Structural control of the Banská Hodruša ore deposit (Štiavnica Stratovolcano)

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Abstract: The Banská Hodruša deposit is located in the central zone of the Štiavnica Stratovolcano of Miocene age. The mineralisation is placed in the low-angle normal fault zone with the dip direction of 125° and generally flat dip (5–30°). This zone was formed at the lithological boundary between the Miocene granodiorite pluton and hanging wall units consisting of fragments of sediments (mainly limestones) and the pre-caldera stage andesites further up in the sequence. The mineralisation consists of stockwork and individual veins of various dips (10–90°) in the low-angle normal fault zone with very strict geometric characteristics, which are conform to the geometry of the shear zone.

Introduction

Neogene volcanism and back-arc related extension is the important area of epithermal deposits of low (intermediate)-sulphidation types in the Carpathian arc. Banská Štiavnica and Kremnica are the most famous mining regions in Slovakia of such type of ore mineralization (cf. Lexa 2005). The studied epithermal precious/base metal mineralization occurs within the Štiavnica–Hodruša ore district in the central zone of the large Štiavnica Stratovolcano of Miocene age.

Mineralogy and geochemistry of the mineralization was recently described in the paper of Kubač et al. (2018). The mineralisation controls were poorly understood yet; however, the study presented in this paper, revealed several unique characteristics. Main goal of the study was to describe geometrical characteristics, structural controls, and tectonic evolution of the Au±Ag, Pb, Zn, Cu epithermal mineralisation in the central zone of the Štiavnica Stratovolcano.

Geological setting

The studied area is located in the central zone of the middle to upper Miocene Štiavnica Stratovolcano in the internal portion of the Western Carpathians. The Štiavnica Stratovolcano has markedly developed an extensive caldera (some 20 km in diameter), a late stage resurgent horst in the caldera centre and an extensive complex of subvolcanic intrusions. The structure of the Štiavnica Stratovolcano can be roughly divided into pre-caldera stage, caldera stage, and post-caldera stage (Konečný et al. 1995).

The deposit is located between Hodruša–Hámre and Banská Štiavnica municipalities in the middle of the central zone of the stratovolcano. The gold mineralization is known to occur between the 10th and 19th levels of the Rozália Mine in ~160–300 m a.s.l. The mineralization is hosted mainly by intensively altered pyroxenic andesites of the pre-caldera stage and rarely by thin, relatively older quartz-diorite porphyry sills. The thickness of the mineralized zone is typically tens of metres. The deposit has a tabular shape and is gently dipping (5–30°) south-eastward. The epithermal mineralisation is hosted in intensive stockwork with veinlets from several centimetres to metres wide. The mineralised zone is disrupted/dismembered by a post-mineral set of quartz-diorite porphyry sills.

Both, the mineralization and the quartz-diorite porphyry sills were later disrupted by late steeply dipping strike-slip to normal faults, base metal veins and subparallel structures (Kodĕra et al. 2005, 2014; Kubač et al. 2018).

Methods

Faults and striae on the fault surfaces are very often present in rock masses and therefore kinematic and dynamic analyses of fault-slip data is very popular tool for reconstruction of the palaeostress fields. Slickenside lineations are formed on fault planes during the motion of the two walls. These lineations are measured in the field so as to provide information on the direction of fault movement. Standard procedures for brittle fault-slip analysis and palaeostress reconstruction are now well established (Angelier 1990, 1994; Michael 1984).

The standard runtime techniques provide a determination of four parameters of the reduced stress tensor. The software applications utilize an inversion method which is based on the assumption of Bott (1959) that slip on a plane occurs in the direction of the maximum resolved shear stress. Fault data were inverted to obtain the four parameters of the reduced stress tensor: σ_1 (maximum principal stress axis), σ_2 (intermediate principal stress axis), and σ_3 (least principal stress axis) and the ratio (Φ) of principal stress differences is expressed by the formula $\Phi=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ (e.g., Angelier 1994).

Results

The structural analysis was carried out predominantly in the eastern sector of the Rozália Mine. A heterogeneous population of fault-slips was collected and separated into homogeneous fault-slip groups using the inversion method.

Structurally, the youngest deformational stage was controlled by extensional tectonic regime with the orientation of the principal tension axis in WNW–ESE direction. During this stage NE–SW normal faults were formed with moderate inclination predominantly in SE. These faults are related to the late extensional event in the Štiavnica area.

Based on cross-cutting criteria, a strike-slip tectonic regime with NNE–SSW dextral strike-slip faults and ENE–WSW sinistral strike slip faults were identified as older than the aforementioned normal faults and σ_1 operated in the NE–SW direction while σ_3 in the NW–SE direction. It is assumed that this deformation was responsible for initial stage of the Štiavnica type dislocations.

The most distinct structure hosting Au±Ag, Pb, Zn, Cu mineralisation at the Rozalia Mine is the low-angle normal fault zone. The zone is characterised by normal faulting with the NE–SW strike of fault planes and complex structures in between the fault zone. As described above, this zone has well developed internal structure. Tension gashes, predominantly oriented in the NNE–SSW direction with moderate dip to the ESE are filled by the Krištof type veins. To the contrary a gentle dipping releasing bends predominantly at the roof are filled by the Agnesa type veins, having the same age as the Krištof type veins. These veins are typically shallow dipping (less than 30°) with the dip direction SE-wards (cf. Kubač et al. 2018).

Most probably, the slightly older kinematics is responsible for the formation of the Karolína stockwork (The Central Stockwork), which was controlled by a NNW–SSE oriented σ_3. It is important to note that this deformation was observed only along the Karolína zone and has practically the same deformation as the low-angle normal fault zone. However, the general strike of the zone is in the WNW–ESE direction. This zone represents the initial phase of Au±Ag, Pb, Zn, Cu mineralisation on the low-angle normal fault zone and understanding of its structural evolution is crucial for the discovery of additional ore bodies within this zone.

The pre-low-angle normal fault deformational stage is controlled by extensional tectonic regime with the orientation of σ_3 axis in a NE–SW direction. During this stage, the NW–SE normal faults were activated with moderate to steep dip on both sides. These faults are considered to be related to pre-granodiorite intrusion phase, because these faults were not observed in the granodiorite pluton yet.

Probably the oldest known deformation is represented by NW–SE dextral strike-slip faults. This homogeneous fault set is weak and some additional information is still missing.

Interpretation and discussion

Geological model of the studied area is based mainly on structural measurements with respect to the mineralisation in the central zone of the Štiavnica Stratovolcano.

During the Early Badenian, a large andesite stratovolcano was formed also known as “the pre-caldera stage”. The Štiavnica Stratovolcano has multistage evolution and the formation of the large andesite stratovolcano was followed by denudation and emplacement of granodiorite pluton (Lexa et al. 1999). The granodiorite intrusion was accompanied by disseminated base metal mineralization and intensive advanced argillic alteration inoverlying complex of andesites.

Subsequent uplift of the granodiorite intrusion caused evolution of the sector collapse related low-angle normal fault zone, which was newly identified during our research. A Central Stockwork at the deposit originated in the early stage of the exhumation process. Geometrically, the stockwork can be characterized as an E–W and ESE–WNW structures with the 40–60° inclination to the south. Typically, the stockwork is composed of a quartz–carbonate gangue rich in Mn-bearing minerals, base metal sulphides, gold, and Ag-tellurides (Kubač et al. 2018). The stockwork has trishear geometry with typical upside down triangular shape with the base of triangle at the subhorizontal roof of the low-angle normal fault shear zone. This structure is interpreted as a result of southward movement of the hanging wall in the low-angle normal fault shear zone. The inclination of the fault zone in an deeper part is less than 30° southward with the slickenside lineations at azimuth of 170° and can be characterized as the low-angle normal fault. It is important to note, the initial stage with randomly-oriented hydrothermal cracks indicate that differences between principal palaeostress axes were relatively small. Randomly directed veinlets were later replaced by slightly younger the NE–SW directed veinlets inside the Central Stockwork trishear zone in the central area.

Exhumation of the granodiorite intrusion caused unroofing, which was carried out by evolution of the low-angle normal fault shear zone. This shear zone is located at the boundary between the Miocene granodiorite and andesite of the lower stratovolcanic structure. In general, low-angle normal fault zone (dip <30°) accommodate much extension of the continental crust and such faults are common in areas of high extensional strain (e.g., Axen 1990). They apparently move under low resolved shear stress and are anomalously weak. Mechanical analysis shows that fault weakening may preclude equality of the regional and fault zone stress tensors, and predicts reorientation and increase of principal stresses in weak fault zones. These changes suppress hydraulic fracturing, which were firstly identified by Nemčok et al. (2000) in the brittle detachment zone and allow slip under frictional sliding conditions typical of upper crustal rocks (Axen, 1992). The low-angle normal fault is weak, partly or totally due to elevated pore fluid pressure. The zone is related to exhumation of the granodiorite pluton and related sector collapse during the pre-caldera stage of the Štiavnica Stratovolcano. The low-angle normal fault zone has complex internal structure with evolution of R and R' Riedel's shears, tension gashes, restraining bends, releasing bends etc. According to recent structural data, these structures correspond to the well-developed low-angle normal fault zone. All these structures have uniform kinematics characterized by hanging wall general displacement vector ESE-wards as it is evidenced by the slickenside lineation on faults. The fluids responsible for Au–Ag mineralization used the extensional internal structures during the unroofing of hanging wall andesite complex.

The Krištof type veins are hosted predominantly by the NNE–SSW striking tension gashes with moderate dip to the ESE. The vein system typically contains stockworks of thin veins or occurs as individual veinlets. The thickness of individual veins is usually 4–40 cm in average, rarely up to 200 cm. Quartz is the dominant gangue mineral accompanied by native gold and infrequent base metal sulphides and carbonates in predominantly banded structures.

The Agnesa-type veins, typically shallow dipping (dip <30°) with dip direction ESE-ward, are usually located in the roof of the low-angle normal fault zone. High pore pressure in such zones may be contained by upper plate strata with mineral precipitation in their hanging walls (Axen 1992). This is also the case of the Agnesa-type of veins. Structurally, the veins were formed in shallow dipping releasing bends in the roof of low-angle normal fault zone or in the local extensional structures in the middle of the zone. The formation of the veins is associated with the normal movement of the hanging wall during continual exhumation of the granodiorite pluton. It is represented by several individual veins with up to 3 m thickness, predominantly rich in base metals accompanied by gold. Quartz is the main gangue mineral in this vein type and carbonates are very rare (Kubač et al. 2018).

The final stage of the granodiorite exhumation is accompanied by emplacement of quartz-diorite porphyry in and around of the low-angle normal fault zone in andesites of the pre-caldera stage of the Štiavnica Stratovolcano evolution. The Au±Ag, Pb, Zn, Cu mineralisation was dismembered by this set of quartz-diorite porphyry sills, which were emplaced along the contact zone of the granodiorite pluton and along individual faults of the low-angle normal fault zone. Generally, the quartz-diorite porphyry sills post-date the Au ± Ag, Pb, Zn, Cu mineralisation in this zone. However, there is at least one older type of quartz–diorite porphyry, which is mineralized by the Au ± Ag, Pb, Zn, Cu veins and it is also affected by brecciation, irregular fracturing, mylonitization or by pervasive alteration, which are features typical for mineralized andesites (Koděra et al. 2005).

Conclusions

Identification of the low-angle normal fault zone is the main new discovery that has remained unrecognized until recently. The studied Au±Ag, Pb, Zn, Cu Banská Hodruša deposit was developed in the pre-caldera stage units of the Štiavnica Stratovolcano and exhibits structures for syntectonic epithermal deposits including structural association with polyphase faulting related to exhumation of the granodiorite intrusion.

The E–W striking Central Stockwork has trishear geometry with a typical triangular shape with the base of triangle at the subhorizontal roof of the low-angle normal fault zone. This structure is interpreted as a result of southward movement of the hanging wall in the earliest stage of shear zone formation. Veinlets forming the stockwork were later disrupted by younger NE–SW oriented epithermal veinlets inside the trishear zone, which are arranged in the formed low-angle normal fault zone. The zone has general dip direction in 120° with the inclination from 5–30°

The low-angle normal fault zone produced generally two types of vein systems: *(i)* The Agnesa-type veins are typically shallow dipping (less than 30°) with dip direction ESE-wards. Structurally, the veins were formed in releasing bends in the roof of the low-angle normal fault zone. *(ii)* The Krištof-type veins, having the same age as the Agnesa-type veins, are hosted predominantly by the NNE–SSW oriented tension gashes with moderate dip to the ESE.

The precious/base metal mineralisation is disrupted by quartz–diorite porphyry sills, which were emplaced mostly parallel to the low-angle normal fault zone, hence the quartz-diorite porphyry sills generally post-date the mineralisation in this zone. However, at least one older type of quartz–diorite porphyry predates the Au±Ag, Pb, Zn, Cu mineralisation.

The quartz-diorite porphyries together with the precious metal mineralization were later displaced by normal faults and epithermal vein mineralization of the Štiavnica type.

Understanding the kinematics and spatial distribution of the low-angle normal fault zone is crucial for future exploration due to its significant economic potential to host high grade Au±Ag, Pb, Zn, Cu mineralization in the central part of the Štiavnica Stratovolcano.

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