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Geotectonic and metallogenetic evolution of Gemericum (Inner Western Carpathians) from Ordovician to Jurassic

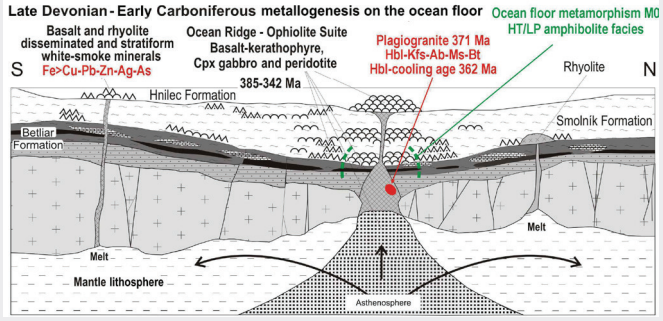
MARTIN RADVANEC and PAVOL GRECULA

State Geological Institute of Dionýz Štúr, Mlynská dolina 1, SK-817 04 Bratislava, Slovakia;
martin.radvanec@geology.sk

Abstract: The Early Paleozoic evolution of Gemericum is connected with opening a riftogeneous basin. The evolution of the pre-rift stage was bound to an active (Gondwana) continental margin in Cambrian to Ordovician times. The first phases of continental rifting represent the megacycles of the sedimentary basin fill with bimodal volcanism of inferred Devonian age. During the last phases of rifting in the middle part of the rift a mid-oceanic ridge has developed, being accompanied with the first metamorphic recrystallization M0 (LP/HT amphibolite facies), producing new oceanic-type crust, recently representing a part of Rakovec (Zlatník) and Klátov ophiolitic complexes (LP/HT amphibolite facies). The massive effusions and extrusions have provided ages ca 410-380 Ma. The Early Paleozoic complexes were deformed in the Early Carboniferous, when also subduction-accretionary wedge metamorphism M1a (pumpellyite-actinolite facies) has occurred. Part of the mid-oceanic ridge complexes and their associated sediments were subducted northward, but the rest underwent obduction, forming an accretionary wedge. This process transported most of the Early Paleozoic basin fill over the northern continental plate in the form of nappes. Subduction ceased in the Late Carboniferous, being accompanied by further plate convergence and formation of mélange-related conglomerates. In Permian period, the late-Variscan post-collision collapse and uplift of the asthenosphere have increased the thermal gradient beneath the overlying plate. The Permian high thermal gradient brought about regional metamorphism associated with anatectic melting, causing formation and emplacement of granite during the late Variscan metamorphic phase M1b (amphibolite facies), coinciding with the beginning of origin of Fe-carbonate mineralization. During Permian, previous subduction processes culminated in the formation of an island arc associated with rhyolitic volcanism and granite intrusions. Late compressional and extensional Variscan tectonic processes completed the Variscan nappe structure of the Gemericum and marked the transition to the extensional phase, associated with the origin of Alpine sedimentary basins. In Jurassic, Gemericum was exposed to a compressional deformation. The structural pattern was a result of the rebound of the lithospheric mantle and asthenosphere after their loading by subducted material in the Permian. At the beginning, reverse movement of the asthenosphere exhumed blocks of metamorphic rocks of the high-pressure, low-temperature blueschist facies (M2), followed towards the end by the uplift of high-pressure metaperidotites from the great depths of minimum 50 km and embedded into unmetamorphosed sediments of Permian-Mesozoic units.
Paper provides summary of metallogenetic processes related to each evolutionary phase.

Key words: geotectonic model, metallogenetic model, Paleozoic, Gemericum, Western Carpathians

Graphical abstract



Highlights

- Paper provides a unique model of continual Early Paleozoic-Mesozoic subduction of the Paleo-Tethys from the south of Gemericum under north located units of Western Carpathians
- Metallogenetic products are summarized for all phases of geodynamic evolution with great emphasis on metamorphic model of fluids generation

Introduction

The Gemericum during its Variscan evolution has underwent several events, being recorded in Gemeric Paleozoic sedimentary and magmatic complexes, several subsequent tectonic deformation and metamorphic events, as well as different genetic types of mineralization, being for the first time summarized by Grecula and Radvanec (2005a) in geotectonic model of continual Ordovician-Jurassic evolution. This model took into account also the previous works by Grecula (1982), as well as Radvanec (1998), Grecula (1998), Grecula et al. (1995), Kobulský

(2001), Grecula and Radvanec (in Kobulský, 2001), as well as Németh (2002). Field works related to exploration and verification of mineral deposits have confirmed a new lithostratigraphic division of the Early Paleozoic rocks and represented a starting point for defining the sequence of sedimentary, magmatic and tectonic events, as well as related general geotectonic interpretation of paleotectonic evolution of Gemericum (Grecula, 1982; Grecula et al., 1995).

This study is based on detail geological mapping of the whole area of Gemericum, construction of new geological map, detail lithological knowledge of Paleozoic sequences, as well as their metamorphic and tectonic overprint (Grecula et al., 2009). Above stated genetic model we make complete by geochronological data (Putis et al., 2009; Radvanec, et al., 2009 and 2010).

Metallogenetic evolution of Gemericum is closely tied with geotectonic evolution of this unit (Grecula et al., 1995). The oldest stratabound sulphidic mineralization is bound on Early Paleozoic oceanic rift zone with bimodal basalt-keratophyre volcanism (Radvanec and Bartalský, 1987, 1988; Radvanec and Grecula, 1985; Radvanec et al., 1993; Grecula et al., 1995). The younger Variscan metallogenetic events are closely related to metamorphic overprint (Fe-, Mn-, Mg-carbonatic and sulphidic mineralization) and anatectic melting (S-type of granite, Sn, Mo, W, B and Li mineralization) within the Late Carboniferous-Late Permian period (Radvanec, 1987; Radvanec et al., 1990; Grecula et al., 1991; Bartalský and Radvanec, 1993; Grecula et al., 1995; Žák et al., 1991; Íro and Radvanec, 1997; Radvanec et al., 2004, Grecula and Radvanec, 2005b; Žák et al., 2005; Jiang et al., 2008; Radvanec et al., 2010). The Permian U-Mo-REE mineralization is tied with a volcanic equivalent of S-type granite (Grecula et al., 1995). Mineralizations of the platinum group elements (PGM), Sc, Cd and **V** occur in metapyroxenite, prehnite-pyroxenite (metalamprophyre), rodingite and serpentinite, being exhumed with blueschists in Jurassic time (Radvanec and Uher, 2016; Radvanec, 2005).

The Early Paleozoic evolutionary riftogeneous phases from the Late Ordovician to Early Carboniferous

The Early Paleozoic evolution of Gemericum we interpret by the model of Late Ordovician-Early Carboniferous riftogenesis of a part of Paleotethys. The sedimentary area was described in details by Grecula (1982), as well as Grecula et al. (1995, 2009 and 2011), which geotectonic evolution (Grecula, 1973; Grecula and Radvanec, 2005a) has started with rift, developing on continental plate in the northern part of Gondwana. The Ordovician pre-rift phase is dated by zircon ages in the range 482-458 Ma, obtained from volcanic rocks of rhyolite and dacite composition, as well as clinopyroxene (Cpx) gabbro in all partial Variscan nappes of Gemericum (Putiš et al., 2009; Grecula et al., 2009 and 2011). In localities Ostrá, Babiná, Šajby and Dobšinský potok in the northern zone of Gemericum and in localities Lastovičí vrch and Zadné Porče in the southern Gemericum, the gabbro encompasses the magmatic diopside (large up to 2.5 cm), Mg-chromite, Sr-epidote and albite, as well as other minerals. Sr-epidote and albite originated by the decomposition of former Sr-plagioclase during following post-Ordovician polymetamorphism (Radvanec, 1999). Cpx-gabbro has the lower crust geochemical characteristics (Fig. 1).

The beginning of the rapid riftogenesis – the second rifting phase - in the Early Paleozoic sequences of Gemericum is indicated by Silurian, resp. Late Silurian-Early Devonian sporomorphs, acritarchs and radiolarians from the upper part of the lower Gemeric lithostratigraphic unit - the Holec Beds. This period represents advanced stage of riftogenesis with formation of anoxic basins with lydites and black pelites and first manifestations of volcanic activity of bimodal basalt-keratophyre volcanism mainly in their overlier (Grecula et al., 2009 and 2011). These volcanic effusions are accompanied with the origin of stratabound sulphidic mineralization of the Smolník type with prevailing Fe>> over Cu>Zn (pyrite prevails over chalcopyrite and sphalerite). In keratophyre the Ba + Mo + Sn association was found (Radvanec and Bartalský, 1987; Radvanec and Grecula, 1985; Radvanec et al., 1993; Grecula et al., 1995). The second riftogenous phase of Late Silurian-Early Devonian age with typical sedimentary facies is interpreted like the first geotectonic-sedimentary megacycle of the Gemeric complex producing the lithology of Betliar Formation, Holec Beds with limestones and Smolník Formation (Grecula et al., 2009 and 2011, Fig. 2).

The main rifting phase (Fig. 3) has continued in the Late Devonian to Early Carboniferous at first with bimodal volcanism and later finished with basalt volcanism (Grecula et al., 2009 and 2011). These geotectonic events have produced distinct segmentation of the sedimentary basin with very variegated facial evolution of clastic sediments (Smolník Formation), characterizing the paleogeographic conditions of their origin and position in the sedimentary space of the rift developing on continental crust. The rocks sequences belonging to these facies are so distinct that can be reliable areally limited and together with further lithologies to be attributed into individual lithostratigraphic and tectonic units. Third main rifting phase has bordered the axial part of the basin. Its beginning was in the Late Silurian or the Early Devonian (Fig. 2). The period between the 1st and 2nd rifting phases would encompass the period of Early to Middle Devonian.

The beginning of the 3rd rifting phase (Fig. 3) is represented with the upper bimodal volcanic complex consisting of the basalt and rhyolite effusions. This volcanic activity was accompanied with stratabound sulphidic

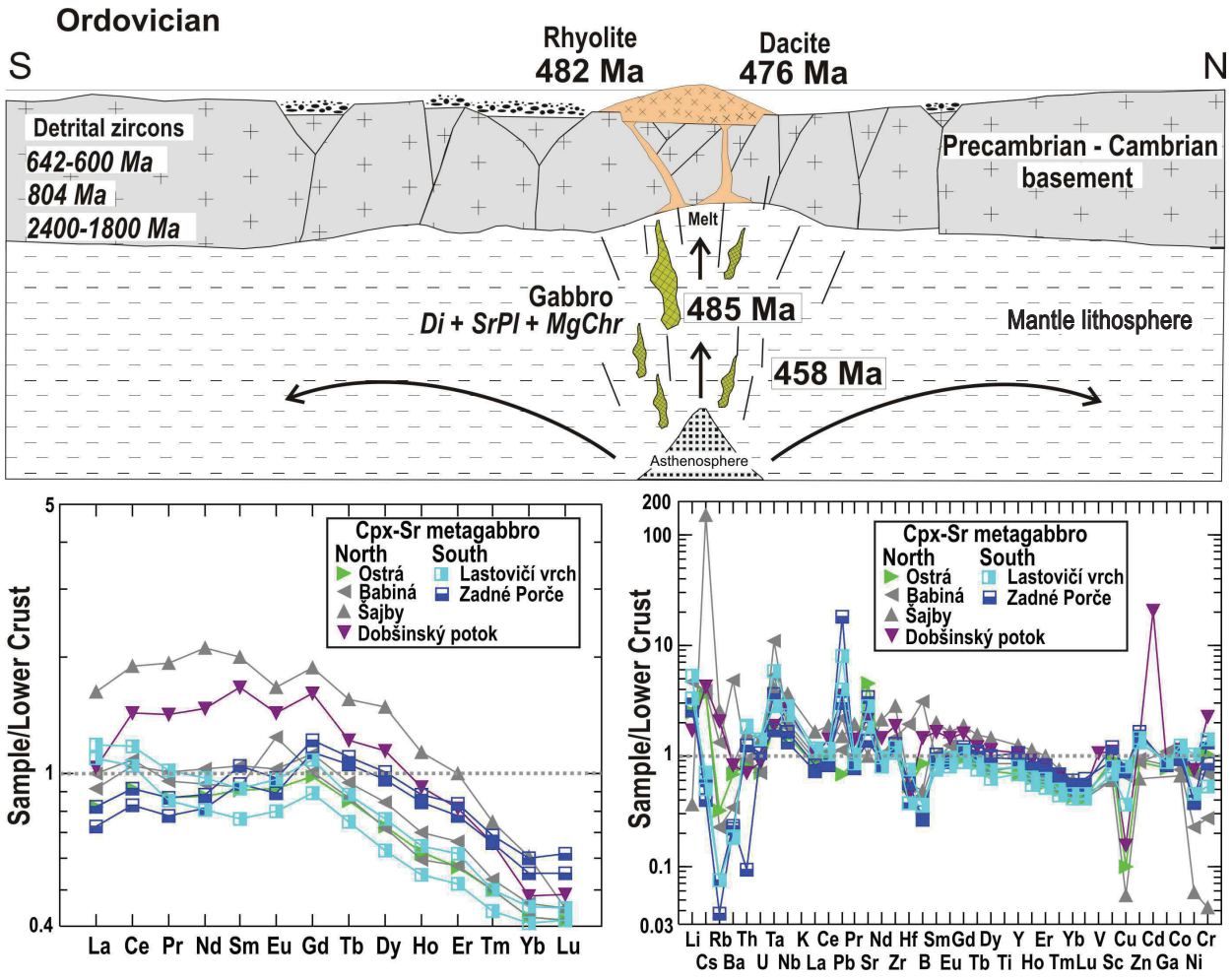


Fig. 1. Model of geotectonic and lithological evolution of the Paleo-Gemeric complex in Ordovician and the whole-rock chemical analyses of Cpx–gabbro with original Sr plagioclase normalized on lower crust contents. Localities of tectonic blocks of Cpx-gabbro with original Sr plagioclase in the northern and southern zones of Gemericum. Di – diopside, SrPl – Sr plagioclase, MgChr – Mg chromite. Numbers state the zircon ages in Ma.

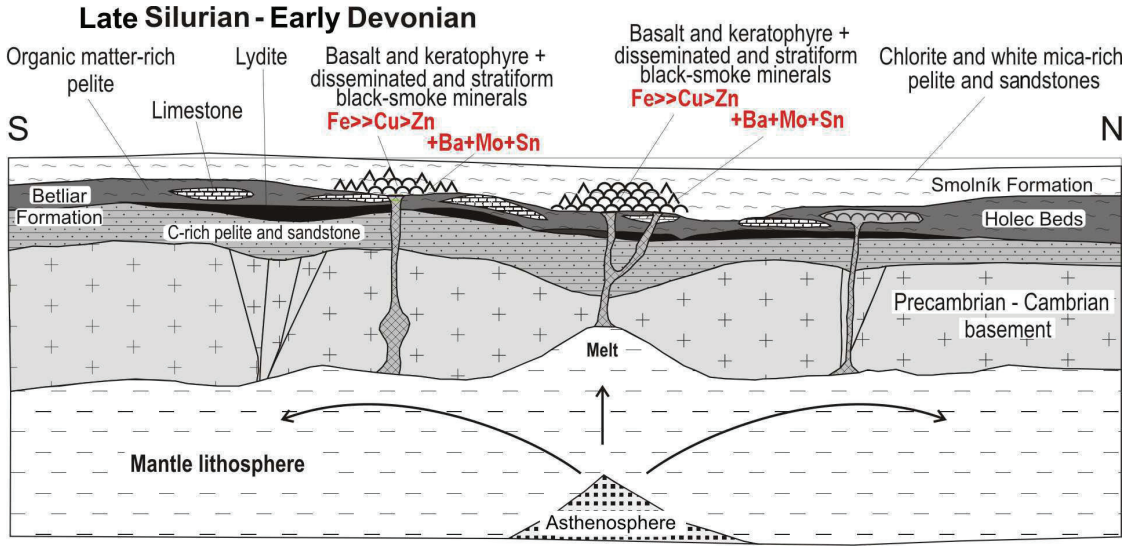


Fig. 2. Model of the Late Silurian-Early Devonian geotectonic and lithological evolution of Gemericum.

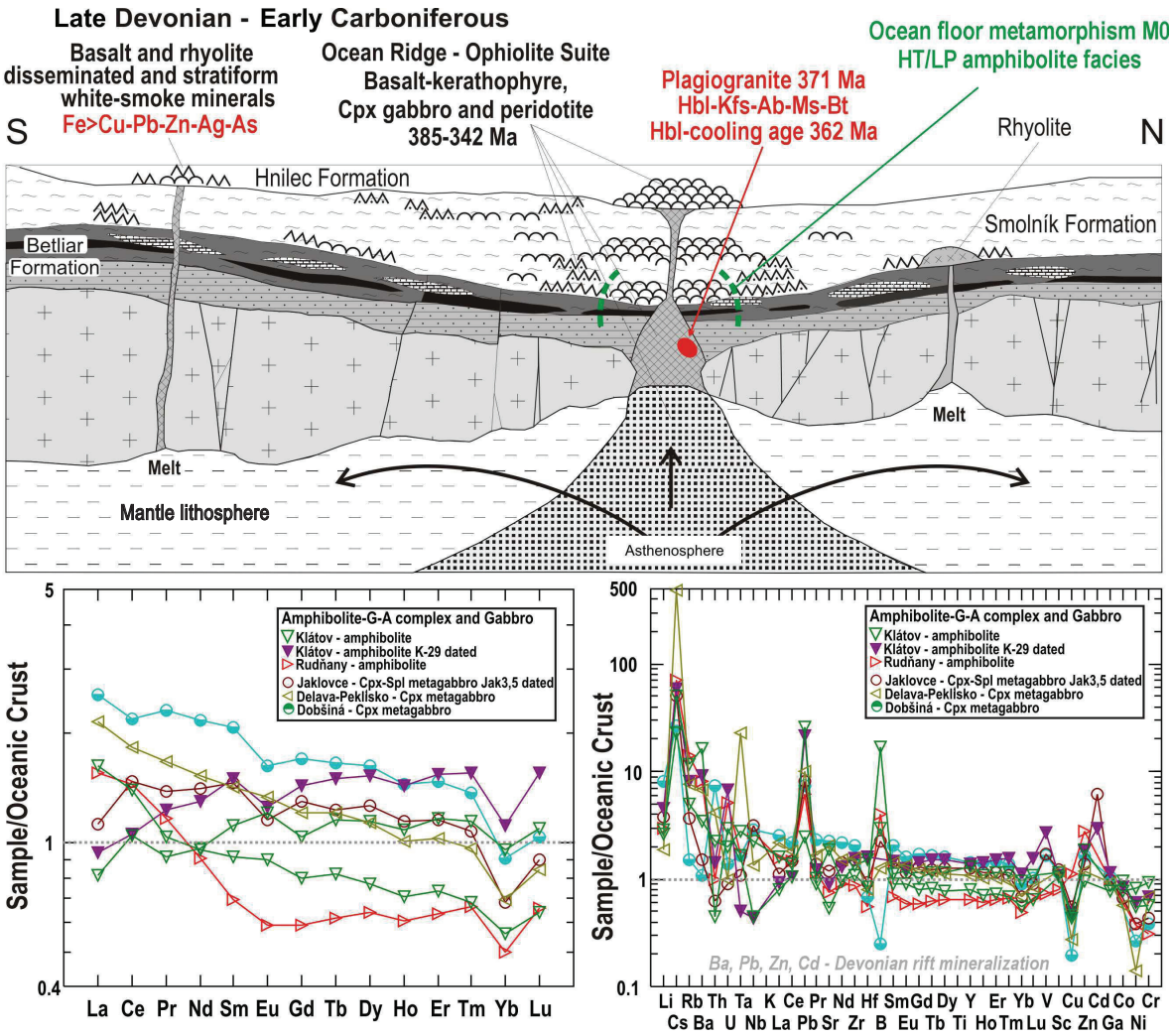


Fig. 3. Model of the Late Devonian to Early Carboniferous geotectonic and lithological evolution of Gemericum. The main phase of the origin of ophiolite suite, plagiogranite and the ocean floor metamorphism M0. Normalization of the whole-rock analyses on oceanic crust.

mineralization of the Mníšek nad Hnilcom type with prevailing Fe over Cu-Zn-Pb-Zn-Ag and As contents, pyrite above chalcopyrite, galenite and sphalerite (Grecula et al., 1995). In the central part of the rift the mid-oceanic ridge has originated with gradually widening oceanic crust with the origin of rocks of the present day Rakovec complex (nappe, Grecula et al., 2009 and 2011). In the area of the mantle asthenosphere uprise the rock complexes of the mid-oceanic ridge have been metamorphosed to amphibolites and gneisses. This metamorphism of oceanic crust is characterized by a high temperature and low pressure conditions and related HT/LP metamorphism M0. In the rift area the plagiogranite has originated, being composed of hornblende, K-feldspar, albite, muscovite and biotite. According to Rb-Sr isochrone from these minerals, the plagiogranite age is 371 ± 4 Ma and cooling of hornblende has an age of 362 Ma. These ages are in good agreement with the zircon ages from the gneiss-amphibolite complex in the range 385-342 Ma (Putiš et al., 2009). The main Late Devonian-Early Carboniferous rifting phase is represented with a complete ophiolite suite: serpentinites/metaperidotites, Cpx-gabbros with plagioclase and chromite and the gneiss-amphibolite complex in localities Dobšiná, Delava, Rudňany, Jaklovce, Strážny vrch and Klátov in the northern, but also southern Gemericum (serpentinite, the Strážny vrch locality). The rocks of ophiolite suite manifest in all known localities the tectonic contact with their surrounding rocks. The normalization of chemical composition of samples from the amphibolite complex and metagabbros of ophiolite suite is in good agreement with the oceanic crust (Fig. 3). The serpentinites from Klátov and Strážny vrch localities manifest a komatiite composition. In further parts of the basin on continental crust the clastic sedimentation with local rhyolite volcanism has continued. The 3rd rifting phase has completed the paleogeography of the Early Paleozoic sedimentary area, and

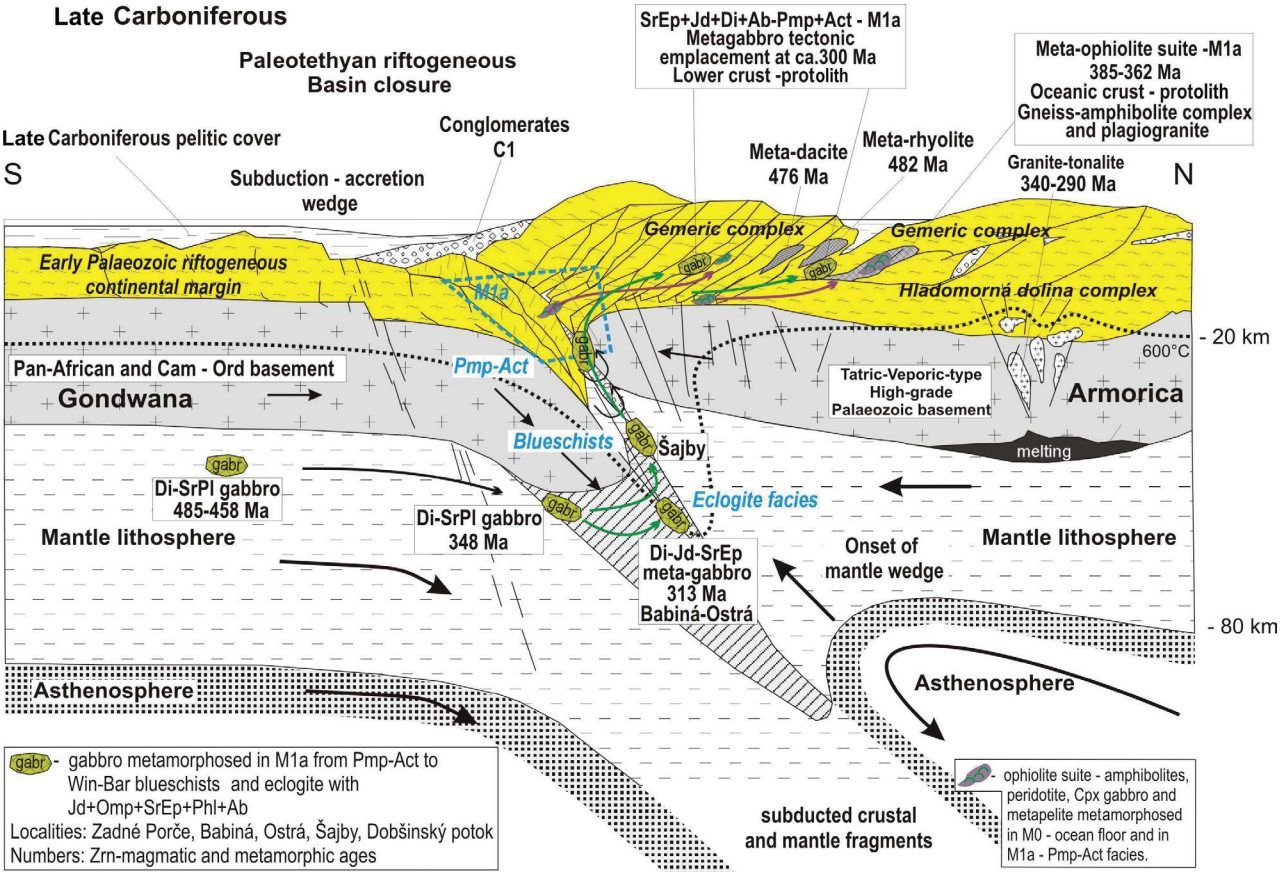


Fig. 4. Model of geotectonic and lithological evolution and obduction of Gemeric complex in the Late Carboniferous. Exhumation and emplacement of tectonic blocks of Cpx gabbros with Di – diopside, Jd - jadeite, SrEp – Sr epidote, Ab – albite, Pmp – pumpellyite, Act – actinolite, Omp – omphacite, Phl – biotite (protolith, lower crust) and position of tectonic blocks of metaophiolite suite (protolith, oceanic crust). M1a – pumpellyite-actinolite facies. Win-Bar – winchite-barroisite - blueschists facies. Jd+Pmp+SrEp+Phl+Ab – boundary of eclogite facies. Conglomerates C1- coarse-clastic conglomerates, Early Carboniferous.

by this way also characteristic facial developments of the uppermost lithostratigraphic unit – the Hnilec Formation – as well as the Early Paleozoic evolutionary phase (Grecula et al., 2009 and 2011).

Late Paleozoic phase of convergent Variscan events

The following phase of Variscan cycle has probable started in the Devonian/Carboniferous boundary period. The paleontologically proved Late Viséan sediments were deposited on folded and metamorphosed Early Paleozoic footwall. In the Early to Middle Carboniferous a new deformation phase in the Early Paleozoic complexes started, encompassing the beginning of **subduction processes**. In this period an accretion basin has originated with sedimentation of coarse clastic material derived from the Early Paleozoic rock sequences prevailingly of oceanic ridge, but also granites-tonalites (Radvanec, 1998). Part of these coarse clastic complexes (e.g. the Rudňany conglomerates) was dragged to subduction channel together with further rocks (Fig. 4). The shortening of the sedimentary space has continued in the Late Carboniferous by obduction and formation of Variscan nappes.

The majority of rocks from the mid-oceanic ridge (ophiolite suite) as well as surrounding sediments were obducted. By this way the accretion prism complexes were thrust on the northern continental plate (Fig. 4). Seven Variscan nappes were distinguished from the south northward: Medzev, Jedľovec, Humel, Prakovce, Mníšek, Kojšov and Rakovec nappes (Grecula, 1982; Grecula et al., 2009 and 2011). Characteristic pumpellyite-actinolite metamorphic facies of this compression/obduction phase and starting subduction is designated as M1a. For the ophiolite suite rocks, being metamorphosed by the M0 metamorphism in the oceanic crust (HT/LP – amphibolite and epidote-amphibolite facies), the M1a metamorphism represents the retrogression and compression metamorphism, similarly as for the Cpx gabbros exhumed from the lower crust (in localities Babiná, Ostrá, Šajby, Dobšinský potok, Lastovičí vrch and Zadné Porče) with jadeite – omphacite – Sr epidote – albite assemblage, being in the Late Carboniferous (313 Ma) exhumed from the depth of eclo-

gite facies on 600 ºC isograd (Babiná, Ostrá) resp. from the blueschists zone (Šajby) to M1a – pumpellyite-actinolite facies metamorphism (Radvanec, 1999 and 2000).

In the Late Carboniferous (Fig. 4) there starts a subduction, as well as convergence of the Gondwana and Armorica plates. The asthenospheric uprise in the footwall of active plate has continued. In the subduction channel a part of earlier subducted material has returned back to surface, including the Rudňany conglomerates (Radvanec, 1998) as well as exhuming tectonic blocks of Cpx-Sr metagabbros from the lower crust (Radvanec, 1999). The uplift of asthenosphere beneath the active plate caused an increase of the temperature. It is supposed that the 600 °C isograde in this stage has reached the upper part of the continental crust and has corresponded to conditions of the gradient of continental orogenic belt, i.e. the regional (orogenic) metamorphism. In Veporic complexes in this isograde there originated the anatectic melt, resp. granite-tonalite melt with revealed ages of 340-290 Ma, being subsequently emplaced in the Veporic rock sequence (Fig. 4).

In Permian and Triassic, the Variscan subduction processes have produced the origin of island arc rhyolite, andesite and basalt volcanism and granite magmatism (Fig. 5). There originated the anatectic granites of S-type with Sn-W-Mo-B-Li-F-As mineralization in their immediate surrounding. In the surrounding of Permian volcanoes, close to the surface, or on the surface, the U-Mo-REE mineralization and gypsum/anhydrite deposits have developed (Grecula et al., 1995). In the area of geothermal gradient along the hot lines, the medium-pressure metamorphic events in epidote-amphibolite or amphibolite facies (M1b) have occurred. Numerous tectonic blocks of Cpx gabbros with Sr epidote, blocks of ophiolite suite, Ear-

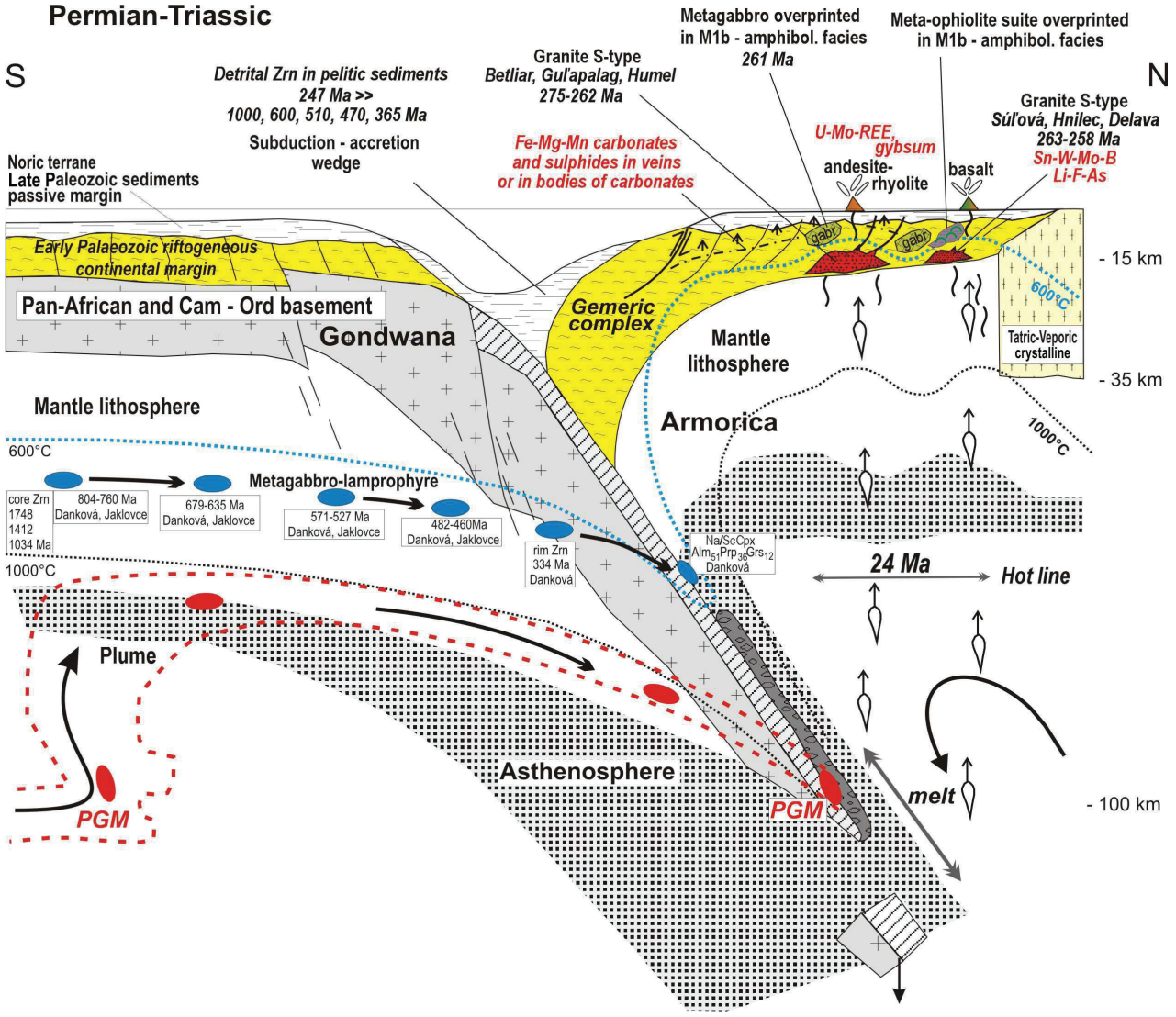


Fig. 5. Model of geotectonic, metallogenetic and lithological evolution in Permian and Triassic. Numbers show the zircon ages. PGM - platinum group minerals.

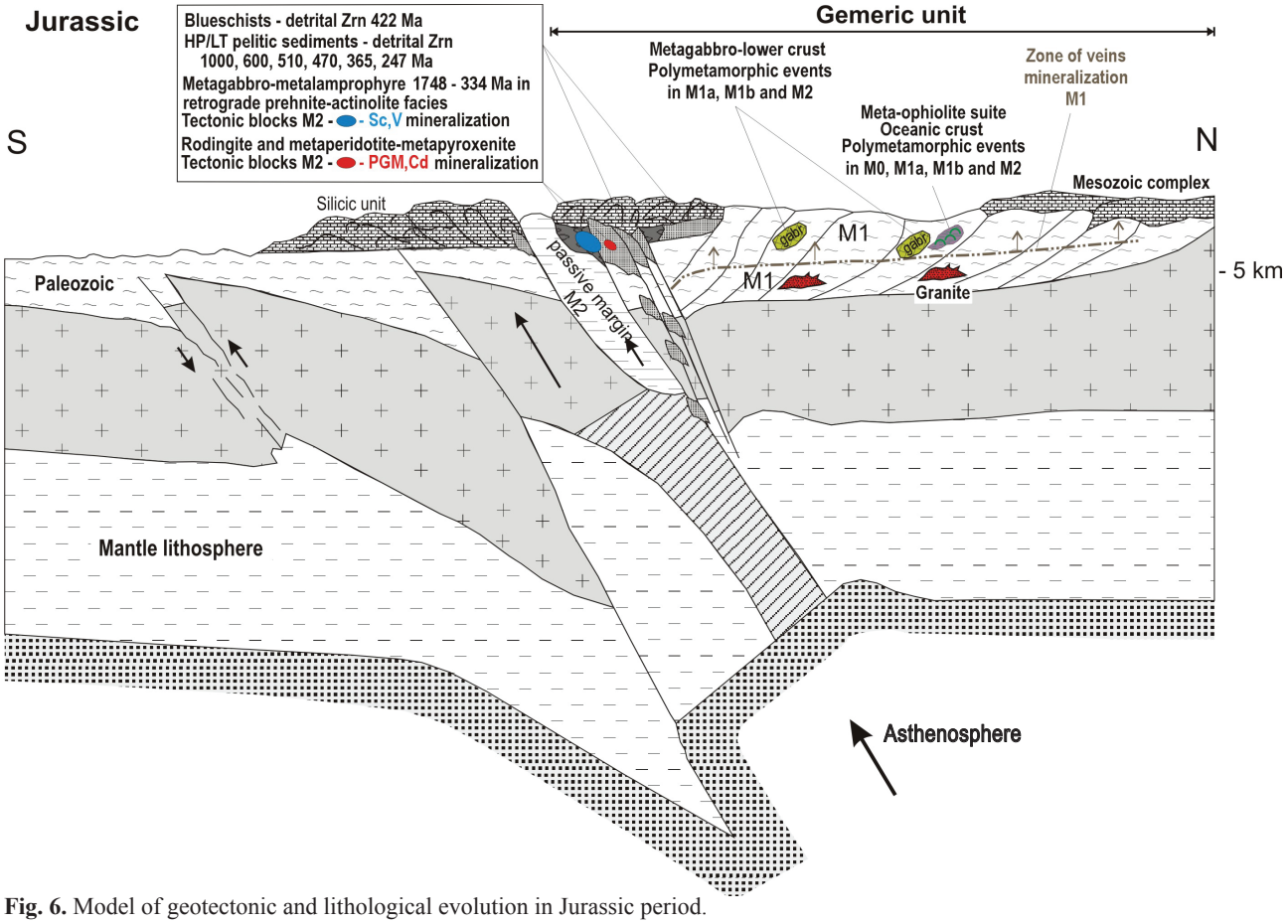


Fig. 6. Model of geotectonic and lithological evolution in Jurassic period.
PGM - platinum group minerals.

ly Paleozoic rhyolites and dacites were in closeness of the hot line again metamorphosed in the epidote-amphibolite facies or in amphibolite facies (M1b). Despite, the relics of older pumpellyite-actinolite facies (M1a), resp. the ocean floor metamorphism M0 have often preserved. The hot lines are characteristic for the island arc metamorphism. In Permian, the main mineralization processes took part there, including the deliberation of fluids prevailingly from the Early Paleozoic rocks (variegated volcanic complex, Holec Beds) and their penetration into extensional tectonic fractures in the cooling zones. There originated prevailingly the siderite-sulphidic vein mineralization, as well as there occurred conditions for the Fe and Mg metasomatism (siderite-ankerite and magnesite bodies) on calcite-limestone protolith, as well as metamorphic overprint of sedimentary and exhalation-sedimentary mineralization in Early Paleozoic formations of the lower and upper ore bearing horizons (Radvanec, 1987; Radvanec et al., 1990; Grecula et al., 1991; Bartalský and Radvanec, 1993; Grecula et al., 1995; Žák et al., 1991; Íro and Radvanec, 1997; Radvanec et al., 2004; Grecula and Radvanec, 2005b; Žák et al., 2005; Jiang Shao-Yong et al., 2006; Radvanec et al., 2010).

In the following period in the area of Permian accretion prism the accretion basin has formed with the sedimentation of the coarse-clastic material (Permian conglomerates), pelites and psammites (Grecula et al., 2009 and 2011). In Triassic, the pelitic sediments in the same continual accretion prism were characterized by the high ratio of quartz and hematite with radiolarites – deep marine trench sediments. At the village of Jaklovce these sedi- ments contain prevailingly detrital zircon with the Early Triassic magmatic age of 247 Ma (Putiš et al., 2011), but also some recycled older zircons of the age 1000-365 Ma (Fig. 5). In the Permian-Triassic lithospheric mantle, on isograde of 600 °C, the metagabbro-metalamprophyre in locality Danková has registered conditions of the eclogite facies with the origin of garnet ($Alm_{51}Prp_{36}Grs_{12}$) and Cr-REE tawmawite (epidote-eclogite facies) from the contact of subducted plate in the depth around 50 km (Radvanec et al., 2009). The age of zircons in this rock in localities Danková and Jaklovce varies from 1748 to 334 Ma (unpublished data set). Various zircon generations have recorded all evolution phases of the Gemericum up to Permian (Fig. 5). In the asthenosphere until Permian-Triassic at high temperatures the platinum group metals (Pd,

Pt, Os, Ir) were transported towards the subducting plate (Radvanec and Uher, 2016).

Alpine geotectonic evolution

The terminating compression and extension of Variscan tectonic processes have finished the Variscan nappe setting of Gemericum and Veporicum, their mutual relations and the beginning of extensional period, connected with the formation of Alpine sedimentary areas of Meliaticum, Silicicum and the Triassic in the North-Gemeric zone (Fig. 6). The Jurassic setting of Gemericum was formed in compression regime (Grecula and Radvanec, 2001 in Kobulský et al., 2001). Such setting was conditioned by the reversal movement of lithospheric mantle, and mainly of asthenosphere after its loading by a large amount of subducted material in Permian. The reversal movement of asthenosphere at the beginning of exhumation in Jurassic, encompassing variegated tectonic blocks, has firstly pushed out the metamorphites of M2 HP/LT blueschists facies, glaucophanites, rodingites and at the end also metaperidotites-serpentinites, metalamprophyres, being the bearers of Sc, V, PGM and Cd mineralization from the eclogite facies depth levels. The mantle has squeezed the exhumed tectonic blocks of M2 metamorphites of various protolith by the reversal movement into the prevailingly non-metamorphosed environment of limestones and clastic sediments of Permian-Mesozoic units, originating in the overlier of Variscan accretion complex (and sediments of weakly metamorphosed passive continental margin from the Permian period). Jurassic exhumation phase, recorded by the crystallization of the youngest generation of phengite, was dated by the Ar/Ar and K/Ar method in exhumed blueschists with glaucophane (Dallmeyer et al., 1996; Faryad and Henjes-Kunst, 1997). The rocks of Silicicum are in the area of reversal exhumation of the subducted wedge in the nappe position to Paleozoic basement of Gemericum. In the North-Gemeric zone the Mesozoic complexes of the same age are in autochthonous position and their gradual transition to underlying Permian rocks can be observed (Grecula et al., 2009 and 2011).

In the Late Jurassic, but mainly Early Cretaceous, the tectonic arrangement of the rock complexes of Gemericum, i.e. of the products of metamorphic events M0, M1a, M1b and M2 to approximately recent position has terminated.

Conclusion

The recent tectonic setting of Gemericum has originated by the displacements on shear zones in the late-Variscan period. The ocean floor metamorphites M0 were preserved as tectonic blocks of the gneiss-amphibolite complex mainly on the north of Gemericum. Metamorphism M1a in the pumpellyite-actinolite facies from the Late Carboniferous was overprinted by the M1b amphibolite facies peak of heat flow at the Late Permian island arc metamorphism. The formation of the Fe-Mn-Mg carbonate and sulphidic vein and stratabound (metasomatic) mineralization, related to M1b metamorphism, has terminated in this period, too.

The presence of exhumed "high-pressure" metamorphosed exotic blocks in the metamorphosed Late Carboniferous of the mélange type confirm an unique interpretation of the closure of Paleotethys basin in European Variscides. We do not exclude also the later local penetration of individual blocks of metamorphic rocks prevailingly into the Permian-Triassic sequences. This later exhumation process was of one-shot type and tightly bound on Jurassic reversal movement of the mantle. This process has terminated the exhumation of the high-pressure metamorphic blocks.

At the end of Jurassic or after Jurassic the M2 metamorphism has obtained regional character related to completion of tectonic "rearrangement" of Gemericum. In the post-Jurassic period the M2 metamorphism has reached conditions at the boundary of the middle-pressure greenschists facies. This metamorphism was caused by the final emplacement of the mantle (its upper boundary) beneath the Gemericum, when the isotherm 500 °C becomes stabilized in the depth of 15-20 km, which corresponds to temperature gradient 25 °C/km of Alpine metamorphism.

The regional character of the M2 metamorphism probable has terminated as late as in the Early Cretaceous. It represented the rejuvenation "Alpine metamorphism M2", in which the rocks of Gemericum in compression regime were metamorphosed again in the middle-pressure (4-5 kbar) greenschists facies conditions. In the older mineral assemblage from the metamorphism M1a and M1b the regional metamorphism M2 was found only locally in shear zones, because the older mineral assemblages of M1a and M1b metamorphism were stable in regional process M2. The metamorphism M2 in Gemericum did not overreach the boundary of the greenschists facies. Metamorphism M2 locally rejuvenated also the vein and stratabound mineralization, because it acted in compressional regime, but the "ore-bearing fluids" have generated only sporadically and without more significant mineralization effects.

It is probable that in Jurassic the mantle beneath Gemericum acquired the recent position, as indicated by the magnetotelluric model (Pawliszynowa, 1978, in Grecula et al., 1995) as well as gravimetric and seismic models (Bezák et al., 1997; Šefara et al., 1996). The shape of lithospheric mantle and asthenosphere beneath Gemericum, as well as metamorphic events of the vein and stratabound mineralization in the last phase of the evolution of Gemericum in Jurassic is schematically visualized in Fig. 6. The configuration of the mantle in the figure, derived from

gravimetric and seismic models has formed owing to the existence of subduction slab from Variscan era, dipping to N. The shape of the mantle in Jurassic-Cretaceous period has initiated the subsequent reversal uplift and exhumation of subducted high-pressure metamorphic rocks and their emplacement into accretion complex.

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Geotektonický a metalogenetický vývoj gemerika od ordoviku po juru

Gemerikum vo vývojovej aj deformačnej etape variskej éry zaznamenalo niekoľko významných udalostí. Tie sa podľa záznamov v sedimentárnych a magmatických sekvenciách paleozoika, odlišností súborov tektonických deformácií, metamorfných udalostí v čase a odlišných genetických typov mineralizácie prvý raz zhodnotili v geotektonickom modeli vývoja gemerika ako spojitej udalosti od ordoviku po juru (Grecula a Radvanec, 2005a). Východiskové práce Greculu (1982), ako aj Radvanca (1998), Greculu (1998), Greculu et al. (1995), Kobulského (2001), Greculu a Radvanca (in Kobulský, 2004) a Németha (2002) boli podkladom tohto ordovicko-jurského modelu. Terénne technické práce pri hľadaní a overovaní ložísk nerastných surovín potvrdili litostratigrafické členenie staršieho paleozoika a boli východiskom pri stanovovaní sukcesie sedimentačných, magmatických a tektonických udalostí a tým aj pri celkovej geotektonickej interpretácii paleotektonického vývoja gemerika (Grecula, 1982; Grecula et al., 1995).

V tejto štúdii vychádzame z podrobného geologického mapovania celého gemerika, t. j. geologickej mapy, dôkladného litologického poznania paleozoických sekvencií, ako aj z ich metamorfného a tektonického prepracovania (Grecula et al., 2009). Uvedený genetický model dopĺňame o geochronologické údaje (Putiš et al., 2009; Radvanec et al., 2009 a 2010).

Metalogenetický vývoj gemerika je neoddeliteľne spojený s geotektonickým vývojom gemerika v čase a odvodený od neho (Grecula et al., 1995). Najstaršia stratiformná sulfidická mineralizácia je viazaná na staropaleozoický oceánsky rift s bimodálnym bazaltovo-keratofýrovým vulkanizmom (Radvanec a Bartalský, 1987, 1988; Radvanec a Grecula, 1985; Radvanec et al., 1993; Grecula et al., 1995) a mladšie, variské metalogenetické udalosti sú úzko späté s metamorfózou (Fe-, Mn- a Mg-karbonátová a sulfidická mineralizácia) a s anatektickým tavením (granit typu S, Sn, Mo, W, B a Li mineralizácia) v období od vrchného karbónu po vrchný perm (Radvanec, 1987; Radvanec et al., 1990; Grecula et al., 1991; Bartalský a Radvanec, 1993; Grecula et al., 1995; Žák et al., 1991; Íro a Radvanec, 1997; Radvanec et al., 2004; Grecula a Radvanec, 2005b; Žák et al., 2005; Jiang Shao-Yong et al., 2006; Radvanec et al., 2010). Na vulkanický ekvivalent granitu typu S sa viaže U-Mo-REE mineralizácia v perme (Grecu-

la et al., 1995). Mineralizácie platinovej skupiny (PGM), Sc, Cd a V sú viazané v metapyroxenite, prehnit-pyroxenite (metalamprofýre), rodingite a serpentinite, ktorý bol exhumovaný v jure spolu s modrými bridlicami (Radvanec a Uher, 2016; Radvanec, 2005).

Vývojové riftogénne etapy staršieho paleozoika od vrchného ordoviku po spodný karbón

Staropaleozoický vývoj gemerika pokladáme za riftogénny od vrchného ordoviku po spodný karbón ako súčasť Paleotetýdy. Sedimentačný priestor, ktorý podrobne opísali Grecula (1982 a 1995) a Grecula et al. (2009 a 2011) a ktorého geotektonickú pozíciu už tiež znázornili (Grecula, 1973; Grecula a Radvanec, 2005), sa najprv vyvíjal okolo tvoriaceho sa riftu na kontinentálnej platni. Tou bol severný okraj Gondwany. Predriftové štádium v ordoviku je datované zirkónmi v rozsahu od 482 do 458 mil. rokov a charakterizuje ho ryolit, dacit a klinopyroxenické (Cpx) gabro vo všetkých čiastkových variských príkrovoch gemerika (Putiš et al., 2009; Grecula et al., 2009 a 2011). Na lokalitách Ostrá, Babiná, Šajby a Dobšinský potok na severe gemerika a na lokalitách Lastovičí vrch a Zadné Porče na juhu gemerika gabro obsahuje magmatický diopsid (do 2,5 cm), Mg-chromit, Sr-epidot, albit a i. Sr-epidot a albit vznikli z rozpadu pôvodného Sr-plagioklasu v procese následnej poordovickej polymetamorfózy (Radvanec, 1999 a 2000). Cpx gabro má geochemické charakteristiky spodnej kôry (obr. 1).

Počiatok rapídnej riftogenézy – druhá etapa riftingu – v staršom paleozoiku gemerika na základe údajov o nálezoch sporomorf, akritárch a rádiolárií z vrchnej časti spodnej litostratigrafickej jednotky gemerika – holeckých vrstiev – indikuje silúrsky alebo vrchnosilúrsky až spodnodevónsky vek. Toto obdobie znamená pokročilejšiu riftogenézu s tvorbou anoxických panví, so vznikom lyditov a čiernych pelitov (holecké vrstvy) a s prvými prejavmi vulkanickej činnosti hlavne v ich nadloží v podobe výlevov vulkanických produktov s bimodálnym bazaltovo-keratofýrovým zložením (Grecula et al., 2009 a 2011). Tieto vulkanické výlevy sprevádzal vznik stratiformnej sulfidickej mineralizácie typu Smolník, kde prevláda Fe >> nad Cu > a Zn (pyrit nad chalkopyritom a sfaleritom) a v keratofýre sa zistila asociácia Ba + Mo + Sn (Radvanec a Bartalský, 1987, 1988; Radvanec a Grecula, 1985; Radvanec et al., 1993; Grecula et al., 1995). Druhé obdobie riftogenézy od vrchného silúru po spodný devón s typickými sedimentárnymi fáciami sa považuje za prvý geotektonicko-sedimentačný megacyklus gemerického komplexu so vznikom betliarskej formácie, holeckých vrstiev s vápencami a smolníckeho súvrstvia (Grecula et al., 2009 a 2011; obr. 2).

Hlavná etapa riftingu (obr. 3) pokračovala vo vrchnom devóne až do spodného karbónu najprv bimodálnym vulkanizmom a v závere bazaltovým vulkanizmom (Grecula et al., 2009 a 2011). Tieto geotektonické udalosti spôsobili výrazné členenie sedimentačného priestoru s veľmi pestrým faciálnym vývojom klastických sedimentov (smolnícke súvrstvie), ktoré charakterizujú paleogeografické podmienky vzniku a ich pozíciu v sedimentačnom priestore riftu na kontinentálnej kôre. Horninové súbory patriace k týmto fáciám sú také charakteristické, že ich možno spoľahlivo priestorovo vymedziť a spolu s ostatnými horninami zaradiť aj do samostatných litostratigrafických a tektonických jednotiek. Tretia hlavná etapa riftingu už ohraničila osovú časť panvy. Jej začiatok bol vo vrchnom silúre alebo až v spodnom devóne (obr. 2) a obdobie medzi 1. a 2. riftingom by mohlo zaberať spodný a stredný devón.

Začiatok tretej etapy riftingu (obr. 3) reprezentuje vrchný bimodálny vulkanický komplex v podobe výlevu bazaltu a ryolitu. Túto vulkanickú aktivitu sprevádza stratiformná sulfidická mineralizácia typu Mníšek nad Hnilcom, kde prevláda Fe nad Cu, Zn, Pb, Zn, Ag a As a pyrit nad chalkopyritom, galenitom a sfaleritom (Grecula et al., 1995). V centrálnej časti riftu vznikol stredooceánsky chrbát s postupne sa rozširujúcim oceánskym typom kôry a na nej vznikali horniny časti dnešného rakoveckého komplexu (príkrovu; Grecula et al., 2009 a 2011). V oblasti výstupu plášťovej astenosféry sa metamorfovali predtým vzniknuté horninové komplexy v oblasti oceánskeho chrbta na amfibolit a rulu. Túto metamorfózu na oceánskom dne charakterizuje vysoká teplota a nízky tlak, je to HT/LP metamorfóza M0. V tejto oblasti riftu vznikol plagiogranit s hornblendom, K-živcom, albitom, muskovitom a biotitom. Podľa Rb-Sr izochrón z týchto minerálov je vek plagiogranitu 371 ± 4 mil. rokov a vek chladnutia hornblendu je 362 mil. rokov. Tieto údaje sú v dobrej zhode s vekom zirkónu z rulovo-amfibolitového komplexu, ktorý je v rozsahu od 385 do 342 mil. rokov (Putiš et al., 2009). Hlavnú etapu riftu v období vrchného devónu až spodného karbónu reprezentuje kompletná ofiolitová suita: serpentinity/metaperidotity, Cpx gabrá s plagioklasom a chromitom a rulovo-amfibolitový komplex na lokalitách Dobšiná, Delava, Rudňany, Jaklovce, Strážny vrch a Klátov na severe, ale aj na juhu gemerika (serpentinit, Strážny vrch). Horniny ofiolitovej suity sú vždy tektonicky obmedzené oproti svojmu okoliu. Normalizácia chemického zloženia vzoriek amfibolitového komplexu a metagabier (ofiolitovej suity) je v dobrej zhode z oceánskou kôrou (obr. 3). Serpentinity z Klátova a Strážneho vrchu majú komatiitový charakter. V ostatných častiach panvy na kontinentálnej kôre pokračovala klastická sedimentácia s prejavmi lokálneho ryolitového vulkanizmu. Tretia etapa riftingu dovŕšila paleogeografiu sedimentačnej oblasti staršieho paleozoika a tým aj charakteristické faciálne vývoje najvyššej litostratigrafickej jednotky – hnileckého súvrstvia – a súčasne aj vývojovú etapu staršieho paleozoika (Grecula et al., 2009 a 2011).

Mladopaleozoické etapy konvergentných variských udalostí

Nasledujúca etapa variského cyklu sa pravdepodobne začala už na hranici devón/karbón. Sedimenty vrchného visénu, doložené paleontologicky, ležia na zvrásnenom a metamorfovanom podloží staršieho paleozoika. V spodnom a strednom karbóne bola ďalšia deformačná etapa staropaleozoických komplexov **s nástupom subdukčných procesov**. V tomto období sa vytvoril akrečný bazén so sedimentáciou hruboklastického materiálu pochádzajúceho zo staropaleozoických hornín prevažne oceánskeho chrbta, ale aj granitov-tonalitov (Radvanec, 1998). Časť týchto hrubých klastík (napr. aj rudniansky zlepencový typ) bola strhávaná do subdukčného kanála spolu s ostatnými horninami (obr. 4). Skracovanie sedimentačného priestoru prešlo vo vrchnom karbóne do obdukcie a tvorby variských príkrovov.

Hlavné množstvo hornín stredooceánskeho chrbta (ofiolitová suita) a okolitých sedimentov obdukovalo. Takto vznikli násuny a prešmyky akrečného komplexu vo forme príkrovov na severnú kontinentálnu platňu (obr. 4). Vznikli variské príkrovy v takomto poradí z juhu na sever: medzevský, jedľovecký, humelský, prakovský, mníšsky, kojšovský a rakovecký (Grecula et al., 2009 a 2011). Charakteristická metamorfóza tejto kompresie/obdukcie a začínajúcej sa subdukcie je M1a – pumpellyitovo-aktinolitová fácia. Pre horniny ofiolitovej suity, ktoré boli metamorfované v oceánskej kôre M0 (HT/LP – amfibolitová a epidotovo-amfibolitová fácia), je charakteristická M1a retrográdna a kompresná metamorfóza, rovnako ako pre exhumované Cpx gabrá zo spodnej kôry (lokality: Babiná, Ostrá, Šajby, Dobšinský potok, Lastovičí vrch, Zadné Porče) s jadeitom, omfacitom, Sr-epidotom a albitom. Tieto gabrá boli vo vrchnom karbóne (313 mil. rokov) exhumované z hĺbky eklogitovej fácie na izográde 600 ºC (Babiná, Ostrá), resp. z hĺbky modrých bridlíc (Šajby) do M1a – pumpellyitovo-aktinolitovej fácie (Radvanec, 1999 a 2000).

Vo vrchnom karbóne (obr. 4) pokračovali procesy začínajúcej sa subdukcie, ako aj približovania konvergujúcich platní Gondwany a Armoriky a zdvihu astenosféry v podloží aktívnej platne. Zo subdukčného kanála sa časť predtým subdukovaného materiálu vracala späť vrátane rudnianskych zlepencov (Radvanec, 1998) spolu s uvedenými tektonickými blokmi Cpx-Sr metagabra zo spodnej kôry (Radvanec, 1999 a 2000). Pri zdvihu astenosféry pod aktívnou platňou stúpla aj teplota. Predpokladá sa, že 600-stupňový izograd v tomto štádiu už dosahoval vrchnú časť kontinentálnej kôry a zodpovedal tak podmienkam gradientu kontinentálneho orogénneho pásma, teda regionálnej metamorfózy. Vo veporických komplexoch na tomto izográde vznikla anatektická tavenina, resp. granitovo-tonalitová tavenina (340 – 290 mil. rokov), ktorá bola následne umiestnená vo veporickom komplexe hornín (obr. 4).

V perme a triase variské subdukčné procesy vyvrcholili vývojom ostrovného oblúka, ryolitovým, andezitovým a bazaltovým vulkanizmom a granitovým magmatizmom (obr. 5). Vznikli anatektické S-typové granity s Sn-W-Mo-B-Li-F-As mineralizáciou v ich bezprostrednom okolí. V okolí permských vulkanitov, blízko povrchu a na povrchu to bola U-Mo-REE mineralizácia a ložisková sadrovca/anhydritu (Grecula et al., 1995). V oblasti geotermického gradientu okolo horúcich línií prebiehali strednotlakové metamorfné udalosti v epidotovo-amfibolitovej alebo amfibolitovej fácii (M1b). Mnohé tektonické bloky Cpx gabier so Sr-epidotom, bloky ofiolitovej suity, staropaleozoické ryolity a dacity boli v blízkosti horúcej línie znovu metamorfované v epidotovo-amfibolitovej alebo amfibolitovej fácii (M1b), pričom relikty staršej, pumpellyitovo-aktinolitovej fácie (M1a), resp. metamorfózy oceánskeho dna M0 sa často zachovali. Horúce línie sú charakteristické pre metamorfózu ostrovného oblúka. V perme prebiehali hlavné etapy mineralizácie, t. j. generovanie fluíd predovšetkým zo staropaleozoických hornín (pestrý vulkanický komplex, holecké vrstvy) a ich prenos v etape kompresného ochabnutia do tektonických tenzných fraktúr. Vznikla prevažne sideritová žilná, sideritovo-sulfidická mineralizácia, ako aj podmienky na metasomatické procesy (Fe a Mg metasomatóza, siderit-ankerit a magnezit) na kalcitovo-vápencovom protolite a na metamorfné prepracovanie sedimentárneho a exhalačno-sedimentárneho zrudnenia v staropaleozoických súvrstviach spodného a vrchného rudonosného horizontu (Radvanec, 1987; Radvanec et al., 1990; Grecula et al., 1991; Bartalský a Radvanec, 1993; Grecula et al., 1995; Žák et al., 1991; Íro a Radvanec, 1997; Radvanec et al., 2004; Grecula a Radvanec, 2005b; Žák et al., 2005; Jiang Shao-Yong et al., 2006; Radvanec et al., 2010).

V ďalšom období sa v oblasti permskej akrečnej prizmy vytvoril akrečný bazén so sedimentáciou hruboklastického materiálu (permské zlepence), pelitov a psamitov (Grecula et al., 2009 a 2011). Pelitické sedimenty v tej istej a neprerušenej akrečnej prizme v triase charakterizuje vysoký podiel kremeňa a hematitu s rádiolériami – hlbokomorské trenčové sedimenty. Pri Jaklovciach tieto sedimenty obsahujú prevažne detritický zirkón spodnotriasového magmatického veku 247 mil. rokov (Putiš et al., 2011), ale aj staršie recyklované zirkóny veku od 1 000 do 365 mil. rokov (obr. 5). Metagabro-metalamprofýr z lokality Danková, pochádzajúci z litosférického plášťa z obdobia permu až triasu, zaznamenal na kontakte subdukujúcej dosky v hĺbke okolo 50 km (Radvanec et al., 2009) na izográde 600 °C v podmienkach eklogitovej fácie vznik granátu ($Alm_{51}Prp_{36}Grs_{12}$) a Cr-REE tawmawitu (epidotovo-eklogitová fácia).

Vek zirkónov v tejto hornine na lokalite Danková a Jaklovce je variabilný, od 1 748 do 334 mil. rokov (ne-

publikované údaje), pričom rôzne generácie zirkónu zaznamenali všetky vývojové etapy gemerického komplexu do permu (obr. 5). V astenosfére boli v období do permu až triasu transportované k subdukčnej doske pri vysokej teplote kovy platinovej skupiny (Pd, Pt, Os, Ir) (Radvanec a Uher, 2016).

Alpínske etapy geotektonického vývoja

Doznievajúce kompresné a extenzné variské tektonické procesy dokončili variskú príkrovovú stavbu gemerika a veporika, ich vzájomné vzťahy a začiatok extenzného obdobia spätého s tvorbou alpínskych sedimentačných priestorov meliatika, silicika a severogemerického triasu (obr. 6). Jurské usporiadanie gemerika bolo v kompresnom režime (Grecula a Radvanec in Kobulský et al., 2001). Takéto usporiadanie podmienil reverzný pohyb litosférického plášťa, a hlavne astenosféry po jej zaťažení významným objemom subdukujúceho materiálu v perme. Reverzný pohyb astenosféry na začiatku exhumácie v jure vo forme pestrých tektonických blokov najskôr vytlačil metamorfity M2 vysokotlakovej a nízkoteplotnej fácie modrých bridlíc, glaukofanitov a rodingitov a na jej konci aj metaperidotity-serpentinity a metalamprofýry, ktoré sú nositeľom Sc, V PGM a Cd mineralizácie z hĺbky okolo eklogitovej fácie. Tektonické bloky metamorfitov M2 z rôzneho protolitu exhumujúce plášť reverzným pohybom vrazil prevažne do nemetamorfovaného prostredia vápencov a klastických sedimentov permsko-mezozoických jednotiek vzniknutých v nadloží variského akrečného komplexu (a sedimentov slabo metamorfovaného pasívneho okraja kontinentu z permského obdobia). Jurské exhumačné štádium kryštalizácie najmladšej generácie fengitu pomocou Ar/Ar a K/Ar datovania v exhumovaných modrých bridliciach s glaukofánom doložili Dallmeyer et al. (1996) a Faryad a Henjes-Kunst (1997). Horniny silicika sú v oblasti reverznej exhumácie subdukovaného klina v príkrovovej pozícii k paleozoickému podkladu gemerika. Na S od gemerika sú rovnako staré mezozoické komplexy v pozícii in situ a možno tam sledovať ich plynulý prechod do podložných hornín permu (Grecula et al., 2009 a 2011).

Vo vrchnej jure, ale najmä v spodnej kriede sa tektonické usporadúvanie horninových komplexov gemerika, a teda aj produktov metamorfných udalostí M0, Mla M1b a M2 do približne súčasnej pozície skončilo.

Záver

Terajší tektonický obraz gemerika vznikol pohybmi na strižných zónach v neskorovariskom období. Metamorfity oceánskeho dna M0 sa zachovali v podobe tektonických blokov rulovo-amfibolitového komplexu hlavne na S gemerika. Metamorfóza M1a v pumpellyitovo-aktinolitovej fácii vrchného karbónu bola prepísaná teplotným vrcholom amfibolitovej fácie pri regionálnej termálnej metamorfóze vo vrchnom perme a M1b. V tomto štádiu metamorfózy Mlb (metamorfóza ostrovného oblúka) sa skončila aj tvorba Fe-Mn-Mg karbonátovej a sulfidickej žilnej a stratiformnej karbonátovej (metasomatickej) mineralizácie.

Vzťah exhumovaných, „vysokotlakovo“ metamorfovaných exotických blokov v metamorfovanom vrchnom karbóne typu melanže je ojedinelým príkladom uzatvorenia paleotetýdneho bazéna v európskych variscidách. Nevylučujeme lokálny prienik metamorfitov prevažne do permsko-triasových sekvencií. Tento exhumačný proces bol jednorazový a úzko sa viazal na reverzný pohyb plášťa v jure. Ním sa exhumácia vysokotlakovo metamorfovaných blokov aj skončila.

Koncom jury alebo až po nej nadobudla metamorfóza M2 regionálny charakter súvisiaci s tektonickým dokončením usporiadania gemerika. V pojurskom období mala metamorfóza M2 regionálnu povahu na hranici strednotlakovej metamorfózy vo fácii zelených bridlíc. Túto metamorfózu spôsobilo finálne umiestnenie (vrchnej hranice) plášťa pod gemerikom, keď sa izoterma 500 °C ustálila v hĺbke 15 – 20 km, čo zodpovedá teplotnému gradientu 25 °C/km alpínskej metamorfózy.

Regionálny charakter metamorfózy M2 pravdepodobne doznieval až v spodnej kriede. Bola to rejuvenizačná „alpínska metamorfóza M2“, v ktorej sa horniny gemerika v kompresnom režime opäť metamorfovali v podmienkach strednotlakovej (4 – 5 kbar) fácie zelených bridlíc. V staršej minerálnej asociácii z metamorfózy M1a a M1b sa regionálna metamorfóza M2 zistila len lokálne v strižných zónach, pretože staršie minerálne asociácie z Mla a M1b boli v regionálnom procese M2 stabilné. Metamorfóza M2 v gemeriku neprekročila hranicu fácie zelených bridlíc. Lokálne prepracovala aj žilnú a stratiformnú mineralizáciu, lebo prebiehala v kompresnom režime, ale „rudonosné fluidá“ sa generovali len sporadicky a bez významného mineralizačného efektu.

Je pravdepodobné, že v jure sa plášť pod gemerikom dostal do súčasnej pozície, ako to vyplýva napr. z magnetotelurického (Pawliszynowa, 1978; Grecula et al., 1995) a gravimetrického aj seizmického modelu (Šefara et al., 1996; Bezák et al., 1997). Tvar litosférického plášťa a astenosféry pod gemerikom, ako aj metamorfné udalosti žilnej pozície a stratiformnej mineralizácie v poslednom štádiu vývoja gemerika v jure schematicky znázorňuje obr. 6. Konfigurácia plášťa na obrázku, odvodená z gravimetrických a seizmických modelov, sa sformovala pod vplyvom subdukčného kanála z variského obdobia so sklonom na S. Tvar plášťa v jursko-kriedovom období podmienil nasledujúci reverzný zdvih a exhumáciu subdukovaných, vysokotlakovo metamorfovaných hornín a ich umiestnenie do akrečného komplexu.

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