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EXCURSION TO THE PB-ZN-AG-BA DEPOSIT ARZBERG IN THE GRAZ PALEOZOIC (EASTERN ALPS, AUSTRIA)
Excursion guide MinPet 2025 conference

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1. Introduction

In the Graz Paleozoic (Drauzug-Gurktal nappe system, Eastern Alps) in Austria, stratiform Pb-Zn-Ag-Ba deposits are known. They are classified as sedimentary-exhalative (SEDEX) deposits (WEBER, 1990; FEICHTER, 2005) and are hosted by polyphase deformed greenschist facies metasediments and –volcanics/-volcanoclastics of the Schönberg Formation (Schöckel nappe), which is upper Silurian to Lower Devonian in age (TSCHELAUT, 1985; FLÜGEL & HUBMANN, 2000). Many of these deposits have been sites of mining for at least 680 years. After several closures and restarts, mining was terminated in 1927. Since then, there has been repeated research work as well as an exploration phase with drilling activity in the 1970s to 1980s (WEBER, 1990). The ongoing project MRI_SEDEXPOT in the course of the MRI ("Forschungspartnerschaften Mineralrohstoffe") investigates these deposits and their exploration potential.

The first part of the excursion is dedicated to the inactive Arzberg mine, which is operated as a show mine since 1995 (WEBER, 2019). During the tour, the sulfide and barite ore horizons as well as the structural and metamorphic overprint can be observed. In the second part, the regional geological framework of the Arzberg deposit is presented. Along the trail of the "Montanlehrpfad" representative outcrops of the Schönberg Formation and its members are visited. Based on the occurring lithologies, the internal subdivision, the depositional environment and the metamorphism of the Schönberg Formation, as well as the genesis and spatial distribution of the Pb-Zn-Ag-Ba deposits of the Graz Paleozoic are discussed. A tasting of the "Arzberger Stollenkäse" (stollenkaese.at) cheese completes the excursion with a culinary experience.

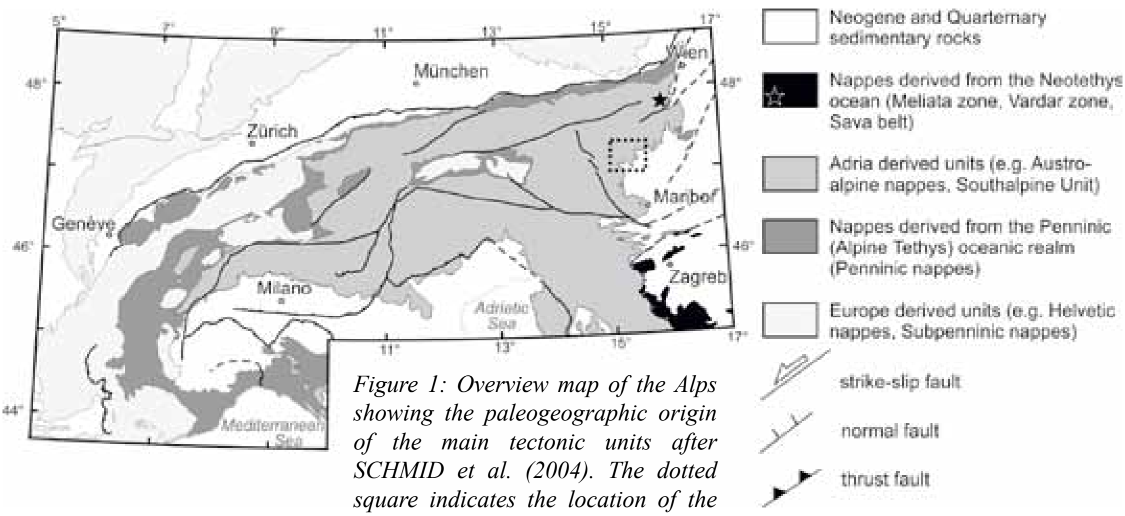

Figure 1: Overview map of the Alps showing the paleogeographic origin of the main tectonic units after SCHMID et al. (2004). The dotted square indicates the location of the map of the Graz Paleozoic in Fig. 2.

2. Geological Overview

The Graz Paleozoic nappe stack consists of diagenetic to low-grade metamorphic Paleozoic (meta)sediments and metavolcanics (FLÜGEL & NEUBAUER, 1984). It is part of the Drauzug-Gurktal nappe system of the Austroalpine Unit and is located in the eastern part of the Eastern Alps (Fig. 1). It is surrounded and underlain by epidote-amphibolite facies to eclogite facies metamorphic units of the Koralpe-Wölz nappe system, some of which are referred to by local names such as Anger crystalline or Radegund crystalline (KRENN et al., 2008). The western part of the nappe stack is locally overlain by Upper Cretaceous sediments of the Gosau Group (Kainach-Subgroup). Neogene sediments of the Styrian and Passail basins cover along the southern margin and north of Arzberg respectively (FRITZ et al., 1992).

There are several concepts for the internal tectonic subdivision of the Graz Paleozoic (FRITZ et al., 1992; GASSER et al., 2010). According to recent work (SCHUSTER et al., 2016) we use the division of the nappe stack into a lower, intermediate and upper nappe group. The upper nappe group comprises the Rannach nappe and Hochlantsch nappe, whereas the intermediate nappe group the Laufnitzdorf nappe and Gschwendt (Kalkschiefer) nappe, the lower nappe group the Gschnaidt nappe, Schöckel nappe and Gasen nappe (Fig. 2).

The lithostratigraphic subdivision of the Graz Paleozoic comprises the five different sedimentological facies units Laufnitzdorf, Kalkschiefer, Schöckel, Rannach and Hochlantsch facies (GASSER et al., 2010). These facies units are, however, not identical with the tectonic units and therefore overlap. Lower Silurian to Lower Devonian volcanoclastics and siliciclastics build the start of these successions, followed by Middle Devonian carbonate platform sediments. The end is marked by pelagic limestones and slates of Upper Devonian to lower Carboniferous age (FLÜGEL & NEUBAUER, 1984; FRITZ & NEUBAUER, 1988; FLÜGEL & HUBMANN, 2000; GASSER et al., 2010; SCHANTL et al., 2015). FLÜGEL & HUBMANN (2000) describe thirty-five formations belonging to the above-mentioned sedimentological facies units.

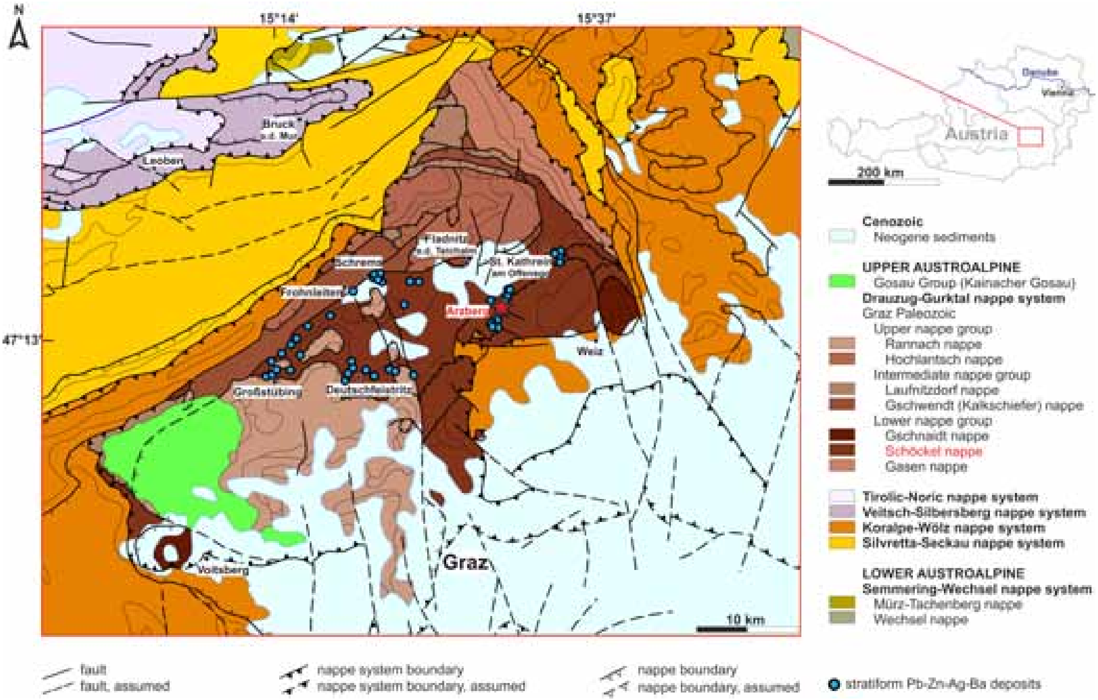

Figure 2: Tectonic map of the Graz Paleozoic in Styria (Drauzug-Gurktal nappe system, Austroalpine Unit) with the locations of the stratiform Pb-Zn-Ag-Ba deposits. The red star highlights the Arzberg mine. Map according to ADB 500 ("Arbeitsdatenbank") of GeoSphere Austria 1.3.2023.

The age of metamorphism and deformation within the Graz Paleozoic is the basis of a long discussion. Different models ascribe the main imprint to either the Variscan or the Eoalpine (Cretaceous) tectonometamorphic events (FRANK, 1981; FLÜGEL et al., 1980; FRITZ, 1988; HASENHÜTTL, 1994; RUSSEGGER, 1996; NEUBAUER et al., 1999; KRENN et al., 2008; GASSER et al., 2010). Most recently, HOLLINETZ et al. (2024) showed both a Permian and a Cretaceous (Alpine) metamorphic and structural overprint for the Schöckel nappe, with greenschist facies metamorphic conditions.

3. Excursion part A: Arzberg mine

3.1. History of mining

Mining activity in the Arzberg area dates back to the early Middle Ages. The first documented mention was in a document of donation from 1242. Until the 19th century, only silver-rich lead ores were mined; zinc ore was not extracted until the early 20th century. The "Neuer Raabstollen" adit in Arzberg was opened in 1911. Mining activity in Arzberg and the neighboring Haufenreith district was discontinued in 1927, and the mines were closed in 1935. Between 1973 and 1975, the ore deposits east of the Mur River were re-examined by the Bleiberger Bergwerksunion mining company. Historical metal production in the Arzberg-Haufenreith districts is estimated at 2,500 tons of Zn, 10,000 tons of Pb, and 20 tons of Ag. Total production from all SEDEX deposits in the Pb-Zn-barite ore district could amount to 65,000 tons of Pb and Zn and 82 tons of Ag. Since 1995 the inactive Arzberg mine is open for visitors as a show mine. The entrance into the mine marks the “Neuer Raabstollen”, from where the tour leads around 500 m through the mine and ending with the exit through the “Erbstollen” (Fig. 4). During the tour, the sulfide and barite ore horizons as well as the tectonic and metamorphic overprint can be observed.

3.2. SEDEX model

The Pb-Zn-Ag-Ba mineralisations are classified as sedimentary-exhalative (SEDEX) deposits (WEBER, 1990; FEICHTER, 2005). SEDEX deposits include some of the largest base metal occurrences in the world and contain more than 50% of the world’s resources for Zn and Pb (LARGE, 1980). Additionally, they are important for Cu, Ag, other minor elements like In, Ge, Ga, Cd and Ni, and especially critical raw materials like barite, Co and Sb (EUROPEAN COMMISSION, 2023). Important SEDEX deposits with resources of up to several 100 Mt are located in Australia (Broken Hill, Mount Isa), Canada (Sullivan), USA (Red Dog/Alaska), India (Rampura Agucha), South Africa (Gamsberg) and Germany (Rammelsberg, Meggen) (LARGE, 1980; MISRA, 2000). Host rocks are marine sedimentary rocks, especially carbonaceous shale, siltstone, black shale and sometimes associated with volcanic rocks. The genetic description of SEDEX deposits after GOODFELLOW & LYDON (2007) is that they are typically tabular bodies composed predominantly of Zn, Pb and Ag bound in sphalerite and galena that occur interbedded with iron sulfides and basinal sedimentary rocks. They were deposited on the seafloor and in associated sub-seafloor vent complexes from hydrothermal fluids, vented into reduced sedimentary basins in continental rifts (Fig. 3).

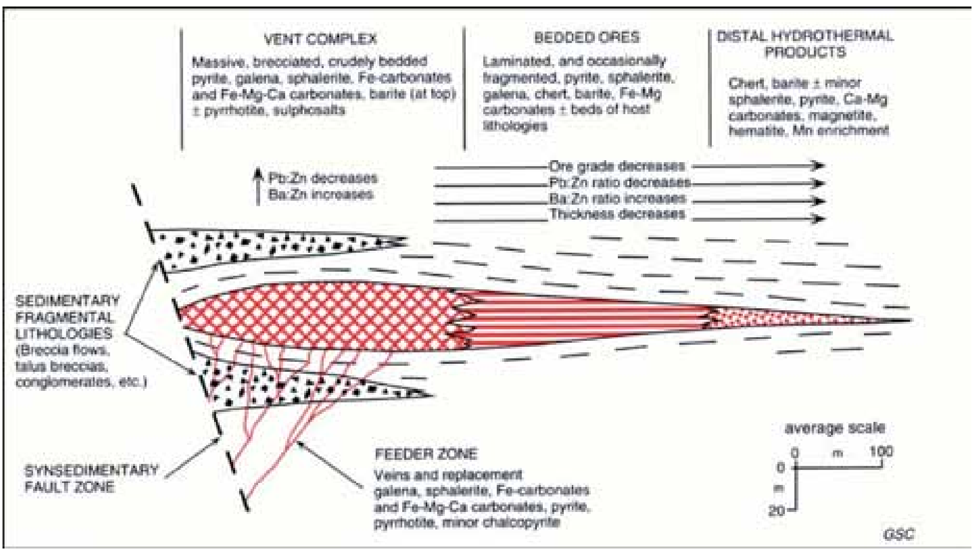

Figure 3: Schematic illustration of the characteristic features of an idealised SEDEX deposit (LYDON, 1996).

Hydrothermal alteration zones (typically silicification, carbonatisation, chloritisation) around the ore bodies are a typical feature that is broadly used for exploration of SEDEX deposits (e.g. LARGE & MCGOLDRICK, 1998; LARGE et al., 2000; RIEGER et al., 2021).

3.3. Pb-Zn-Ag-Ba mineralisation

The Pb-Zn-Ag-Ba mineralisations occur as more than one ore horizon in several mining sites in the Graz Paleozoic. The ore horizons are either sulfide or barite dominated. Their regional correlation is questionable. Galena, sphalerite, barite, pyrite, pyrrhotite and magnetite are the dominating ore phases, which are accompanied by chalcopyrite, arsenopyrite, Ag-bearing tetrahedrite, pyrargyrite, tetradymite, cobaltite, ullmannite, breithauptite, electrum and others. Host rocks are polyphase deformed greenschist facies metasediments, mostly represented by black shale, carbonate rocks and (chlorite) phyllite. Layers of greenish, chlorite rich phyllite associated with the ore horizons are interpreted as basic metavolcanics/-volcanoclastics (WEBER, 1990). However, partly they may represent metamorphosed siliciclastics enriched in iron in the course of the ore-forming event.

In the inactive Arzberg mine, the mineralisations are primarily concentrated within two up to several decimetre-thick layers roughly parallel to the main foliation, which are structurally separated by approximately 30 m. The lower ore horizon is dominated by Fe-Pb-Zn-Cu-sulfides, whereas the upper ore horizon by barite along with magnetite, galena and sphalerite. The ore horizons are displaced by two major E-dipping faults, where an offset about several tens of meters is presumed (Fig. 4).

Distinct hydrothermal alteration zones related to the ore-forming processes are developed in the hanging and footwalls of the ore horizons (ROHRHOFER et al., 2024). Disseminated ore phases, Fe and Mn rich carbonates (carbonatisation), Fe rich chlorite (chloritisation), K- and Ba-feldspars, Ba-bearing white mica and locally stilpnomelane, fluorapatite as well as REE and HFSE minerals characterise these zones. Below sulfide ore horizons albitisation is typical, whereas silicification is typical in the hanging wall.

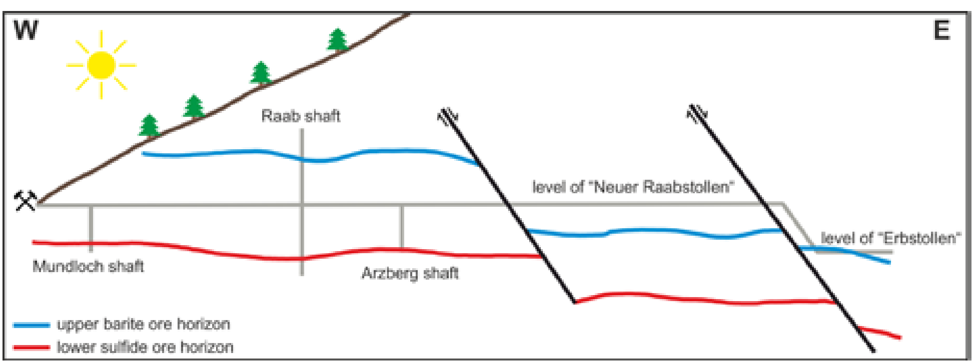

Figure 4: Schematic cut through the Arzberg mine, parallel to the "Neuer Raabstollen" (modified after WEBER, 2005).

Although the various sulfide and barite ore horizons have similar stratigraphic positions in the Schönberg Formation, as well as ore mineral assemblages, host rocks and isotope compositions, they show clear differences regarding trace element

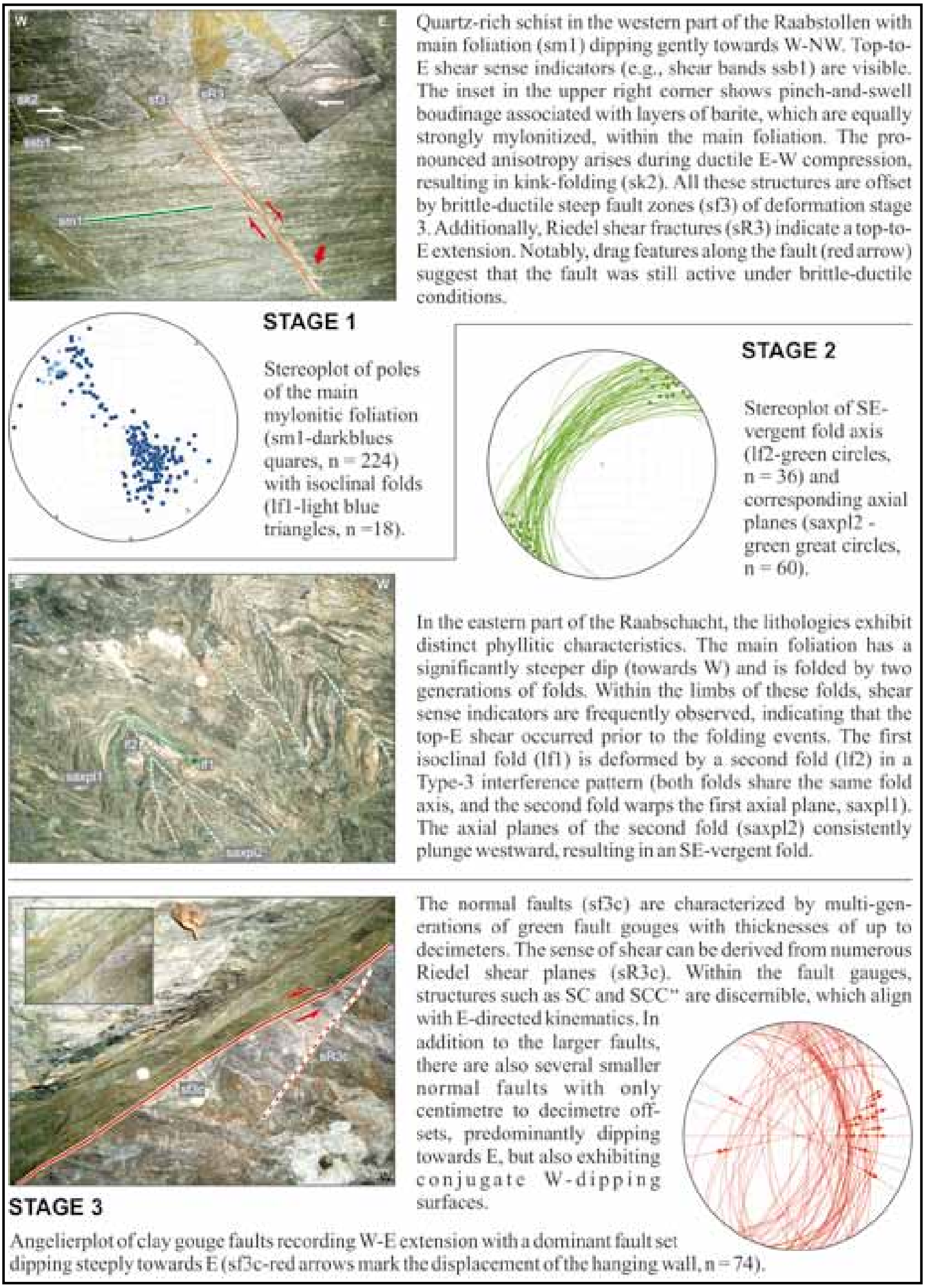

Figure 5: Main structural features in the Arzberg mine.

concentrations. Sphalerite is characterised by variable Fe concentrations with median values ranging from 0.6 to 7.3 wt.% in different mine sites, and elevated Mn, Co and Ag compared to sphalerite from carbonate-hosted Alpine-type Pb-Zn deposits. Sphalerite is also slightly enriched in Sb (median values of 5-10 ppm) and locally in In (21 ppm at Haufenreith). Overall, the rare elements Ga, Ge and In play a limited role in sphalerite and bulk rock.

Pyrite and pyrrhotite are Co and Ni-bearing, with median concentrations exceeding 100 ppm. Pyrite is the main carrier of As in the assemblage, however at generally low concentrations. Chalcopyrite is a subordinate mineral in the assemblage, and varies from Ag to Sn-rich. Silver occurs in solid solution in sphalerite, chalcopyrite and galena (REITER & WEBER, 2005), and as discrete Ag-rich phases (e.g. freibergite, pyrargyrite, Au-bearing silver; FEICHTER, 2005). Median sulfur isotope values of sphalerite range from $\delta^{34}S$ +5 to +11 ‰ (ONUK, 2018). In galena-pyrite-pyrrhotite assemblages that prevail over sphalerite assemblages at Arzberg, $\delta^{34}S$ ratios of +0.3 to +5.5 ‰ (FEICHTER, 2005) are lighter than in sphalerite (+6.6 ‰).

Sulfide thermometry using sphalerite and chalcopyrite indicates temperatures slightly below 300°C, clearly lower than maximum metamorphic conditions (500°C at 5 kb pressure) recorded by silicate and carbonate assemblages (FEICHTER, 2005; RANTITSCH et al., 2005). Based on ore textures and chemical composition, the small deposits in the Graz Paleozoic are interpreted as partly effusive, but also as subseafloor SEDEX ores with a weak volcanogenic contribution and probably epithermal fluid temperatures. Ore lead indicates Neoproterozoic model ages (550-580 Ma; KÖPPEL & SCHROLL, 1983; REITER & WEBER, 2005). During the Cretaceous Eoalpine metamorphic event, sulfide ores have been overprinted together with their host rocks. Ore mineral assemblages now reflect sulfide equilibration close to 300°C.

3.4. Stratigraphic position and age of the deposits

According to fieldwork and detailed evaluation of historic mining documents WEBER (2020) argues, that the ore horizons occur in the lower part of the Schönberg Formation. It is represented by the Rauchenberg Member, mostly below the almost carbonate free graphite phyllite (see chapter 4.2.).

The age of ore formation is best constrained by conodonts found in marble layers in the area of Arzwaldgraben west of the Mur river. According to TSCHELAUT (1985), the conodonts indicate a Lochkovian age. As the conodonts were found in the upper part of the Rauchenberg Member, an upper Silurian to lowermost Devonian age of the primary ore deposition is expected (WEBER, 1997).

3.5. Deformation

In the Arzberg mine three macroscopically visible deformation stages, postdating the upper Silurian/Lower Devonian synsedimentary ore forming events, can be recognised (Fig. 5): (1) The first stage of ductile deformation occurred during greenschist facies metamorphism in the Permian, where the W-NW dipping main schistosity formed. It was associated with ductile shearing towards SE and led to the development of metamorphic layering, mylonites and phyllonites, as well as the

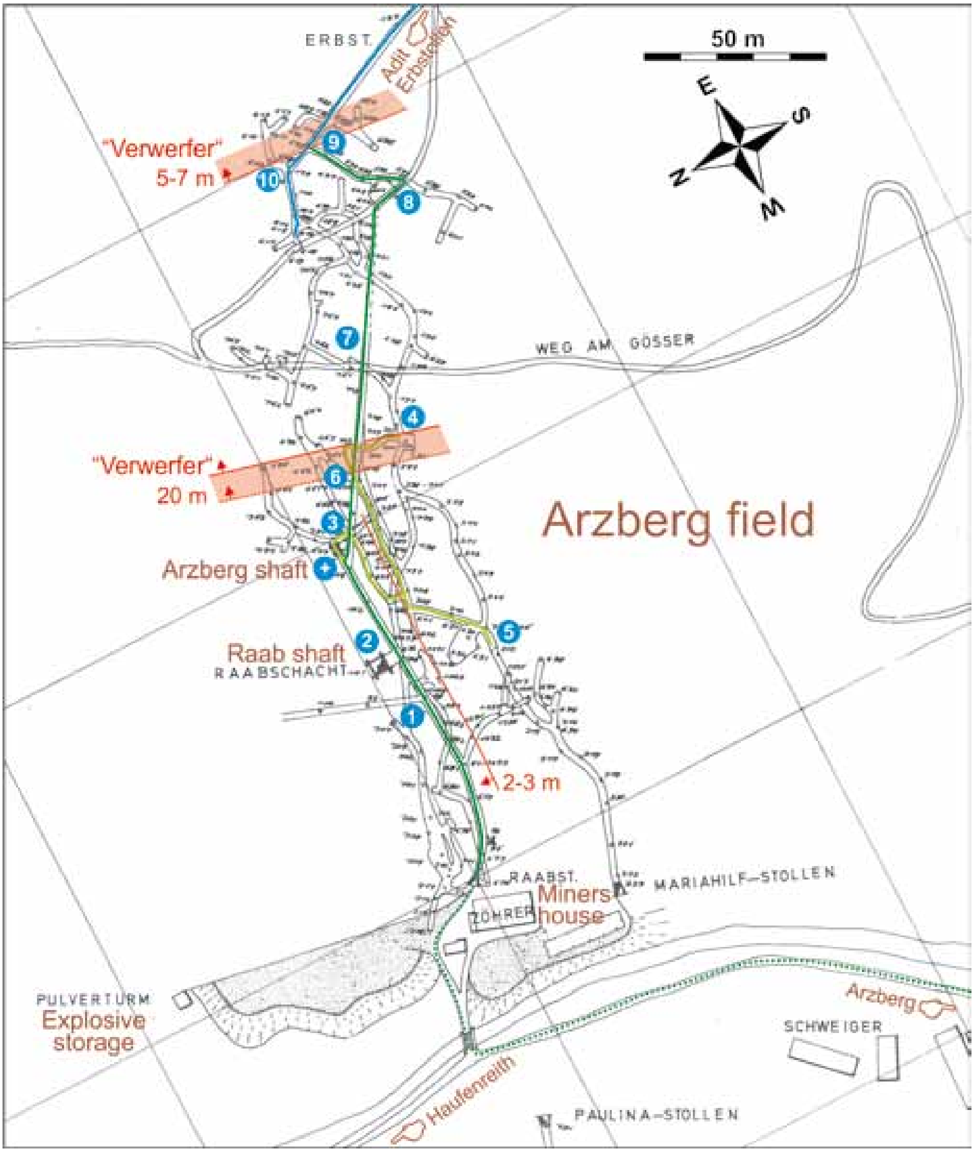

Figure 6: Extract from the mine map of the Arzberg mine from the archive of the Berghauptmannschaft Graz (WEBER, 1990). Numbers in blue circles indicate stops described in the text. Coordinates of the entrance of the Raabstollen are E 15.519417/N 47.250514.

formation of isoclinal folds with fold axes roughly parallel to the shear direction. Within this shearing process, multiple fluid pulses contributed to the creation of syn-shearing veins, exhibiting rotation and stretching to varying degrees confirming the SE-directed kinematics. (2) Subsequently in the Cretaceous, an overprinting phase of ductile deformation under greenschist facies conditions occurred and resulted in the formation of a second generation of folds. These new SE-vergent folds refold

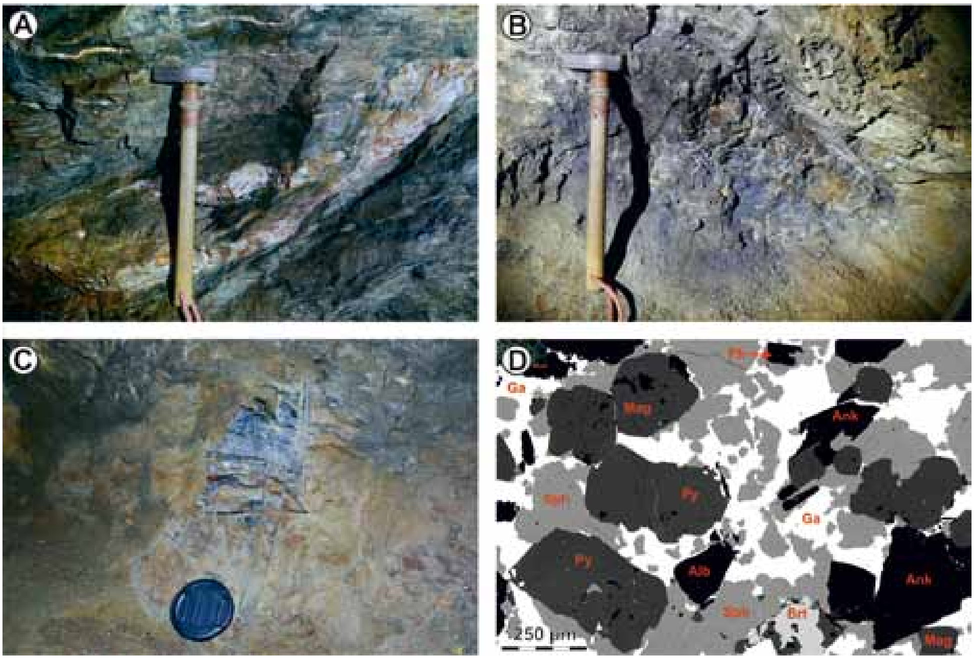

Figure 7: Photographs of sites within the Arzberg mine. A) Stop A1 with view to the East B) Stop A3 with view to the East, C) Outcrop a few meters east of Stop A3 with view to the South, D) Back scattered electron image of sulfide rich ore of the lower ore horizon. Alb…albite, Ank…ankerite, Brt…barite, Ga…galena, Mag…magnetite, Ph…phengite, Py…pyrite, Qz…quartz, Sph…sphalerite. Description see text.

the first generation. The rocks exposed in the area of the Raabstollen may represent the upper limb of a SE-verging antiform, with a hinge area located at both the entrance and the end of the Raabstollen. After the Cretaceous metamorphic peak all of these preceding ductile structures have been overprinted by a (3) deformation stage of ductile/brittle faulting along with hydrofracturing and EW-extension accommodated by normal faults with clay gouges. It is not clear at present to which extent this last stage occurred during the Late Cretaceous and early Paleogene contemporaneous to the deposition of the Kainach Gosau Group, or during the Neogene lateral extrusion of the Eastern Alps.

3.6. Description of stops in the Arzberg mine

Stop A1: Lithology and structure of the host rocks

Location: Junction "Neuer Raabstollen" with "Käsestollen"

This part of the gallery is situated within greenish-grey chlorite sericite phyllite. The schistosity and the metamorphic layering respectively is Permian in age. In several places discordant and concordant veins composed of white quartz and reddish-brown, iron bearing carbonate, locally carrying galena-pyrite mineralisation, are visible (Fig. 7A).

Stop A2: Position of the ore horizons - Raab shaft
Location: Junction “Neuer Raabstollen” and “Raabschacht”

The 36 m deep Raab shaft penetrates both the upper and lower ore horizon. Looking upward, a bright-colored layer is visible. It probably represents the upper ore horizon. The foot of the shaft is connected to the old „Raabstollen“ that followed the lower ore horizon. The „Raabstollen“ is located approximately at the level of the Raab stream and is therefore partially under water. Chlorite sericite phyllite is present in the area of the stop.

Stop A3: Sulfide dominated lower ore horizon at “Raabstollen”
Location: “Raabstollen“ close to “Arzbergschacht”

Galena rich ore of the lower ore horizon embedded within grey carbonate phyllite and impure marble (Fig. 7B). Just a few meters further on the way to “Große Zeche” another galena rich mineralisation is exposed (Fig. 7C). The ore is a mixture of galena and pyrite with minor freibergite, pyrrhotite, sphalerite, magnetite, ankerite, albite and quartz (Fig. 7D).

Stop A4: Lower ore horizon and fault at “Große Zeche”
Location: “Große Zeche“ at “Mariahilf-Stollen”

The “Große Zeche” forms one of the largest excavations in the mine. It is situated along the western normal fault (“Erster Verwerfer”), which displaces the ore horizons towards the east by about 20 metres. Remnants of galena-pyrrhotite-rich ore are visible in the gallery.

Stop A5: Sulfide dominated lower ore horizon at “Mariahilf-Stollen”
Location: “Mariahilf-Stollen” c. 70 m east of former entrance.

At this site another outcrop of the sulfide dominated lower ore horizon is visible. The ore is several centimetres in thickness and rich in galena. It forms a concordant layer within carbonate phyllite and impure marble. At some surfaces, nice aragonite is present as flos ferri (“Eisenblüte”). Please do not destroy!

Stop A6: Normal fault at “Neuer Raabstollen”
Location: “Neuer Raabstollen“ c. 20 m east of “Arzbergschacht”

Along the gallery, deformation related to the western normal fault (“Erster Verwerfer”), indicated in Figure 6, is visible. It represents a prominent normal fault with an offset of about 20 m. In the damage zone, over a length of about 10 m several secondary-faults characterised by multi-generations of green fault gouges (Please do not scrape out the clay with the tip of the hammer! Fig. 8A) with thicknesses up to decimetres are visible. Top-to-E normal offset can be derived from numerous Riedel shear planes; SC and SCC‘ structures within the fault gouges are discernible. In addition to the larger faults, there are also several smaller normal faults with only centimetre to decimetre off-sets, predominantly dipping towards E, but also exhibiting conjugate W-dipping surfaces (see also Fig. 5).

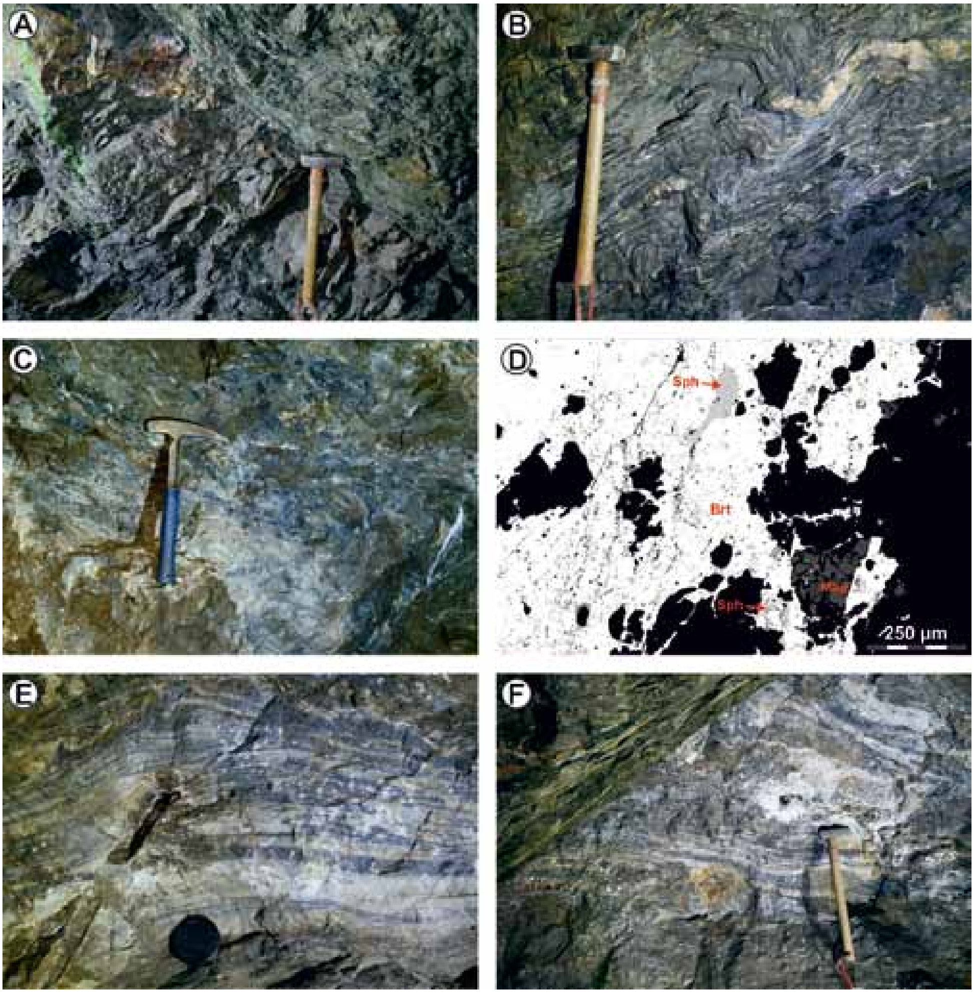

Figure 8: Photographs of sites within the Arzberg mine. A) Stop A6 with view to the North, B) Stop A7 with view to the North, C) Stop A8 with view to the North-West, D) Back scattered electron image of barite dominated ore of the upper ore horizon. Brt…barite, Mag…magnetite, Sph…sphalerite and quartz, E) Stop A9 with view to the South-West and F) Stop A10 with view to the South. Description see text.

Stop A7: Structures at "Neuer Raabstollen"

Location: "Neuer Raabstollen" c. 50 m east of "Arzbergschacht"

As in several other places along the "Neuer Raabstollen" the chlorite sericite phyllite shows intense folding of the Permian schistosity and metamorphic layering respectively (Fig. 8B). The schistosity (sm1) is gently dipping towards northwest. Fold axes (lf2) are NE-SW trending and the axial planes (saxpl2) consistently dip westward, resulting in an SE-vergent fold (see also Fig. 5).

Stop A8: Barite dominated upper ore horizon at Mariahilf with normal fault
Location: "Neuer Raabstollen" shortly before the route descends towards the NW to the junction with "Erbstollen"

At this site the barite dominated upper ore horizon (Fig. 8C) is visible before it is offset for about 7 m by the eastern normal fault ("Zweiter Verwerfer"). The barite ore shows a layering of deformed white and greyish layers. The ore consists of barite, quartz, sphalerite, galena and magnetite (Fig. 8D). The latter sometimes forms centimetre thick layers at the contact to the host rock.

Stop A9: Lithology and structure of the host rocks
Location: Junction "Neuer Raabstollen" with "Erbstollen"

In the gallery, the barite dominated upper ore horizon to the east of the eastern normal fault ("Zweiter Verwerfer") is visible (Fig. 8E). In some places folding and refolding of Type-3 (hooks-and-crescents) occur.

Stop A10: Barite dominated upper ore horizon at Mariahilf with normal fault
Location: Deepest part of "Mariahilf-Stollen" close to connection with "Erbstollen"

Behind the gate the barite dominated upper ore horizon is well exposed in the gallery. Partly, the walls are covered with tiny gypsum needles and other secondary minerals, e.g. jarosite. Please do not destroy! Upside the climbing tree ("Steigbaum") to the seismic station operated by GeoSphere Austria, the barite dominated upper ore horizon is offset by a normal fault related to the eastern normal fault ("Zweiter Verwerfer"). A green fault gauge with spectacular SC/SCC' fabrics is developed (Fig. 8F).

4. Excursion part B: Outcrops along the trail of the "Montanlehrpfad Arzberg"

The outcrops along the Geotrail Arzberg-Haufenreith provide a good overview of the Schönberg Formation and the rapidly decaying traces of historical mining. The numbers beside the coordinates refer to the sites described in WEBER (2020).

4.1. Structure and stratigraphy of the Schöckel Nappe

SCHWINNER (1925) mentions a "Schöcklkalkdecke" for the first time, which differs greatly in scope and interpretation from today's Schöckel Nappe. The latter is named after Mount Schöckel (1445 m) on map sheet ÖK50 164 Graz.

It is the largest nappe of the Graz Paleozoic in terms of surface area, but it can be assumed that it is also continuously present under the overlying nappes and below Neogene sediments of the Styrian Basin. At a minimum, it extends 60 km in an ENE-WSW direction with a width of around 20 km. Due to the internal deformation the maximum thickness is difficult to estimate but will be more than 1 km (GASSER et al., 2010). In terms of lithostratigraphy it includes from bottom to the top the Semriach Formation of the Passail Suite, the Taschen-, Schönberg-, Raasberg- and Schöckel Formations of the Peggau Suite (FLÜGEL & HUBMANN, 2000) as well as the Hirschkogel Lithodeme (SCHUSTER et al., 2016) (Fig. 9).

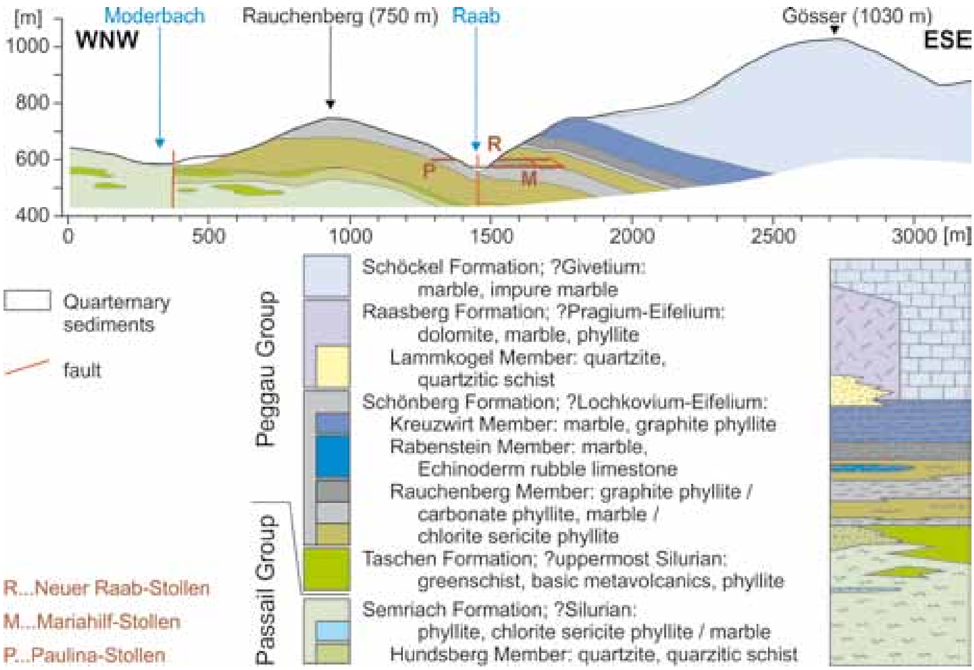

Figure 9: Section and stratigraphy of the Schöckel Nappe in the Arzberg area.

The Schöckel Nappe has a complex geometry, which is still under discussion. Since CLAR (1935), an isoclinal fold with the marbles of the Schöckel Formation in the centre, separating the lower (Semriach) schists from the upper (Taschen) schist, is proposed for the section north of Graz (FLÜGEL, 1958). The hinge of the fold is expected to be in the south. In contrast, SCHUSTER et al. (2016) argue for an upright succession in the more easterly section north of Weiz, because of the internal stratigraphy of the Schöckel Formation.

The mining sites of Arzberg, Haufenreith and also Burgstall and Kogl-St.Kathrein/Offenegg are located within soft phyllites of the Schönberg Formation just northwest to the boundary towards the more competent marbles of the Schöckel Formation. Along this contact, deformation is concentrated. It is expressed by folding, imbrications and minor NW-directed overthrusting of the marble onto the phyllite. The rocks of the Schöckel nappe experienced a greenschist facies metamorphic overprint in Permian and Cretaceous time. For the easternmost part peak conditions of 475-520°C and 0.4 GPa are indicated at c. 270 Ma, whereas 440-470°C and 0.4-0.8 GPa were reached at c. 110 Ma (HOLLINETZ et al., 2024).

The Pb-Zn-Ag-Ba deposits are located on several GK50 map sheets and the symbols of the mining sites appear in several lithologies of the Semriach, Taschen and Schönberg formations. This is against the observations in WEBER (2020) that the ore horizons occur in the lower part of the Schönberg Formation. However, the GK50 map sheets were published in a time span of 27 years by several people and the symbols of the mining sites in the maps indicate adits instead of ore horizons, which may be in neighbouring lithologies. A revision of the maps is necessary.

4.2. Schönberg Formation

The Schönberg Formation was introduced by FLÜGEL & HUBMANN (2000) instead of "Arzberg Schichten", because this local name is in use for another unit. The type region is located around the municipality of Schönberg close to Arzberg on map sheet ÖK50 134 Passail. The thickness of the Schönberg Formation is expected to be more than 300 m. Main lithologies are sericite phyllite, chlorite sericite phyllite, graphite phyllite, carbonate phyllite, marble, and probably intermediate metavolcanic rocks. According to the maps and literature, a larger portion of the Schönberg Formation is built up by greenschist, formed from basaltic or andesitic lava or volcanoclastics. However, greenschist or chlorite phyllite respectively is rare according to our observations. The stratigraphic age of the Schönberg Formation is not well defined, but in marble layers of the lower part, conodonts indicating a Lochkovian age were found (TSCHELAUT, 1985). Therefore, a chronostratigraphic range of Lochkovium to Eifelium is suggested, but an onset in the latest Silurian cannot be excluded. The Schönberg Formation was deposited in an euxinic to progressively oxygenated shelf environment. As only fine-grained material was deposited, a low relief is likely.

The Schönberg Formation is overlying phyllite, quartzite and metaconglomerate of the Semriach Formation and basic metavolcanics of the Taschen Formation. Above, quartzite or dolomite of the Raasberg Formation or marble of the Schöckel Formation follow. The contacts to the phyllite in the footwall as well as to the marble in the hanging wall are transitional. Internally, the Schönberg Formation appears in the Gasen and Schöckel nappes. According to FLÜGEL & HUBMANN (2000), it can be subdivided into four members.

The **Rauchenberg Member** forms the stratigraphic lowest part of the Schönberg Formation. In general, it is composed of phyllite with variable contents of graphite, chlorite and carbonate. Graphite rich types are grey to dark grey, graphitic sericite phyllite or even graphite phyllite. The latter are sometimes carbonate free and contain centimetre to a few decimetre thick layers of brownish metasandstone. Increasing carbonate content causes layers of carbonate phyllite and impure marble, also mostly with a dark grey colour and a fine-grained texture. Without graphite the sericite phyllite is yellowish grey, silvery shiny. In carbonate rich types, millimetre sized calcite crystals occur locally, which cause pitted weathering surfaces. More chlorite rich chlorite-sericite phyllite shows a greenish grey colour. Sometimes the chlorite is concentrated in patches aligned in the schistosity. These types are referred to as „Fleckengrünschiefer" in the older German literature and are interpreted as tuff or tuffite (e.g. FLÜGEL, 1975). All rock types may contain up to millimetre sized pyrite. During weathering, the pyrite is transformed into rusty-brown, porous patches, which consist of iron hydroxides and carbonate. In general, the mica rich rocks are incompetent and break up thinly into small pieces, whereas at higher carbonate contents, the rocks are layered and break blocky or into slabs that are centimetres to a few decimetres in size.

Until now, no type section is defined for the Rauchenberg Member. However, according to the maps and profiles in WEBER (1990), a stratigraphic succession can be defined. In the main lower part, graphitic sericite phyllite, sericite phyllite and chlorite-sericite phyllite are intercalated with thicknesses of several tens of

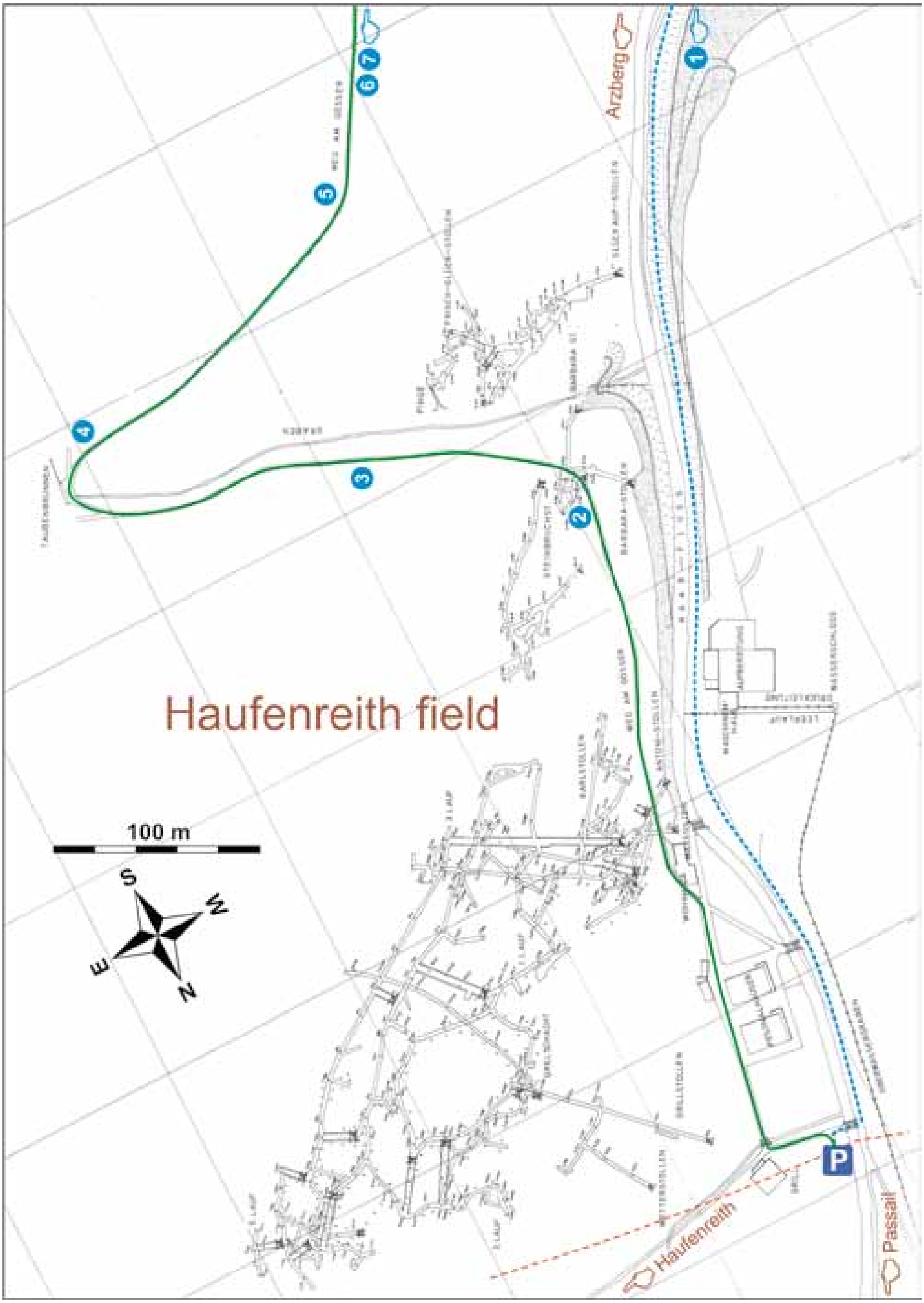

Figure 10: Extract from the mine map of the Haufenreith mine from the archive of the Berghauptmannschaft Graz (WEBER, 1990). Numbers in blue circles indicate stops along the trail of the "Montanlehrpfad Arzberg" described in the text. Coordinates of the parking space are E 15.526595/N 47.262973.

meters, with thinner layers of calcareous phyllite and marble in between. The uppermost tens of meters are formed by graphite schist with some metasandstone intercalations.

The **Rabenstein Member** (FLÜGEL & HUBMANN, 2000) or Poys Member (EBNER et al., 2017) respectively, forms a characteristic marble layer within the Rauchenberg Member. It is well exposed between the villages Großstübing and Rabenstein. Up to 50 m in thickness, it can be followed over several kilometres, even if it is interrupted in several places. As it is massive and more competent than the surrounding rocks, it is visible in the topography and was recognised by the old miners, who called it "Kalkrippe". It is more coarse-grained than the usual marble layers and represents an Echinoderm rubble limestone (TSCHELAUT, 1985).

The **Kreuzwirt Member** develops from the upper part of the Rauchenberg Member. Towards the hanging wall, more and more dark grey marble layers are incorporated into the graphite phyllite, until the graphite-phyllite layers have almost completely disappeared.

The type locality of the **Weizbauer Member** is east of Mount Hochschlag (1580 m) in the Gasen nappe and it represents the whole Schönberg Formation of this nappe. The main lithologies are thin-layer breaking, dark grey graphite phyllite, graphitic sericite phyllite with some intercalations of greyish marble, calcschist and quartzite as well as some greenish, more chlorite rich phyllite.

4.3. Description of stops along the trail of the "Montanlehrpfad Arzberg"

Stop B1: Sericite-chlorite phyllite with marble layers of the Rauchenberg Member
Location: E 15.52033/N 47.25332 (8)

Close to the road, a short exploration adit within silvery-greyish phyllite with intercalated layers of dark grey marble is visible (Fig. 11A, 11B). Weathered surfaces exhibit a brownish color. The schistosity is gently dipping towards SE. Especially in mica rich layers a crenulation with NE dipping fold axes is visible. The phyllite is mainly composed of sericite, chlorite and quartz with variable contents of calcite and graphite.

Stop B2: Impure marble with layers of sericite-chlorite phyllite of the Rauchenberg Member
Location: E 15.52610/N 47.25989 (17)

The walls of the little quarry are composed of impure marble and carbonatic sericite phyllite. As before, the schistosity is dipping towards SE and folded by dipping fold axes.

Stop B3: Chlorite-sericite phyllite of the Rauchenberg Member
Location: E 15.52728/N 47.25939 (17)

In the outcrop, grey and greenish-grey phyllite with sericite and chlorite is visible. In some layers, chlorite rich patches with a greenish colour appear in the schistosity. The rock breaks in small pieces along the schistosity and shear planes that are oriented at a slight angle. The planes are gently dipping towards NNW and are slightly folded by NNW plunging fold axes. The axial planes dip steeply towards the WNW (Fig. 11C).

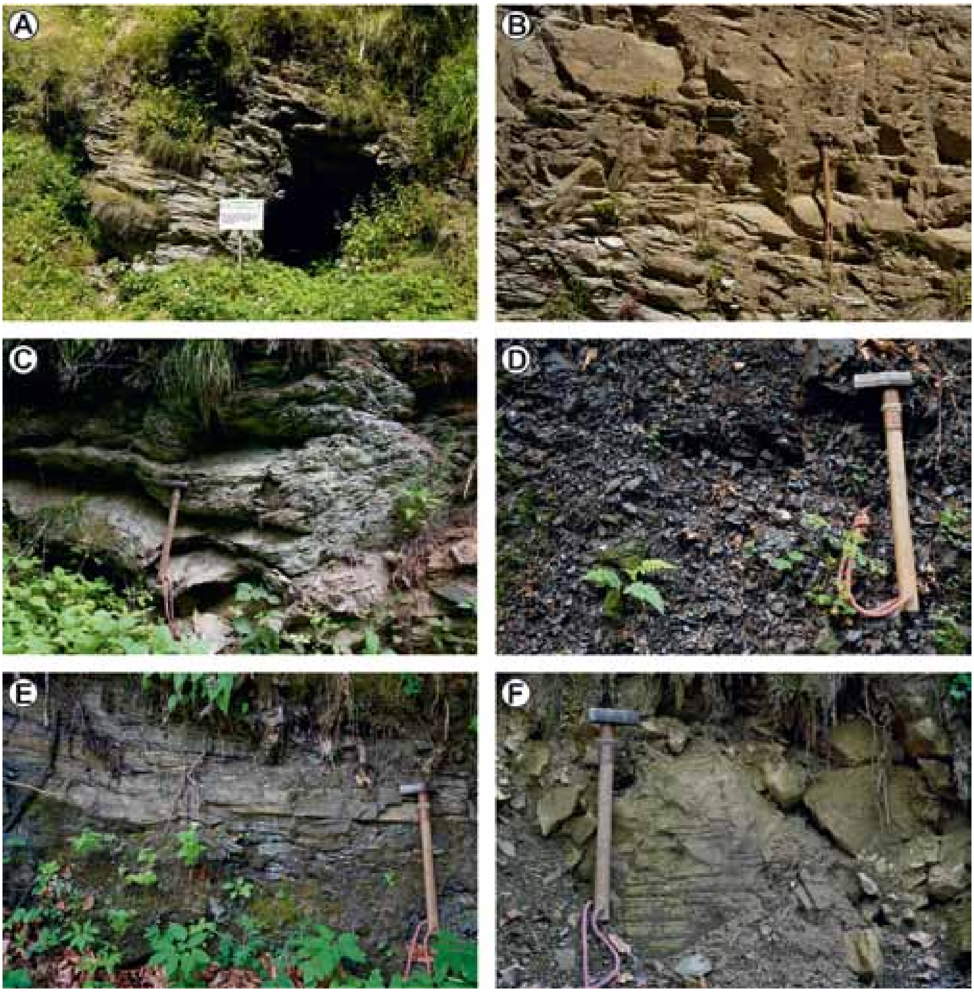

Figure 11: Field photographs of outcrops along the trail of the "Montanlehrpfad Arzberg". A) Stop B1 with view to the North-West, B) Stop B1 with view to the North-West, C) Stop B3 with view to the North, D) Stop B4 with view to the North, E) Stop B5 with view to the East and F) Stop B6 with view to the East. Description see text.

Stop B4: Graphite-phyllite of the Rauchenberg Member
Location: E 15.52844/N 47.25876 (21)

Small outcrops of finely fractured, black graphite phyllite can be seen on the slopes on both sides of the path (Fig. 11D). On the schistosity planes, a fine crenulation is visible. Only very rarely rusty-brown areas of iron hydroxides are visible on the surfaces, indicating a low pyrite content. Compared to the other lithologies, the rock is generally free of carbonate with only occasionally showing carbonate contents. Layers of brownish quartz-rich metasandstone up to a few decimetres are intercalated.

Stop B5: Graphite-sericite phyllite with marble layers of the Kreuzwirt Member
Location: E 15.52538/N 47.25719

Along the path finely fractured black graphite phyllite with more competent layers of dark grey calcschist and marble are visible (Fig. 11E). Towards the hanging wall, the proportion of carbonate rocks increases rapidly. The rocks are gently dipping towards SE.

Stop B6: Marble of the Schöckel Formation
Location: E 15.52417/N 47.25640 (22)

From the bend in the path, the slope contains outcrops of marbles with a layering in the range of a few centimetres to decimetres (Fig. 11F). Interlayers of graphite phyllite are almost absent. The marbles weather light grey, show a grey coloration and a fine-grained recrystallised structure at fresh fractures.

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