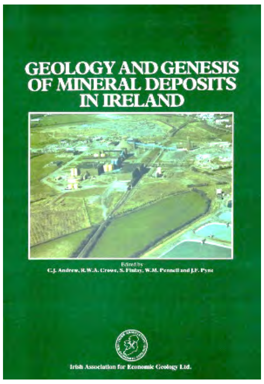

# On the formation of Alpine Middle and Upper Triassic Pb-Zn deposits, with some remarks on Irish carbonate-hosted base-metal deposits.

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**To cite this article:** Klau, W. & Mostler, H. (1986) On the formation of Alpine Middle and Upper Triassic Pb-Zn deposits, with some remarks on Irish carbonate-hosted base-metal deposits. *In:* Andrew, C.J., Crowe, R.W.A., Finlay, S., Pennell, W.M., and Pyne, J.F. '*Geology and Genesis of Mineral Deposits in Ireland*', Irish Association for Economic Geology, Dublin. 663-675. DOI:

**To link to this article:** https://

# On the formation of Alpine Middle and Upper Triassic Pb-Zn deposits, with some remarks on Irish carbonate-hosted base metal deposits.

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## Abstract

The stratabound, carbonate-hosted, Pb-Zn deposits in the Eastern Alps are related to an unstable shelf on the margin of the evolving Tethys ocean. As a result of tectonic activity along the opening Tethys, a geosyncline was formed which was filled with a thick sequence of Variscan molasse. These sediments were overlain by platform carbonates. Intra-Triassic tectonic activity uplifted the carbonate platforms above sea-level; this uplift subsequently resulted in the formation of karst systems. As part of the same tectonic activity, basins were formed on down-faulted blocks marginal to the platform carbonates. The main phase of mineralization occurred within karst features and synsedimentary fault systems. The metals were leached from pre-Permian basement rocks and possibly from Permian volcanics. Lead isotopes are extremely homogeneous (B-type) over the whole Alpine region. In comparison, major Irish base metal deposits are structurally controlled, occur within a range of host rocks, and are classified as submarine exhalative, sediment-hosted deposits. Lead isotopes (J-type) in Ireland become more radiogenic southwards.

## Introduction

There are more than 200 Pb-Zn occurrences known and, at present, four exploited deposits (Bleiberg, Mežiča, Raibl and Salafossa) of the so-called "Alpine Middle and Upper Triassic Pb-Zn Deposits" in the Dolomites of the Southern Alps and in the Northern Limestone Alps.

Structurally, the little-deformed Southern Alps are separated from the Northern Limestone Alps by the metamorphosed crystalline rocks of the Alpine axis (Tauern Window) which crosses Austria in an easterly direction. Stratigraphically the South Alpine Triassic succession is identical to rocks of this age in the complexly overthrusted Northern Limestone Alps (Fig. 1). The precise root zone of the Northern Limestone Alps is still one of the mysteries of Alpine geology; it could be either north or south of the crystalline basement.

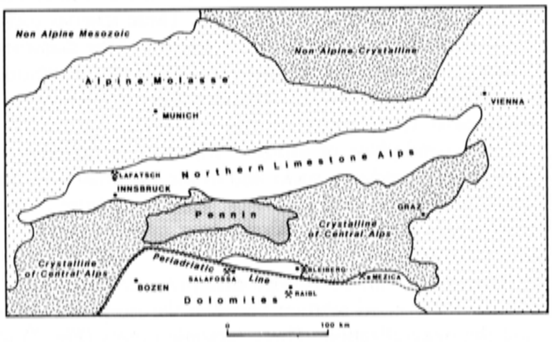

**Figure 1.** Geological sketch map of the Eastern Alps.

The Alpine geosyncline developed from an initial rifting stage of an early Red Sea type, along which the Tethys ocean opened (Fig. 2). As a result of this a taphrogenic sedimentary basin was formed, which was filled with 4000m to 5000m of continentally-derived detritus (including the Variscan molasse). This sequence was overlain by platform carbonates. Thick carbonate build-ups (up to 1000m and more) and the basic volcanic rocks in sediments around them indicate geosynclinal subsidence on the outer continental margin.

Two platforms, one to the north and another to the south of the developing Tethys ocean, exhibit similar tectonic and sedimentological features. Lithological variations between the North and South Alpine Triassic are caused by differences in magmatic activity.

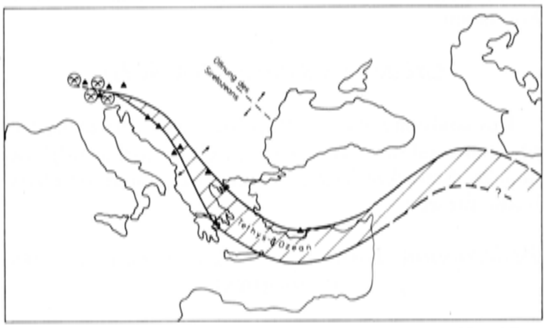

**Figure 2.** Pb-Zn deposits on the northern and southern margins of the opening Tethys ocean (after Mostler, 1981).

Figure 3 illustrates the situation immediately before the Triassic tectonic activity in the late Variscan to early Alpine times.

### *Bozen Quartz Porphyry (rhyolite, dacite)*

This quartz porphyry (c. 2000m) exhibits a broad range of Pb-Zn-(Cu-U)-Ba-F mineralization. The mineralization is dominantly contained within ignimbrites (stockwork type of mineralization).

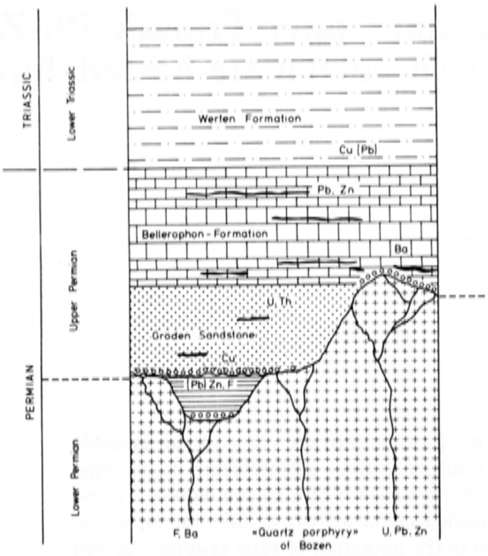

**Figure 3.** Stratigraphic section through the Upper Permian and Lower Triassic sedimentary sequence, illustrating the relation of the mineralization in the Bozen Quartz Porphyry to the occurrences in the sediments (after Mostler, 1981).

### *Tregiovo Formation (lacustrine sediments, particularly interbedded black shales and black limestones)*

The Pb-Zn mineralization in this Formation (200m) is strictly conformable within the laminated limestones, and is also preserved in diagenetic concretions. Hydrothermal activity related to the mineralization is indicated by the high $SiO_2$ content, associated with very fine-grained sphalerite concentrated along joints and faults of Alpine age (Klau and Mostler, 1983). Pebbles of the underlying mineralized quartz porphyry have been reworked into the Tregiovo Formation.

### *Gröden Sandstone (Red Beds)*

This sandstone unit (c. 200m) contains matrix-filling sulphide mineralization (Pb, Zn, Cu, U), as well as sulphide nodules. Reworked detritus of mineralized quartz porphyry is also present.

### *Bellerophon Formation (algal limestone and evaporites)*

This Formation (50-150m) characteristically hosts stratiform and facies-controlled mineralization with very well-developed replacement structures and abundant gel textures. There is little gangue material. The trace element composition in the galena is similar to that in the galena mineralization in the quartz porphyry.

### *Werfen Formation (interbedded sandstones, siltstones and detrital limestones)*

Pb-Zn mineralization in the Werfen Formation (150-300m) is rare and is only found in the dolomites of the Save area (Yugoslavia) where it can be traced for a distance of 30km.

In the overlying Anisian-Carnian (see Fig. 4), there is a marked facies boundary between carbonate platform and basinal sediments; this sudden change marks the beginning of the taphro-geosynclinal phase.

As a result of synsedimentary vertical tectonics, contrasting sediments were deposited on the carbonate platform and in the basin, the sediment type reflecting the prevailing water depth.

Pb-Zn mineralization is closely related to a particular facies (Hauptdolomit "magnafacies") that characterizes the sedimentation in the North Alpine region (Fig. 5). All the Pb-Zn mineralization occurs within sediments deposited in a peritidal, lagoonal environment.

## The regional setting of the economically interesting mineral deposits

The economically important, carbonate-hosted, ore deposits are located close to the Peri-Adriatic Line, a prominent fault zone between the Northern and Southern Alps. It is steeply dipping with both significant right-lateral and vertical displacement. Mezića, Bleiberg-Kreuth and Lafatsch (presently inactive) lie to the north of the Line; Raibl, Salafossa and Gorno lie to the south. The Pb-Zn mineralization is partly stratiform and is partly in stratabound veins and mineralized faults within the Upper Ladinian to Lower Carnian strata which have been termed "strata- and time-bound" by Maucher and Schneider (1967).

The present and the reconstructed original situation of these ore deposits are shown in Figure 6. During the Eocene, the block to the south of the Peri-Adriatic Line was moved about 100km to the west relative to the block north of the Line. Salafossa would have originally been situated south of Bleiberg, Raibl south of Mezića, and Gorno south of Lafatsch.

## Volcanic and tectonic activity

The Alpine magmatism occurred in two phases of rifting during the early stages of geosynclinal development. The first indications are found in the Upper Permian of the North Alpine area (Hallstatt district) and continued into the Lower Triassic. The first phase produced pillow lavas, whose geochemistry accords with ocean-floor tholeiites as well as alkali-basalts (Kirchner, 1980), and associated gabbroic rocks, particularly serpentinites, which are considered to be products of continental rifting. These igneous rocks are overlain by evaporites and, as a result of the diapirism of this unit, blocks of serpentinite are chaotically distributed through the evaporites. The evaporites grade laterally into continental, clastic rocks.

The second phase of rifting commenced in the Anisian with acidic pyroclastic rocks and in the Ladinian with the eruption of basalts and andesites. The main centre of this activity was in the South Alpine area where it continued into the Carnian.

According to the Pb-isotope data presented by Koeppel (1983), there is no relation between the magmatic rocks and the mineralization. Three tectonic events (Fig. 7) of the Middle and Upper Triassic can be traced from the Alps into Greece (Füchtbauer and Richter, 1981). The first tectonic event in the Anisian resulted in strong uplift of the hinterland and consequent erosion of the crystalline basement. This event also caused the breakup of the stable shelf and the development of small basins and rises (carbonate platforms).

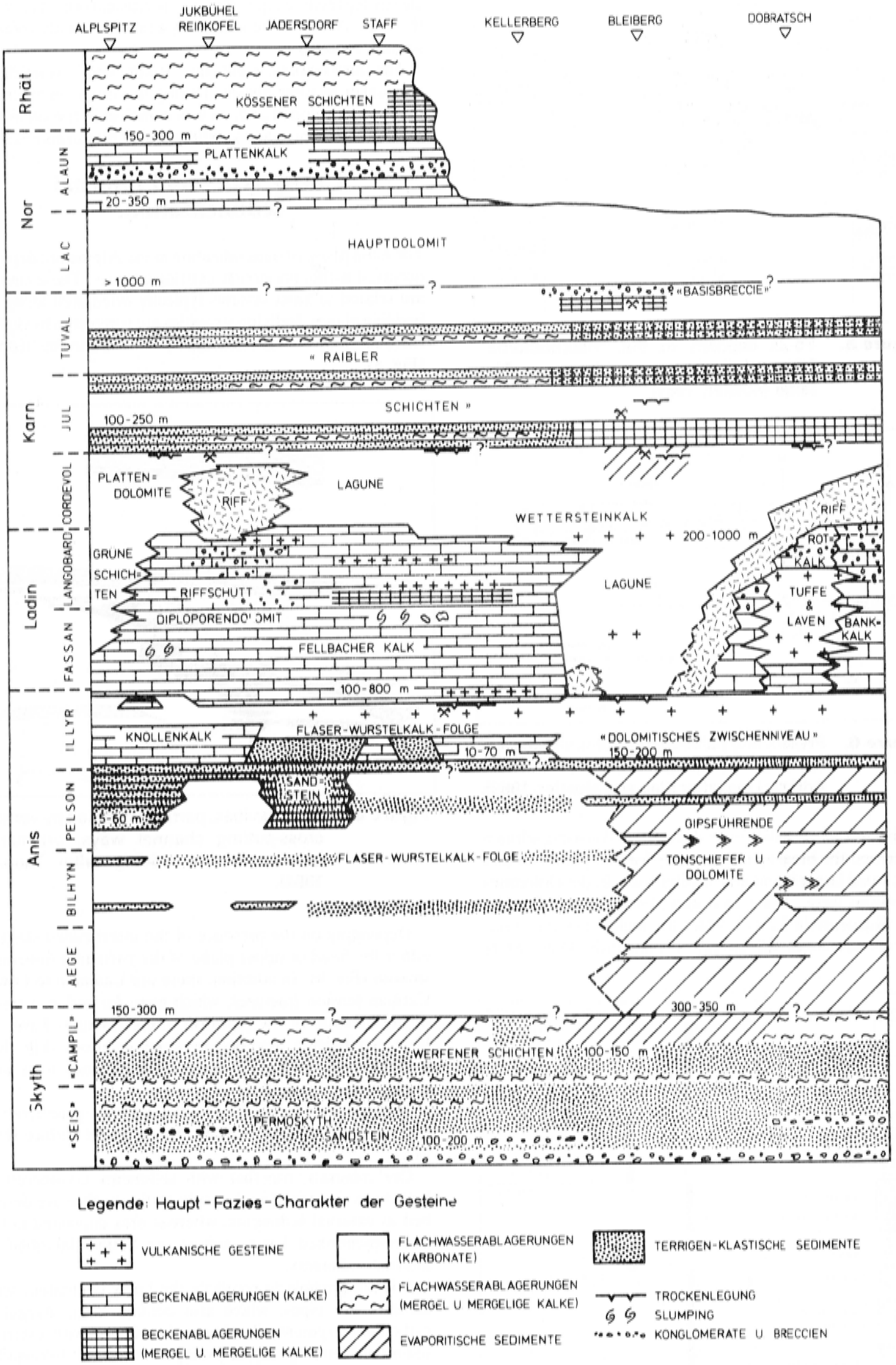

**Figure 4.** Stratigraphic section through the Triassic sequence, illustrating the strong facies variations (after Bechstädt et al., 1976).

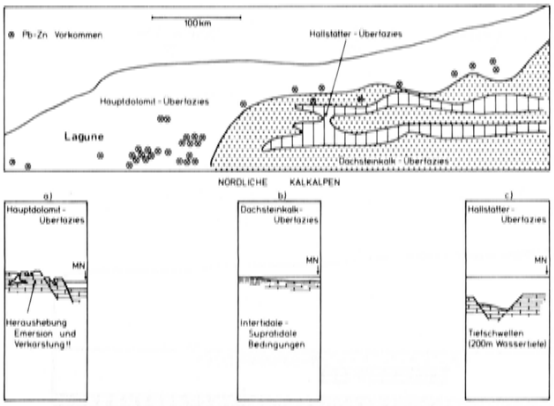

**Figure 5.** Pb-Zn deposits in the "Hauptdolomit" facies of the Northern Limestone Alps (after Mostler, 1981).

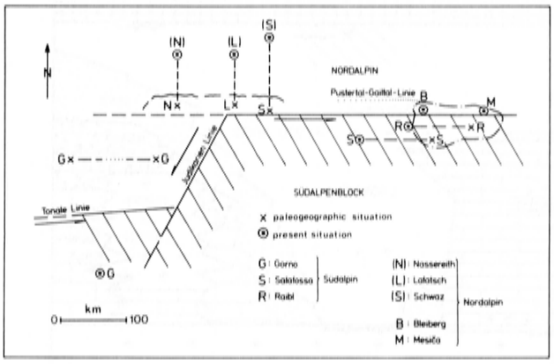

**Figure 6.** Present and palaeogeographic situation of the Pb-Zn deposits with respect to the Peri-Adriatic Line (after Klau and Mostler, 1983).

The second tectonic event during the Anisian/Ladinian continued the breakup of the newly formed platforms and developed larger basins and smaller rises. In the Dolomites the basins were filled with a dark, basinal facies, termed the "Buchenstein Strata", which are mainly nodular, bituminous limestones with altered volcanic tuffs. These strata clearly represent deep water, euxinic facies formed between the rises. Above these sediments a predominantly volcanic sequence occurs.

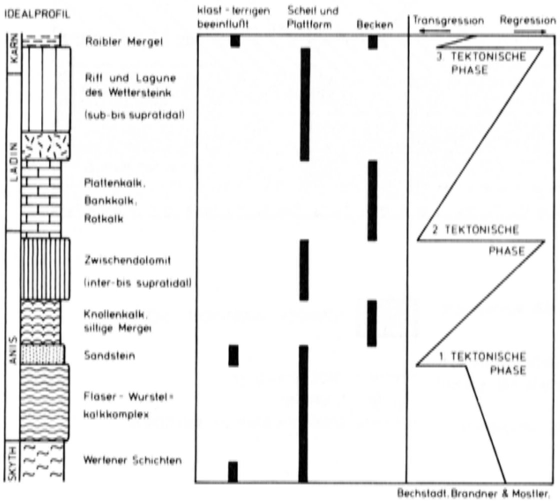

**Figure 7.** An idealized section illustrating tectonic cycles in the central Gailtal Alps (Bechstädt, Brandner and Mostler, 1976).

The third tectonic event, the "Raibl event", is similar to the earlier tectonic phases. During this event an extensive platform developed and, as was common in the other two events, emergences and karstification of platforms resulted.

# Cavity types and internal sedimentation.

The main phase of mineralization in the Alpine ore deposits occurred within previously existing cavities. These cavities are related to karst systems typically orientated along the bedding planes. Individual cavities are connected by slightly corroded joints, which lie subperpendicular to the bedding (Fig. 8).

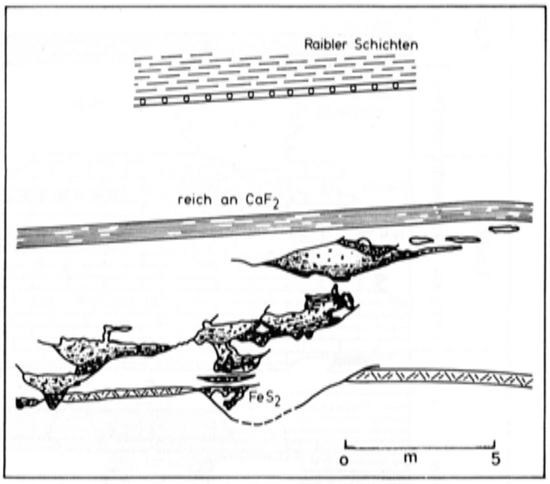

**Figure 8.** Karst cavities, partly connected by vertical cross-cutting channel ways, orientated parallel to the bedding (after Taupitz, 1954).

Depending on the presence of the interbedded clastics, either the basal or upper plane of the particular horizon is smooth (Fig. 9). In addition, there are Ladinian to Lower Carnian tension fractures, which were formed as a result of the breakup of the platform; these fractures have not been significantly modified by karst solutions (Fig. 10). Furthermore, the synsedimentary fault zones were also mineralized (e.g. Raibl).

The cavities produced by Ladinian karsts penetrated to depths of up to 800m beneath the emersion surface (Fig. 11).

Ore minerals, together with sediments considered to have been deposited in channels on the surface are described as external sediments, whereas ores deposited in the above-mentioned karst cavities are better described as internal sediments.

It is not possible to reconcile the finely laminated, sedimentary ore types, which also contain large, irregular, carbonate fragments floating within them, with external sedimentation (Fig. 12), and it is just as difficult to consider the carbonate clasts with marginal mineralization as being sea-bottom sediments. The sharp contact between a previously lithified carbonate rock and the ore sediments, which exhibit angular disconformities as a result of tectonic movement, is particularly persuasive for the karst hypoth-

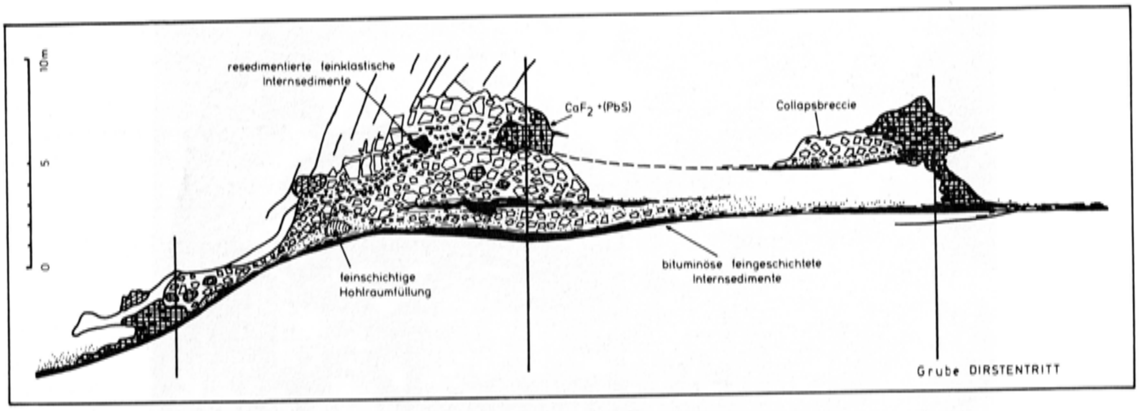

**Figure 9.** Karst cavity-filling sediments (after Taupitz, 1954).

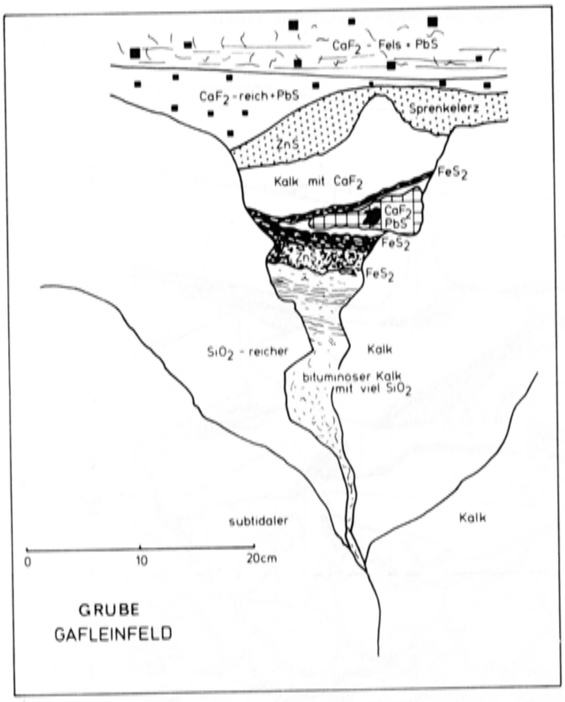

**Figure 10.** Typical intra-Ladinian to intra-Cordevolian tension fractures, which were formed during the formation of the Alpine geosyncline (after Taupitz, 1954).

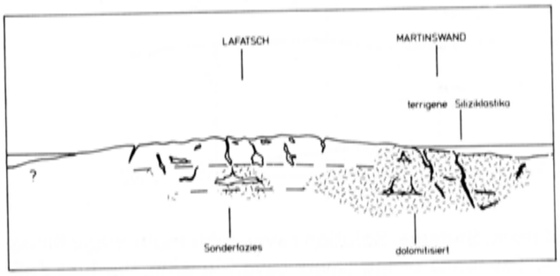

**Figure 11.** Schematic section through the carbonate platform of the upper Wetterstein Limestone at the time of the commencement of Raibl sedimentation (after Brandner, 1978).

esis. Moreover, there are also examples of cross-bedded, graded, detrital sphalerites which can also be interpreted as internal sediments as well as sphalerite stalactites. There is now a well-established opinion that the cavities were formed by the mineralizing solutions themselves. This type of cavity formation results in analogous internal sediments.

In contrast to cavities formed by the mineralizing solutions, palaeokarst cavities are filled by sediments formed after the emergence of the carbonate platform. In other words, after the formation of the karst cavity, the cavity-filling sediments were deposited and were followed by the mineralization, and, finally, by the overlying external sediments that penetrated into and filled the cavities (Fig. 13). The mineralization, therefore, must have been intra-Triassic (over a period of approximately 2-3Ma).

## Geochemistry

Geochemical investigations of the host-rocks in the immediate vicinity of the ore deposits revealed only very weak Pb, Zn and F anomalies. These values are somewhat higher in the areas of early dolomitization, and especially at the the contact between the limestones and dolomites.

### (a) Middle to Upper Triassic volcanics

The Pb, Zn and Ba contents of these rocks are only slightly greater than the background of similar rocks from other formations, and it is improbable that the metals were derived from these rocks. The Pb-isotope ratios also do not support an origin of the metals from these volcanics.

### (b) Ore and gangue minerals (galena, sphalerite, fluorite, barite)

Minor amounts of Ag, Sb, Bi, Cu and Sn have been detected in the galena. On the basis of trace element studies Schroll (1979) demonstrated that it is possible to ascertain the conditions of formation of the sphalerite. ZnS with high indium contents are indicative of a high temperature sphalerite such as that which is found in the veins of Freiberg (Saxony); ZnS in acid volcanic rocks (e.g. quartz porphyry) is characterized by high Hg and Ga. Thus high temperature and volcanogenic sphalerites are readily distinguished from sedimentary sphalerites which are characterized by the presence of Ge, Th and As.

In this context, the rare earth element distribution in the fluorite can possibly be used to distinguish sedimentary from hydrothermal fluorite (Schneider, 1977).

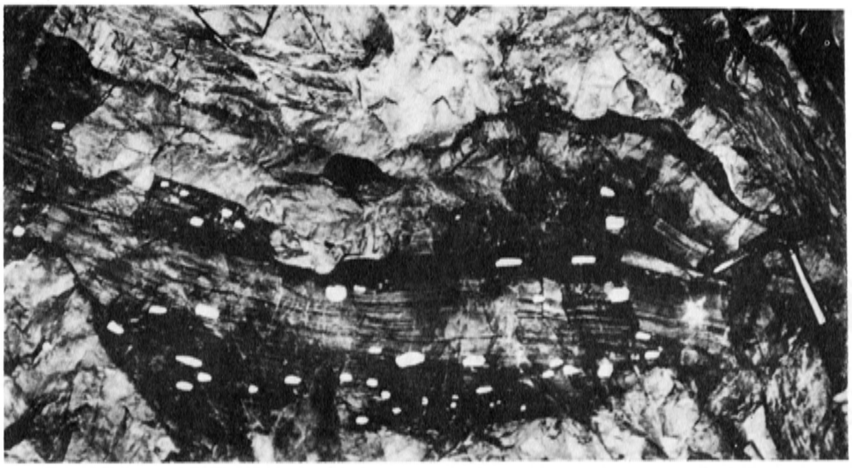

**Figure 12.** Finely laminated ore-sediment with irregularly interbedded, large carbonate clasts.

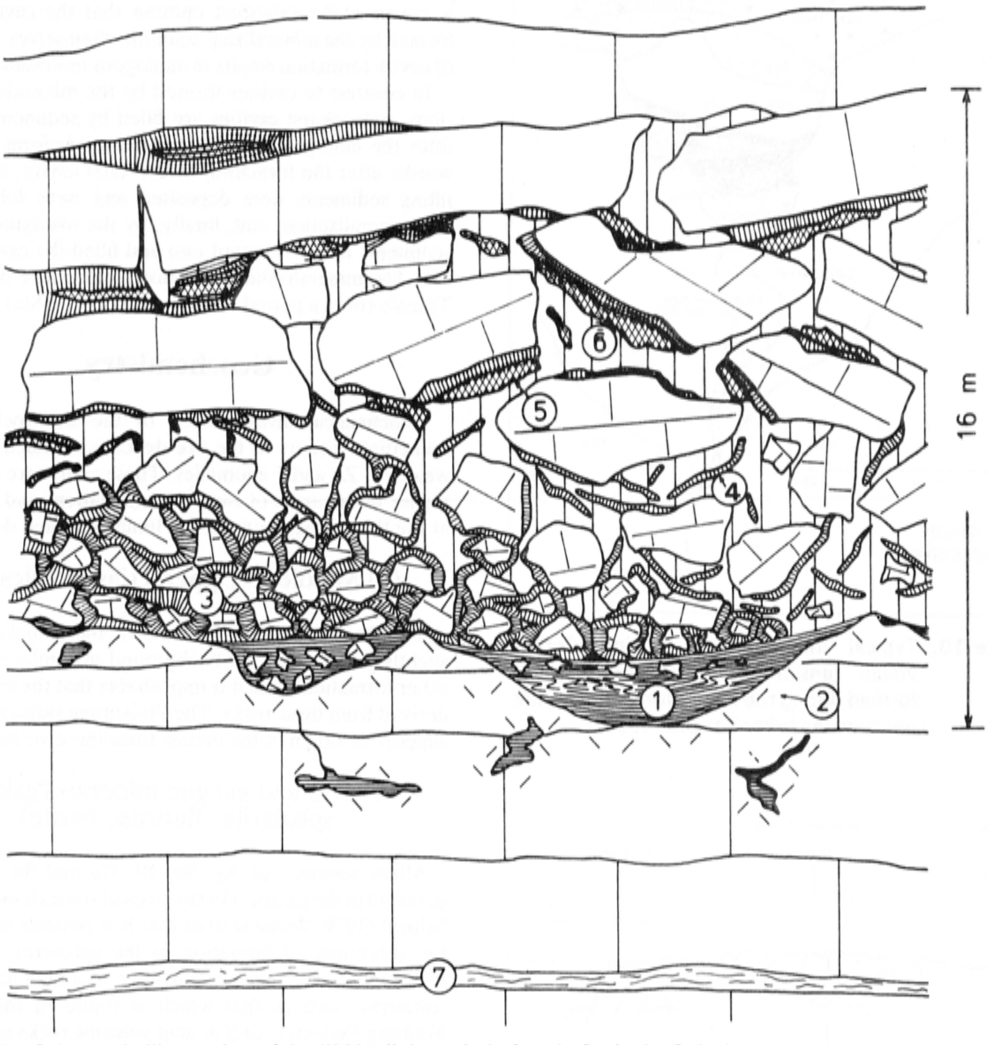

**Figure 13.** Schematic illustration of the "880m" deposit, Lafatsch, Stefanie. Solution cavity with multi-stage filling of internal sediments and chemical precipitates. The walls of the cavity caved in after the first ZnS mineralization, hence the basal contact with the host rocks appears to be primary. 1-primary, ore-free, banded laminites, poorly dolomitized and partly mineralized with secondary sphalerite. 2-dolomitization. 3-banded sphalerite (Schalenblende) and broken fragments of Schalenblende, formed as a result of collapse of the cavity walls. 4-sphalerite-stalactite. 5-galena. 6-sparry calcite. 7-green marl within the Wetterstein Limestone (after Brandner, 1981).

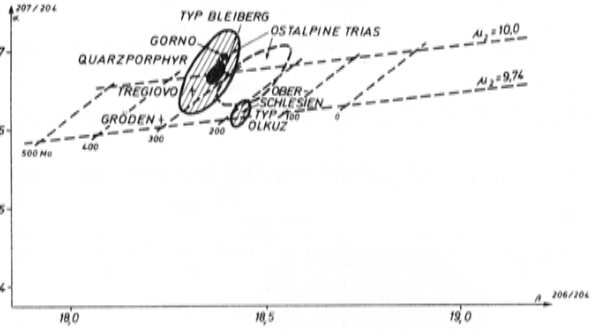

**Figure 14.** Plot of 207/204 against 206/204 Pb-isotope ratios illustrating the relation of the Bozen Quartz Porphyry, the Tregiovo Formation and the Gröden Sandstone ore-Pb to the data from selected European Triassic ore-Pb (adapted from Koeppel and Schroll, 1979).

### (c) Isotopes

The sulphur isotopes of all the Pb-Zn deposits have an average value of $\delta^{34}S = -19.7‰$. Pb-isotopes, which are extremely homogeneous for the whole district (Fig. 14), from galena-bearing deposits with a model age of more than 300Ma (B-type), suggest that the lead derives from the lower crust (Koeppel, 1983) and was transported by tectonic activity to the surface where it was leached.

## Genesis

Various genetic models have been developed for the Triassic Pb-Zn deposits of the Alps and include the following concepts:

1. Epigenetic, formed during the Alpine metallogenetic phase (Tertiary).
2. Submarine-exhalative, sedimentary (intra-Triassic).
3. Hydrothermal karst (post-Triassic).
4. Brines from the basin.
5. Palaeokarst.

1. Abundant sedimentary structures described from numerous locations suggest the epigenetic theory to be unacceptable. The mineralization in the Alpine fault systems apparently represents a younger remobilization of the Triassic ore.

2. The absence of contemporaneous volcanism (the older basic volcanics cannot be considered as a Pb source on the basis of completely different Pb-isotope characteristics, (Koeppel, 1983)), as well as the absence of external sediments, does not support the submarine-exhalative sedimentary theory of genesis. The ore Pb has a different isotopic composition from the trace Pb in the host-rocks (Koeppel, 1983).

3. The absence of feeder channels beneath the mineralized cavities, the presence of beds of clastic sediments within the ores, as well as the Upper Triassic sediments that fill the mineralized cavities, all contradict the hydrothermal karst origin for these deposits.

4. The metal solutions may have originated in the basins adjacent to the platforms. These solutions might have been expected to travel as chloride complexes in the sandstone aquifers. The expelled brines could have mixed with a second sulphate- and sulphide-containing solution where organic reduction may have produced the sulphides. The sulphides would then have been deposited in synsedimentary fault systems or palaeokarst networks of the platforms. At Salafossa sulphides were deposited 1.5km from the basin margin. Migration of ore fluids was probably caused by basinal compaction during the Middle and Upper Triassic. This model, as introduced by Beales (1975), matches exactly with the Pb isotope data published by Koeppel (1983).

5. As a result of the previously mentioned tectonism in the Middle Triassic, there was locally strong uplift and emergence, and the consequent development of an intense Triassic karstification (mature karst system). The cavities of this karst system were filled with Upper Triassic mudstones, siltstones and ore minerals during the transgression. The most likely source for the metals is from the uplifted basement, and particularly from the Permian quartz porphyry.

Hoehndorf (1984) has shown (Fig. 14) that the quartz porphyry Pb has exactly the same isotopic ratio and model age as the ore Pb. The question of how the metal concentration itself occurred, however, remains unresolved.

The relief inversion and the consequent transgression of clastic sediments that took place during the Upper Triassic as a result of tectonic activity is a particularly important feature. In the hinterland intensive weathering could have led to a concentration of metals. During the transgression the products of this weathering may have penetrated the karst cavities as they became submerged beneath the sea.

## Comments on the geology and metallogenesis of the Alpine Triassic ore deposits

The mines were occasionally worked during the Middle Ages. Only with the introduction of new mining and beneficiation methods after the end of World War II, which permitted the working of low-grade ores, could the production rates be significantly increased. The total production from the Alpine "Mining camp" up to 1980 was about 75Mt of ore (Fig. 15).

**TOTAL PRODUCTION UNTIL 1980.**

| | Ore | Metal | Zn/Pb |
|---|---|---|---|
| Bleiberg | 35.0 Mt | 2.6 Mt | 5 : 1 |
| Mezica | 16.2 Mt | 1.2 Mt | 1 : 2 |
| Raibl | 18.1 Mt | 1.3 Mt | 5 : 1 |
| Gorno<br>(until 1978) | 6.2 Mt | 0.85 Mt | 5 : 1 |

**RESERVES.**

| | | | |
|---|---|---|---|
| Salafossa | 10 Mt | 4.9 % Zn, 1 % Pb | 5 : 1 |
| Lafatsch | 1 Mt | 6.0 % Zn, 1 % Pb | 6 : 1 |

**Figure 15.** Total production from the Alpine deposits up to 1980.

### Bleiberg-Kreuth

The economic Pb-Zn mineralization (Fig. 16) is confined to four stratigraphic levels.

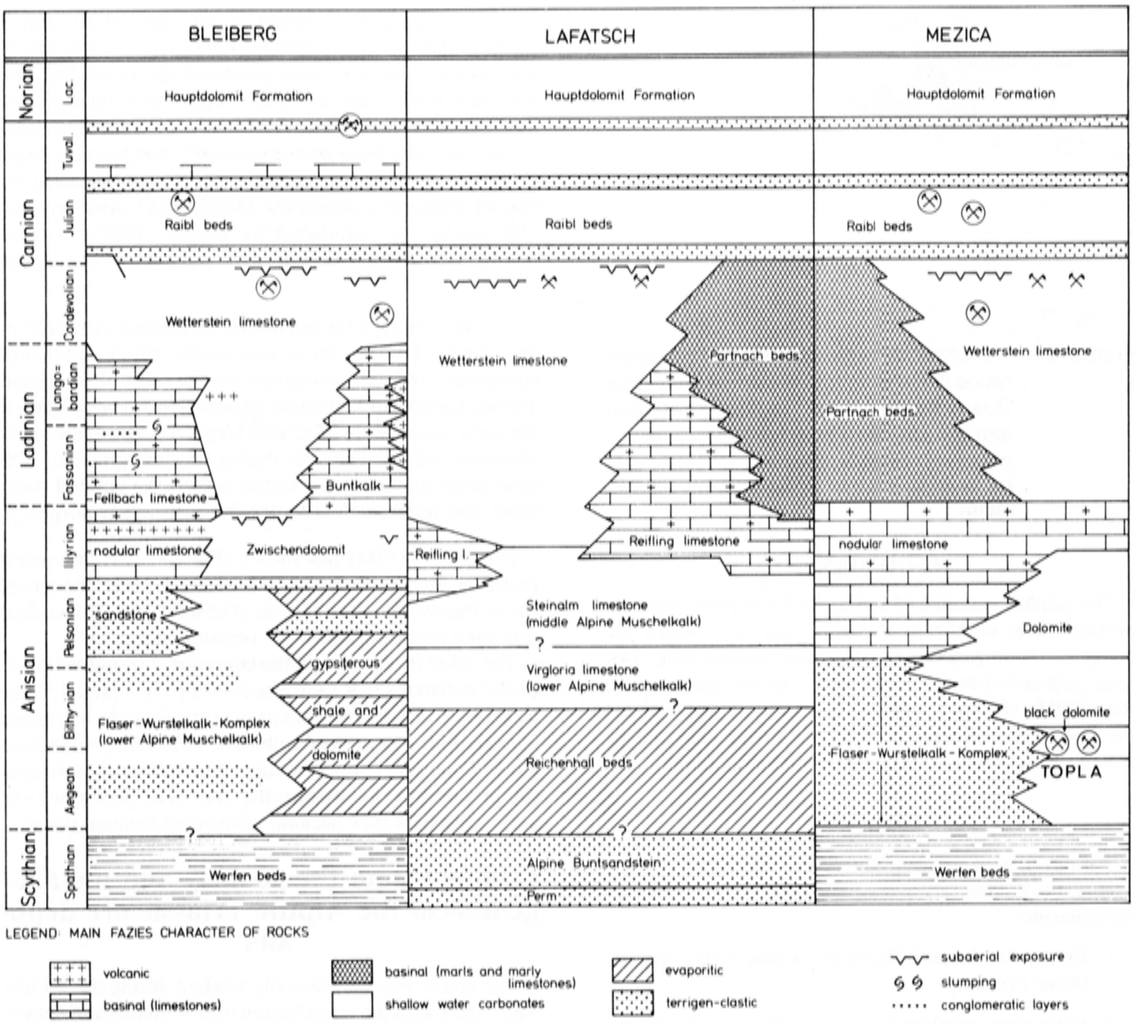

**Figure 16.** Stratigraphy and facies distribution at the Bleiberg, Lafatsch and Mezića deposits (after Bechstädt, Brandner and Mostler, 1976).

The lowermost ore horizon (150-200m below the Raibl marker bed) includes stratiform bodies up to about 1m in thickness.

The second ore-bearing horizon is in the uppermost 120m of the Wetterstein Limestone, which is in the Bleiberg facies. Within this interval are 10 marker beds (milky-white beds). The mineralization is either (a) stratiform, with bodies up to several hundreds of metres in length, up to 30m in width and thickness or, (b) in veins some hundreds of metres long and up to 30m thick.

The third ore-bearing horizon is in the 'Zwischendolomit' or Cardita Dolomite (Raibl Beds), in which the ore bodies are stratiform, are several hundred metres in length and attain thicknesses greater than 5m. At their base these ore bodies grade into breccias and reworked clastic sediments.

The fourth, stratabound, ore horizon was recently discovered in the hanging-wall of the Raibl Shale.

A "new" type of ore body has been found in the tectonized limestone area (known as the "Kalkscholle") in the western mining district. This area is fault-bounded and consists of Wetterstein Limestone with tectonic fragments of Cardita Shale and Dolomite. The mineralization is contained within cavities and breccia zones. Bechstädt et al. (1976) consider these "new" ore bodies to be brecciated karst cavity-filling.

The average areal extent of the ore bodies is about 60m$^2$, with the biggest (in the west) at about 2500m$^2$. The Bleiberg-Kreuth deposit strikes easterly for about 10km and has a maximum width of mineralization of about 1.5km.

The mine has been worked for many centuries, and 1200km of underground workings have been driven.

## Mezića

The Pb-Zn mineralization at Mezića (Fig. 16) is both stratiform and in discordant stock-like bodies and veins.

Conformable stratiform mineralization is found at 10-15m, 25m, 50-60m, 90m, 140-150m and 650m below the first Raibl Shale in the Wetterstein Limestone. The ore-bearing horizon is a lateral stratigraphic equivalent of the Bleiberg facies. The mineralization is dominantly Pb and Zn within a dolomite gangue.

The following types of cross-cutting mineralization have been distinguished:

(a) Stratabound mineralized veins and joints at 50-60m below the first Raibl marker bed are up to 1m thick and extend vertically for about 30m. This type of mineralization is very galena-rich and is characterized by a calcitic gangue.

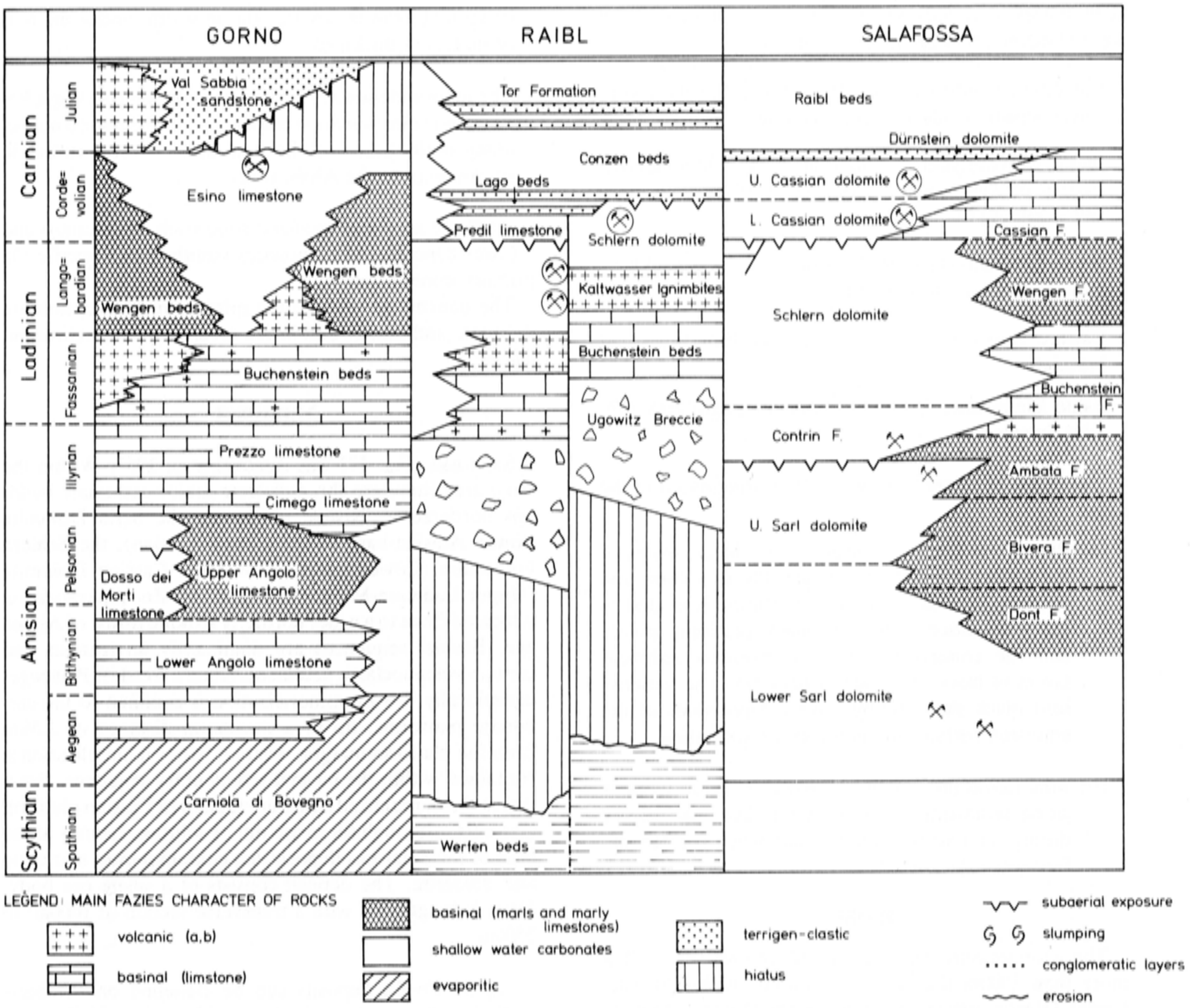

**Figure 17.** Stratigraphy and facies distribution at the Gorno, Raibl and Salafossa deposits (after Klau and Mostler, 1983).

(b) Mineralized faults and fault zones may be very extensive (e.g. the northerly striking 'Union System' extends to depths of more than 600m beneath the first Raibl marker horizon). The paragenesis of this mineralization is similar to that in type (a).

(c) Mineralization unrelated to specific strata within the Wetterstein Limestone and dolomitized limestone.

(d) Several different types of brecciated mineralization occur within the Wetterstein Limestone; the majority are collapse and dissolution breccias, but resedimentation breccias are also present.

In the "Graben" district, the Pb-Zn mineralization is contained within a Carnian reef. Zn is dominant in the dolomitized reef carbonates, and the higher concentrations of Pb are confined to the breccias between the reef and a clayey-dolomitic, evaporite zone. The gangue consists of dolomite with minor calcite and quartz.

The mineralization at Mezića strikes E-W for about 3km and has a maximum width of about 1.5km. There are about 700km of underground workings.

## Lafatsch-Vomperbach

This deposit (Fig. 16) lies within a major syncline (7.5 × 2km) that contains Wetterstein Limestone, Raibl Beds and "Hauptdolomit" in its axial region.

The total thickness of the Wetterstein Limestone is more than 1000m, and it consists of thick-bedded, massive limestone with interbeds of thin-bedded, laminated, stromatolitic limestones. In the stratigraphically higher parts of the Wetterstein Limestone, these interbeds are characterized by a higher content of clay, bitumen and pyrite. Laminated interbeds are probably inter to supra-tidal laminites comparable to the milky-white beds in the Bleiberg-Kreuth area, whereas the thick-bedded limestones were deposited in a sub-tidal environment.

These palaeokarst-type ore bodies are contained within the upper 240m of the Wetterstein Limestone, and consist of lens-like bodies with dimensions of several metres to tens of metres (Fig. 13).

In the unmineralized areas, particularly beneath and laterally to the mineralization, there is an enrichment of Pb and Zn at the contact between the thick-bedded, subtidal limestones and the thin-bedded, inter- to supra-tidal limestones. This enrichment is considered to be the result of diagenetic effects.

## Gorno

At Gorno (Fig. 17) the Ladinian-Carnian ore-bearing sedimentary sequence is known as the "Metallifero". From top to bottom the sequence is as follows:

Val Sabbia Sandstone; up to 150-200m of red and green, volcanoclastic sandstones and siltstones.

Metallifero Bergamasco Limestone (Upper Metallifero); 10-35m of well-bedded, dark grey to black limestones and overlying black shales.

Breno Formation (Lower Metallifero); up to 40m of light grey, internal peritidal limestones.

Calcare Rosso; 0-15m of red, peritidal limestones and breccias.

Esino Limestone; 750-800m of massive, light grey subtidal limestones.

Two types of mineralization can be distinguished in the area:

(a) Pb-Zn ore bodies confined to the black shales of the Upper Metallifero are typically stratiform and laterally extensive. This mineralization is related to the termination of the carbonate platform growth and the commencement of terrigenous sedimentation of black shales and limestones. The mineralized black shales occupy small depressions of the emersion surface and fill mineralized cavities.

(b) Mineralization was also hosted in karst features along sedimentary Triassic faults and was formed during the Ladinian and Carnian when the Metallifero was emergent.

### Raibl

The economically important Raibl deposit (Fig. 17) is more than 1000m thick and is contained within Middle-Upper Triassic carbonates known as the Dolomia Metallifera.

The "Buchenstein" horizon, which consists of about 50m of green, tuffaceous sandstones and tuffites, subdivides the Dolomia Metallifera into a lower and upper part. Mineralization is mainly confined to the upper Dolomia Metallifera and is present up to the contact with the overlying Raibl Beds ("Contatto Scisti"). Mineralization is partly controlled by northerly and northeasterly trending synsedimentary faults, and the ore localization is thus dependent on the presence and intensity of Triassic tectonism.

The Raibl deposit is located at the eastern margin of the easterly trending Valbruna-Raibl Carnian basin which is 2500m long and 1400m wide. Mineralization in this area is located along the lowermost part of the Raibl Formation within dark grey bituminous marls and dolomites.

Within the mine are the following types of mineralization (Brigo et al., 1977):

"Stratiform" mineralization at the contact between the Dolomia Metallifera and the lowermost Raibl Beds adjacent to northerly striking faults (e.g. the Struggl Fault Zone).

Stockworks parallel to the general bedding of the upper Dolomia Metallifera (e.g. the Colonna Principale, Bärenklammzone). These stockworks are aligned along northerly trending faults, and are particularly concentrated at the intersection of the northerly and northeasterly striking faults. These stockworks have dimensions of up to 1200m in length, 50m in width, and some tens of metres in thickness.

The main sedimentary faults often contain colloform Pb-Zn-filled veins which extend over several hundred metres along both strike and dip, and up to several metres in thickness (e.g. the Aloisi vein).

At Raibl an upper oxidized zone (rich in limonite) and a lower zone rich in carbonates (smithsonite) overlie the primary mineralization.

The gangue minerals in the primary mineralization are dolomite and barite, and in the secondary mineralization, calcite.

### Salafossa

Salafossa (Fig. 17) was discovered in 1957. Within the mine area there are three discrete major carbonate buildups bordered by basinal sediments, the Serla Dolomite (lower Anisian-base of the Upper Anisian), the Schlern Formation (Lower Ladinian) and the Cassian Dolomite (Upper Ladinian-Middle Carnian). Pb-Zn mineralization is located close to a wide, northerly striking thrust of Alpine age. Basinal sequences are dominantly terrigenous and contain volcanoclastic sediments (Pietra Verde). Palaeogeographically, Pb-Zn mineralization is confined to the carbonate platforms, up to a maximum distance of 1.5km from the platform margin, whereas barite mineralization is contained within the basinal sedimentary sequence. Breccias in the mineralized zones are related to Cassian platform tectonics, although there are minor solution cavities at the base of the Salafossa deposit that contain pyrite, marcasite and dolomite. The deposit consists of a single ore body, 650m in length and with a transverse section of $1600m^2$ to $2500m^2$.

Alpine Pb-Zn deposits can be classified on the basis of their style of mineralization as Mississippi Valley-type deposits. Table 1 is an attempt to relate these deposits to the Irish deposits.

## Conclusion

The Pb-Zn deposits of the Alpine Middle and Upper Triassic are palaeogeographically located on an unstable shelf on an inactive (passive) plate margin near the boundary between carbonate platforms and their associated basins.

The stratigraphically lowest type of mineralization is contained within a continental-detrital facies (late Hercynian molasse stage), and the higher, carbonate-hosted, Pb-Zn mineralization is contained within a limestone sequence that is characterized by strong facies variations, attributed to synsedimentary faulting. The part of the carbonate platform that was uplifted during this phase of Triassic synsedimentary tectonism was subjected to a long period of erosion and karst systems were developed. This tectonism also produced the basins and rises and their associated characteristic facies.

Possible genetic models for the Alpine Middle and Upper Triassic Pb-Zn deposits have been developed. Those related to epigenetic, submarine-exhalative, and hydrothermal karst are considered to be inapplicable to these deposits.

The following two models are compatible with our observations:

**Table 1.**

Comparison of the Alpine Middle and Upper Triassic Pb-Zn deposits and Irish Lower Carboniferous Pb-Zn-Cu deposits.

| | **Alps** | **Ireland** |
|---|---|---|
| **Tectonostratigraphic setting of mineralization.** | Pb-Zn deposits are related to an unstable shelf at the boundary of the developing Tethys ocean. The stratigraphically lowest type of mineralization is contained within a continental-detrital facies (Variscan molasse), while the Middle and Upper Triassic Pb-Zn deposits are hosted by a more than 1000m thick sequence of carbonates. They occur within an area of peritidal depositional environment at the boundary between platforms and basins. Only Mezića is connected with a basin across a reef. Synsedimentary tectonism (block-faulting) led to formation of basins and rises. the consequent development of karst networks which were filled with ore solutions. Molasse and carbonates are separated from the underlying Palaeozoic rocks by an unconformity. | Pb-Zn-Cu deposits are located in the Variscan foreland. The stratigraphically lowest part of the host rocks passes from tidal-flat calcareous siltstones, shales and argillaceous limestones into shallow water, dark shaley, bioclastic limestones of early and middle Courceyan age into the Waulsortian mudbank "Reef" of pale biomicrites and calcilutites. At and above the contact of the shallow-water muddy bioclastic limestones with the Waulsortian, major base metal deposits (Tynagh and stratiform ore bodies of Silvermines) developed (Taylor and Andrew, 1978). The Lower Carboniferous is separated from the Lower Palaeozoic by an unconformity. |
| **Host rocks** | Mineralization is related to coarse crystalline dolomite developed as an alteration from pre-existing Wetterstein and Raibl Limestones. | Lower Carboniferous rocks vary in grain size from sandstones to carbonate rocks with diverse textures. There is no common host rock to the deposits. Dolomitization is ambiguously associated with mineralization (Schultz, 1971). |
| **Igneous activity** | No relationship between pene-contemporaneous volcanics and mineralization. | There is no spatial association with igneous intrusives and sediments of volcanic origin (Morrissey et al., 1971). |
| **Nature of mineralization in basement rocks** | Galena and sphalerite veins or stratiform ore bodies in Palaeozoic strata.<br>Of economic significance is the stratiform Pb-Zn mineralization of the Palaeozoic of Graz (Meggen type). | Galena, sphalerite and chalcopyrite veins occur in Lower Palaeozoic strata. Avoca is an Ordovician volcanogenic sulphide deposit (Kuroko type). |
| **Relation of mineralization to faults** | By tectonism in the Middle and Upper Triassic a synsedimentary fault system (block faults) was developed which was filled with metal-bearing fluids. The metals were derived from the weathering products of the Palaeozoic basement and Permian quartz porphyry. | All major base metal deposits are in the vicinity of steeply dipping ENE-striking faults. In some localities fault-controlled mineralization extends into pre-Carboniferous rocks. Andrew and Ashton (1982) suggest that the Caledonian fault system in the basement was reactivated during Lower Carboniferous and served as a feeder system for metal-bearing fluids. |
| **Styles of mineralization** | Main phases of mineralization occurred within previously existing karst cavities or within synsedimentary fault systems. Dominant type, however, is along bedding planes.<br>Ore-bearing solutions were emplaced epigenetically. | There is no common host rock and mineralization is a function of the lithology (Morrissey et al., 1971). Geometrically mineralization varies from strongly discordant, tabular to conformable, replacements, veinlets, breccias and disseminations. |
| **Metal ratios** | Zn:Pb=5:1 (no Ag), except Mezića with a Zn:Pb ratio of 1:2. | Zn:Pb ratios range from 5:1 to 1:1. This does not indicate a common mode of formation of the deposits. |

**Table 1. (Cont.)**

Comparison of the Alpine Middle and Upper Triassic Pb-Zn deposits and Irish Lower Carboniferous Pb-Zn-Cu deposits.

| | Alps | Ireland |
|---|---|---|
| **Depositional temperatures** | S isotope geothermometry exhibits temperatures of 95°C-140°C (Schroll, 1979). | Mineralizing solutions show temperatures of 100°C-350°C. Temperatures increase towards faults (Morrissey et al., 1971). |
| **Pb isotopes** | Pb isotopes are extremely homogeneous for the whole region. Model age (300Ma or more) is older than of the host rock (B-type). | Pb isotopes fall close to a single growth curve. They become more radiogenic southwards (J-type). Model ages range from 270 or 215Ma (Keel) to 115 or 60Ma for Silvermines (Morrissey et al., 1971). |
| **S isotopes** | The S isotopes have an an average value of $\delta^{34}S = -19.7‰$, suggesting a Triassic age of formation. | Rather widespread isotopes do not indicate a common mode of formation for the base-metal deposits. |
| **Type of deposit** | Mississippi Valley-type | Sediment-hosted, submarine-exhalative (Large, 1980). |

### Basinal brines

Metal solutions originated in the basins adjacent to the platforms. Migration of the ore fluids into the platforms in synsedimentary fault systems or palaeokarst networks was caused by basinal compaction and tectonic events (Beales, 1975).

### Palaeokarst cavities

The metal enrichments of basins and rises were derived from the weathering products of the Palaeozoic basement and Lower Permian quartz porphyry; both have a trace-Pb isotopic model age of 300Ma or more, which is directly comparable with that of the galena in the Alpine Pb-Zn deposits. The cavities of the karst system were filled with Upper Triassic mudstone, siltstone and ore solutions during the transgression. The mineralization is always associated with dolomitization.

## Irish carbonate-hosted base metal deposits

A marine transgression during the Courceyan-Visean resulted in deposition of limestone on shelfs and Waulsortian Mudbank "Reef" of pale biomicrites and calcilutites in slightly deeper basins. The major base metal deposits hosted by Courceyan-Visean limestones developed at and above the contact of the shelf sediments and the Waulsortian Mudbank "Reef". All major base metal deposits are in the vicinity of steeply dipping ENE-striking faults, often extending into pre-Carboniferous rocks. Andrew and Ashton (1982) suggested that these faults served as feeder systems for metal-bearing fluids. In contrast to the Alpine Middle and Upper Triassic Pb-Zn deposits, the Irish base metal deposits bear stronger resemblance to sediment-hosted, submarine-exhalative deposits.

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