In the central thrust sheets of the Inner Magura Flysch, the magnetic fabric is relatively strongly affected by ductile deformation represented by a combination of simple shear and lateral shortening, probably associated with creation and motion of the thrust sheets driven by a push from the rear side. The ductile deformation is generally stronger in the frontal areas of the individual thrust sheets than in their central areas.

The Krosno lithofacies, mostly occurring in the Outer Krosno-Menilite Flysch, represents the youngest synorogenic flysch sediments largely terminating the last depositional history in the Flysch Belt, embracing the interval from the Late Oligocene to Early Miocene. The deposition of this flysch lithofacies replaced the euxinic sedimentation of underlying Menilite Formation. This change in deposition was connected with Neoalpine orogenetic movements during the Oligocene, which evoked the fundamental re-arrangement of the orogenic belt. In terms of plate tectonics, this re-arrangement represents the stage of closing subduction and starting collision.

Fluid Inclusion, Stable Isotope and Geochronologic Evidence of Cretaceous Collision-Related Formation of Hydrothermal Veins in the Gemeric Basement (Western Carpathians)

Vratislav HURAI[1], Raymond MONTIGNY[2], Ondrej LEXA[3], Karel SCHULMANN[2], Marián URBAN[1], Patrik KONECNÝ[4] and Martin CHOVAN[1]

[1] Department of Mineralogy and Petrology, Comenius University, Mlynská dolina G, 842 15 Bratislava, Slovak Republic
[2] Université Louis Pasteur, UMR CNRS 7516-17, 1 Rue Blessig, Strasbourg, France
[3] Institute of Petrology and Structural Geology, Charles University, Albertov 6, 12843, Praha, Czech Republic
[4] Geological Survey of Slovak Republic, 817 04 Bratislava, Slovak Republic

Palaeozoic basement of the Gemeric tectonic unit contains around 1300 siderite-sulphide and quartz-stibnite veins oriented parallel with regional cleavage structure. Origin of the veins has been widely discussed since introduction of modern geochronology methods. Granitic source of ore elements and Cretaceous age of the Gemeric hydrothermal deposits was proposed by Varček (1957). Magmatogenic models invoked Variscan granitoids (Ilavský et al. 1977) or deep mafic intrusions of Cretaceous-Eocene age (Rozložník 1989) as the main sources of ore elements. Metamorphogenic models favoured mobilization of the ore elements during Variscan (Grecula 1982) or Alpine (Varček 1985) tectono-metamorphic processes.

Žák et al. (1991) and Grecula et al. (1995) proposed a metamorphic-hydrothermal model, according to which precipitation of the Gemeric hydrothermal veins was induced by mixing of Variscan metamorphic fluids with evaporite-leaching meteoric waters within Permian rifts. High bromine concentrations in the ore-forming fluids (Hurai et al. 2002) ruled out the presence of evaporite-leaching meteoric water, which was replaced by residual, halite-fractionated seawater infiltrating the Palaeozoic basement from the periodically swamped and evaporated Permian rift/graben in the last versions of the metamorphic-hydrothermal model (e.g. Radvanec et al. 2004, Grecula and Radvanec 2005).

Available stable isotope and fluid inclusion data from the Gemeric hydrothermal veins (Hurai et al. 2002, Urban et al. 2006) are controversial with the concept of rift-related metamorphic-hydrothermal origin. Recalculations based on new fluid inclusion and stable isotope data define formation temperature of 177 to 217 °C, paleodepth of 6.0 ± 0.3 km, and thermal gradient of 33.5 ± 5.5 °C/km for the siderite stage of the Droždiak vein in the northern part of the Gemeric unit. The temperatures of 227–263 °C, paleodepth of 11.2 ± 0.6 km, and thermal gradients of 22 ± 3°C/km have been obtained from the siderite veins in the Rožňava ore field of the southern Gemeric unit. Uniform character of primary fluid inclusions in siderite, i.e. $NaCl-CaCl_2-H_2O$ brines with salinities between 18–25 wt.% NaCl equivalents, and oxygen isotope composition of the parental fluid positively correlated with the metamorphic grade of country rocks (from 5 ‰ in low-grade Permian to 11 ‰ in medium-grade Lower Palaeozoic rocks) are reminiscent of a closed, rock-buffered fluid system. The normal-to-low thermal gradients and paleodepths substantially exceeding available thicknesses of overburden during Permian-Triassic times rule out opening of the vein structures during the extensional tectonic regime incidental with rifting.

Sulphide stage of the Gemeric hydrothermal veins exhibits highly variable fluid compositions, ranging from high salinity (max. 35 wt.%) $NaCl-CaCl_2-H_2O$, CO_2-poor brines to CO_2-dominated aqueous fluids with signs of heterogeneous trapping. The contrasting fluid compositions indicate an open-system fluid behaviour. In the Cucma stibnite deposit of the southern Gemeric unit located near Roznava town, the carbonic fluid is extremely dense (up to 1.197 g/cm3) and admixture of minor CH_4 and N_2 is typical. Fluid inclusion trapping *PT* parameters in the Klement vein of the Cucma deposit correspond to 183–237°C, and 1.6–3.5 kbars, possibly up to 4.5 kbars. The *PT* conditions point to a 15–18 km thick overburden and low thermal gradients, corresponding to only 12–13 °C/km (Urban et al. 2006). These parameters are controversial with the partially molten hot continental crust, and up to 7 km thick overburden at the base of the south-Gemeric basement during the Permian-Triassic rifting. Composition of the gaseous mixture is typical of an externally derived metamorphic fluid, and high-salinity aqueous component probably represents basinal brine modified by cationic exchange reactions with crustal rocks.

U-Pb-Th age of monazite from quartz-tourmaline-white mica assemblage from the Cucma deposit revealed Early and Upper Cretaceous mineral-forming events culminating at 120±9 and 76±12 Ma. The first event is coincidental with thrusting of the Gemeric unit over the adjacent Veporic basement and the formation of the Alpine cleavage structure of the Gemeric basement. The second event corresponds to transpressive shearing and the formation of major trans-Gemeric shear zone.

Geometry of the Gemeric hydrothermal veins together with fluid inclusions, stable isotopes, K-Ar and U-Pb-Th dating support the model of vein opening at gradually increasing thickness of the overriding nappe piles, attaining ~4–5 and 6–7 km during crystallization of early siderite in the northern and the southern Gemeric basements, respectively. A 8–10 km thickness of the overthrusted nappe units must be expected in the south-Gemeric basement to explain high fluid pressures during precipitation of quartz-tourmaline-(white mica-phosphate) assemblage of the quartz-stibnite veins near Roznava (Urban et al. 2006).

K-Ar and U-Pb-Th dating shows short veining interval compared to the age span of the Gemeric cleavage fan formation. The fact that most veins are subparallel to the cleavage indicates Pfluid > T + σn (Pfluid – fluid pressure, T – tensional strength of rock, σn - plane-perpendicular stress; Cosgrove 1997). The opening of tensile fracture parallel to the main anistropy (i.e. Cretaceous cleavage) can be explained in terms of low differential stress (σ1 – σ3), corresponding to small difference between horizontal tectonic stress and vertical overburden pressure, and large difference between tensional strengths (Tp – Tn, where Tp is parallel to main anisotropy, and Tn perpendicular to it). Cosgrove (1997) showed that the tensional failure occurs parallel to main anisotropy in direction perpendicular to the main compressive stress, if (Tp – Tn) > (σ1 – σ3). Therefore, the veining event in the Gemeric unit might have occurred within a narrow time interval at specific stress conditions marked by building of high overburden pressure (vertical load due to thrusting) and strong horizontal stress (horizontal push related to the formation of the Gemeric cleavage fan).

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References

COSGROVE J.W., 1997. Hydraulic fractures and their implications regarding the state of stress in a sedimentary sequence during burial. In: S. SENGUPTA (Editor), Evolution of geological structures in micro- and macro-scales. Chapman and Hall, London, pp. 11-25.

GRECULA P., 1982. The Gemericum – segment of Palaeotethynian riftogeneous basin. *Mineralia Slov – Monograph*, Bratislava (in Slovak).

GRECULA P., ABONYI A., ABONYIOVÁ M., ANTAŠ J., BARTALSKÝ B., BARTALSKÝ J., DIANIŠKA I., DRNZÍK E., ĎUĎA R., GARGULÁK M., GAZDAČKO Ľ., HUDÁČEK J., KOBULSKÝ J., LÖRINCZ L., MACKO J., NÁVESŇÁK D., NÉMETH Z., NOVOTNÝ L., RADVANEC M., ROJKOVIČ I., ROZLOŽNÍK L., ROZLOŽNÍK O., VARČEK C. and ZLOCHA J., 1995. Mineral deposits of the Slovak Ore Mountains. Mineralia Slov – Monograph, Bratislava.

GRECULA P. and RADVANEC M., 2005. Age of siderite-sulphide mineralization of the Gemericum: Variscan or Alpine? *Mineralia Slov.*, 37: 343-345. (in Slovak)

HURAI V., HARČOVÁ E., HURAIOVÁ M., OZDÍN D., PROCHASKA W. and WIEGEROVÁ V., 2002. Origin of siderite veins in the Western Carpathians I. P-T-X-δ^{13}C-δ^{18}O relations in ore-forming brines of the Rudňany deposits. *Ore Geol. Rev.*, 21: 67-101.

ILAVSKÝ J., MALKOVSKÝ M. and ODEHNAL L., 1977. The iron ore deposits of the Czechoslovak socialist republic. In: A. ZITZMANN (Editor) The iron ore deposits of Europe and adjacent areas. Explanatory notes to the Internaltional map of the iron ore deposits of Europe 1:2 500 000, vol. 1. Bundesanstalt f. Geowiss. und Rohstoffe, Hannover, pp. 111-124.

RADVANEC M., GRECULA P. and ŽÁK K., 2004. Siderite mineralization of the Gemericum superunit (Western Carpathians, Slovakia): review and a revised genetic model. *Ore Geol. Rev.*, 24: 267-298.

ROZLOŽNÍK L., 1989. Problems of age and source of the siderite formation of the Western Carpathians. *Geol. Pruzkum*, 31: 67-72.

URBAN M., THOMAS R., HURAI V., KONEČNÝ P. and CHOVAN M., 2006. Superdense CO_2 inclusions in Cretaceous quartz-stibnite veins hosted in low-grade Variscan basement of the Western Carpathians, Slovakia. *Mineral. Deposita*, DOI 10.1007/s00126-005-0042-6

VARČEK C., 1957. Overview of paragenetic relationships in ore deposits of the Gemericum. *Geol. Práce – Zošit*, 46: 107-131. (in Slovak)

VARČEK C., 1985. Metalogenetic characteristics of the Spišsko-gemerské rudohorie Mountains and the position of the Rudňany ore field. In: B. CAMBEL and J. JARKOVSKÝ (Editors), The Rudňany Ore Field – Geochemical and Metallogenetic Characteristics. Veda, Bratislava, pp. 61-77. (in Slovak)

ŽÁK K., RADVANEC M., GRECULA P. and BARTALSKÝ B., 1991. Sr, S, C, O-isotopes and metamorphic-hydrothermal model of vein mineralisation in the Gemericum. *Mineralia Slov.*, 23: 95-108. (in Slovak).