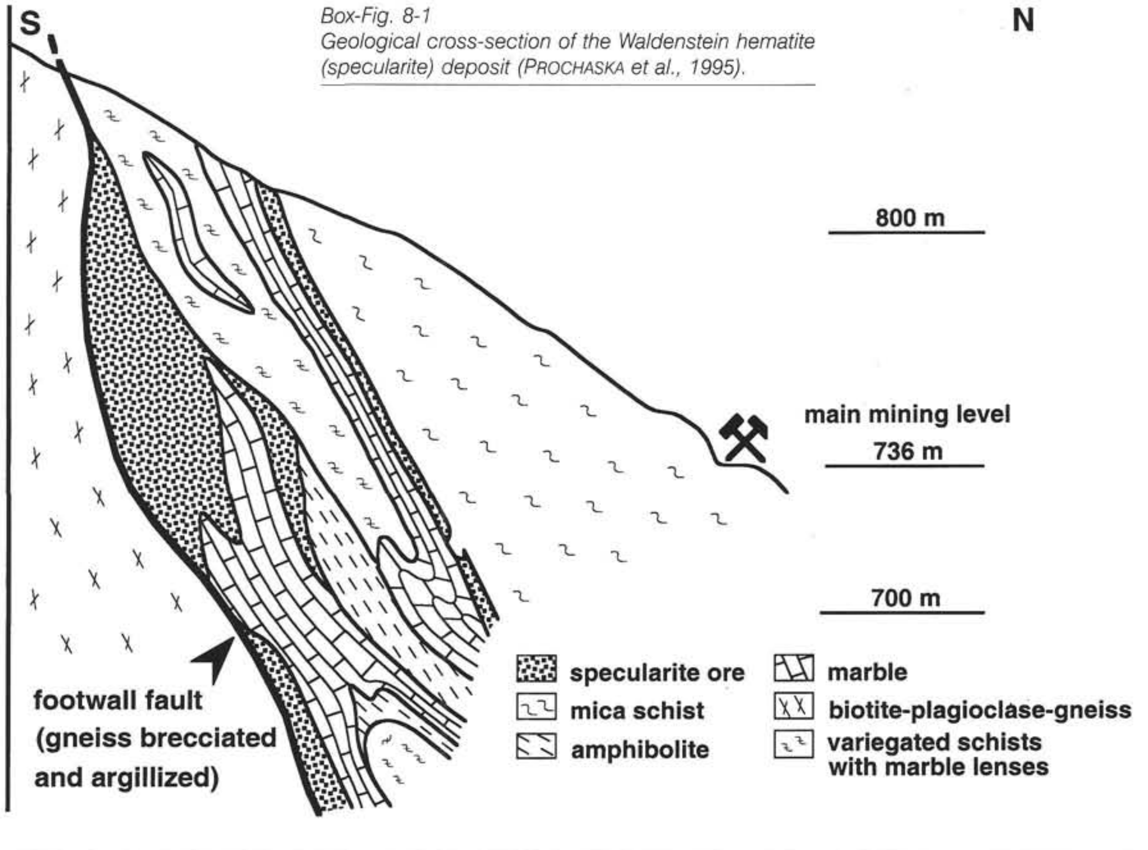
W. PROCHASKA

Innumerable vein mineralizations are hosted in the polymetamorphic complexes east of the Tauern window (Fig. 1, loc. 17). They were formed from deep-seated fluid sources (metamorphogenic?), possibly being expelled from overthrusted tectonic units, which mixed with supergene, meteoric or marine fluids that had been incorporated into shallow hydrothermal systems along faults operating during the Tertiary escape tectonics. Beside some small scale Au-As mineralizations, the deposits and occurrences of the Hüttenberg-Waldenstein iron ore district (eastern Carinthia; Fig. 1, loc.9) are the most important mineralizations of this type (CLAR & MEIXNER, 1981).

This district comprises a number of siderite mineralizations hosted by prominent marble series. The largest is the Hüttenberg deposit (Fig. 1, loc. 9b), which was worked from Roman times until 1979. A few mineralizations are associated with hematite. Currently the Waldenstein deposit (Fig. 1, loc. 9a; Box-Fig. 8-1) is producing specularite for industrial purposes.

The geological setting of all these deposits is similar. Predominant rocks are muscovite-garnet schists, biotite

Box-Fig. 8-1
Geological cross-section of the Waldenstein hematite (specularite) deposit (PROCHASKA et al., 1995).

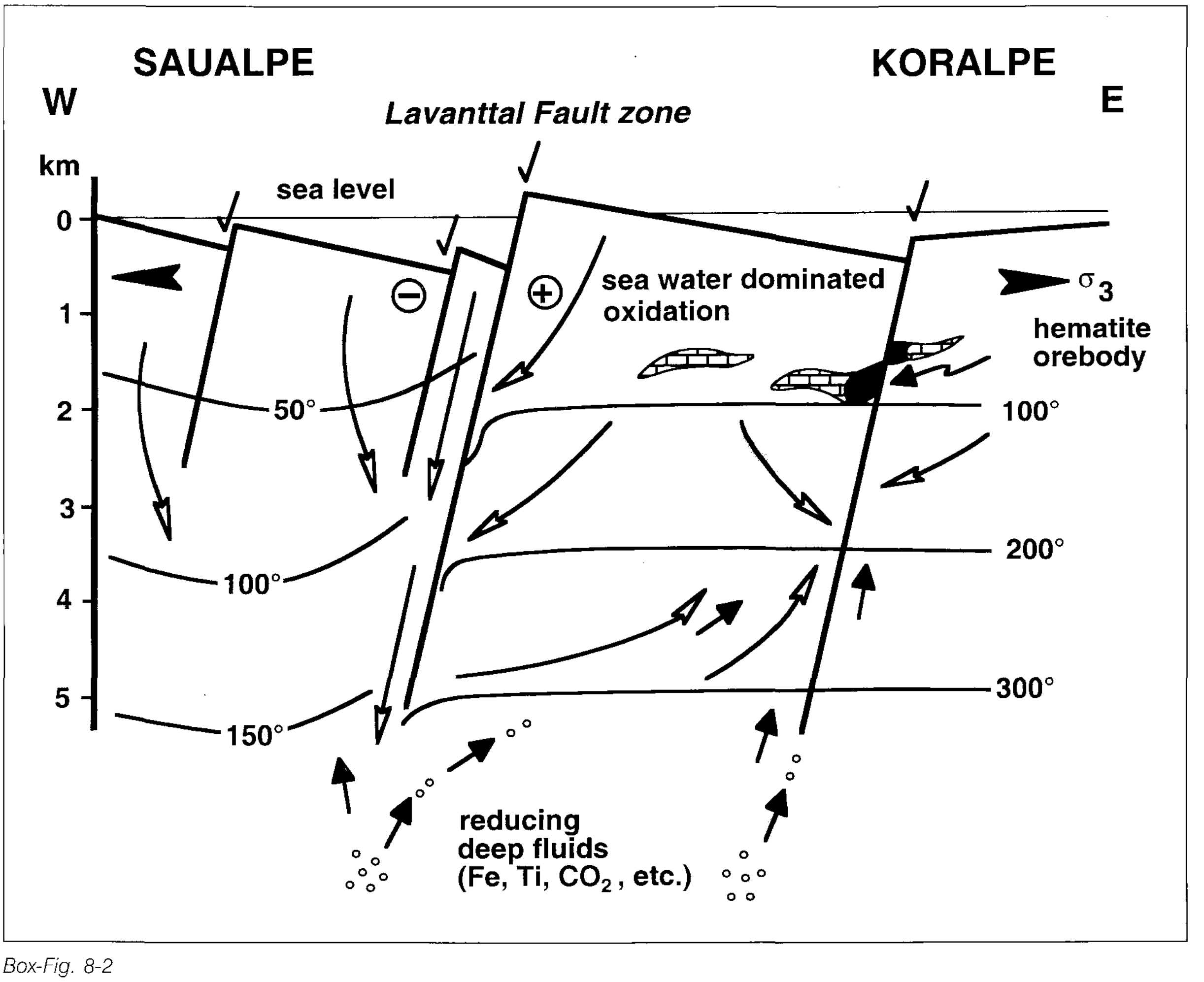


gneisses, calc-silicate schists and quartzites with interbedded bands and lenses of amphibolite and possibly Devonian calcite marble. Several phases of ductile deformation and metamorphism are distinguished. The youngest (Cretaceous) metamorphic event is best developed in the deeper parts of the complex.

In the Tertiary, during the final compressive stage of the Alpine orogeny, a system of faults developed in the Eastern Alps east of the Tauern window. They caused thinning of the crust towards the Pannonian Basin. The Waldenstein-Hüttenberg iron ore district is spatially and genetically associated with these trans-tensional fault systems (Box-Fig. 8-2). The NNW-SSE trending Lavanttal fault zone occurs some 5 km W of Waldenstein. This zone, which is marked by several Miocene basins, shows a downthrow to the west and a right-lateral component of movement. To the west the Hüttenberg siderite deposit is associated with a comparable fault system, which was initiated in the Early Tertiary. Minor activity along these faults is still taking place today, as shown by earthquakes and hot springs.

In spite of the different genetic models, it is generally accepted that the mineralizations formed during one metallogenetic event. It has been convincingly demonstrated that the mineralizations are surrounded by a wide hydrothermal alteration halo and mineralizations postdate metamorphism and orogenic deformation of the country rocks. These field observations, together with microthermometry-, fluid chemistry data, and isotope ages indicate that the mineralizations must be the result of epigenetic, hydrothermal metasomatism of the hosting calcitic marbles.

During the Cretaceous, the crystalline country rocks had been subjected to a regional amphibolite to eclogite grade metamorphism at deep crustal levels (metamorphic δD-signature in the unaltered host rocks of the deposits). During the Tertiary, transtensional faulting and exhumation of the metamorphic dome resulted in positive temperature anomalies at higher crustal levels. This rapid uplift induced large hydrothermal convection cells where the faults acted as channelways for the percolating fluids. Fluids of deep seated origin started rising through cooler rocks at the beginning of faulting (Middle Eocene), precipitating early ilmenite, magnetite and siderite under more reducing conditions, and hematite and chlorite during the main stage of ore formation.



Box-Fig. 8-2
Model of hydrothermal fluid circulation along Tertiary transtensional structures forming the Waldenstein hematite deposit (PROCHASKA et al., 1995).

The fluid chemistry in the Hüttenberg-Waldenstein iron ore district is more heterogenous and suggests the influence of seawater (decrease of $\delta^{18}O$ values and the relatively heavy D values) and/or meteoric or river water (decrease of Br with respect to Na and Cl compared to seawater). The hydrothermal regime was evidently dominated by surface fluids in a shallow crustal environment, depending on the local morphologic situation.

Probably the depth of the hematite formation at Waldenstein deposit was very shallow (~ 700 m) and the temperature 300 °C. It seems to have been formed by mixing and oxidation of deep fluids (metamorphogenic fluids from deeper Penninic units or magmatic fluids related to Early Tertiary Periadriatic intrusions) by seawater at very shallow crustal levels.

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During the Early Tertiary escape tectonics the Periadriatic lineament zone – the border zone between Eastern and Southern Alps – was one of the major operating strike-slip zones. It was active after the Oligocene intrusion of dioritic-granodioritic bodies. Recently this magmatic activity has been regarded as the result of the slab breakoff of southward-subducted Penninic units. Some Fe-Cu skarn mineralizations at magmatic contacts are of subordinate importance. Nevertheless, heat flow related to the intrusions will be discussed as a motor for a variety of subeconomic epigenetic As, Sb, Au mineralizations situated in polymetamorphic complexes south of the Tauern window (Fig. 1, loc. 17) (RANTITSCH et al., 1999).

During the final continent collision, the Alpine-Carpathian system was thrusted above its own foredeep sediments and the European margin. Due to the indentation of the Apulian plate in the Eastern Alps, this movement was directed to the north. However, segments of the eastern part of the Eastern Alps and some Carpathian-Pannonian crustal segments were also moved even farther to the east. During the final collision, they formed the Carpathian arc.

The eastward advance of the Inner Carpathians was further driven by subduction rollback with final verticalization and breakoff of the subducted slab. Uprising asthenospheric material initiated melting of upper mantle and lower crust in extensional back arc domains and further subduction of the flysch basin gave rise to silicic and andesitic volcanism. Continuation of rollback was responsible for further extension and Plio-Pleistocene mafic basaltic-basanitic volcanism. This Inner-Carpathian calcalkalic-alkaline magmatic province produced some remarkable ore mineralizations in Slovakia and Hungary.

In Slovakia, the Tertiary volcanism produced a great variety of noble and base metal mineralizations (CHOVAN et al., 1994; LEXA et al., 1999). These have been grouped into three major genetic types (STOHL et al., 1993): (1) epithermal veins, (2) stockwork and disseminated mineralizations closely related to stockwork-type intrusions and (3) porphyry-type or contact metasomatic mineralizations related to granodiorite and diorite porphyries intruding Triassic carbonatic rocks. The main ore potential is concentrated in vein type mineralizations: Banská Štiavnica (Fig. 1, loc. 35) and Zlatá Bana (Fig. 1, loc. 53) Pb-Zn-Cu ±(Au, Ag); Kremnica (Fig. 1, loc. 36) Au-Ag ±(Pb, Zn, Sb, Hg). Significantly, there are also volcanic-hosted Sb mineralizations located towards the foreland at a distal position relative to the subduction zone (DILL, 1998).

Similar noble and base metal mineralizations are also known from the Hungarian Central mountains. Beside these mineralizations, silica, alunite, bentonite, pumice tuff deposits and hydrothermal alteration products (zeolite, kaolinite, mixed-layer clays) were formed in Slovakia and Hungary. Bentonite, derived from volcanic ashes transported over a great distance is also known from the Styrian and Slovenian basin.

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Artikel/Article: Mineral Resources in the Eastern Alps and Adjoining Areas. 157-184