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Origin of earthquake swarms in the western Bohemian Massif: Is the mantle CO_2 degassing, followed by the Cheb Basin subsidence, an essential driving force?

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ABSTRACT

We propose a new model of the origin of earthquake swarms in West Bohemia/Vogtland (central Europe) by extensive CO_2 degassing of carbonates in the metasomatized junction of three mantle domains. The associated volume change of the decarbonation reaction accounts for the continuing subsidence of the Cheb Basin adjacent to the major focal zone. The local stress perturbation created by the subsidence, in combination with the regional stress field, may account for the recurring swarm seismicity. The largest earthquake energy has been continuously released along a steep contact between orthogneisses of the uplifting Krušné Hory/Erzgebirge domain and granites of the subsiding Smrčiny/Fichtelgebirge domain, forming boundary between two lithospheric segments. The physical parameters of both lithologies, Poisson's ratio and bulk modulus, derived from the P- and S-wave velocities at different depths indicate that this high-friction suture might be able to accumulate deformation energy that is being released as periodically recurring seismic swarms. The proposed model represents an alternative to prevailing considerations suggesting that the earthquake swarms were triggered by pressurized fluids of mantle origin, whose sources are however separated from the earthquake foci.

1. Introduction

The Bohemian Massif is a part of the Variscan orogenic belt representing a collage of microplates and magmatic arcs assembled during the collisions of Laurussia (Laurentia-Baltica) and Africa (Gondwana). The western part of the Bohemian Massif belongs to the most tectonically active regions in central Europe (Fig. 1A). It is also known as a spa region, with Karlovy Vary as their flagship (Fig. 1C). Apart from Quaternary volcanic activity, the continuing tectonic activity is mainly manifested by frequent, weak to moderate earthquake swarms, which occur in several-year intervals, high flux of mantle-derived CO_2 focused to mofette emanations, carbonate-rich mineral springs, and a high and extensive CO_2 soil flux (Horálek and Fischer, 2010; Kämpf et al., 2013; Nickschick et al., 2015). The high quantities of ^{3}He-bearing, mantle-derived carbonic fluids are associated with the Pleistocene volcanic events (Bräuer et al., 2005; Kämpf et al., 2005; Weinlich et al., 1999), continuing to 0.26–0.29 Ma (Mrlina et al., 2009; Ulrych et al., 2011). Another characteristic feature of the region is the movement of crustal segments in the area of the earthquake swarms with vertical displacement reaching up to 8 mm (Mrlina, 2000). Bankwitz et al. (2003) suggested that the earthquake activity in the epicentral area of Nový Kostel commenced between 120,000 and 12,000 years ago based on the morphology of escarpments above the seismoactive zone. An independent estimate of the subsidence rate of the Cheb Basin (0.014–0.048 mm y^{-1}) has been provided by vertical displacement of the Quaternary river terraces (Peterek et al., 2011). The close spatial association of the earthquake epicenters, quaternary volcanic edifices, and ^{3}He-bearing CO_2-rich springs led to a hypothesis that earthquake swarms in the West Bohemia/Vogtland region were triggered by magmatic activity (Špičák et al., 1999). Hypothetical injections of magma, or fluids of mantle origin, were then postulated in numerous studies (see Horálek and Fischer, 2010 and Fischer et al., 2014, for reviews). This hypothesis was further supported by similarity of the earthquake swarms to the hydraulic injection-induced seismicity observed in geothermal fields. Since the regional stress field in the West Bohemia/Vogtland area alone is insufficient to accumulate stress for generating the earthquake swarms with the relatively short time spans, the fluid overpressure was proposed as a substantial driving force (Kurz et al., 2004). The question of external forcing remains still poorly understood (Fischer et al., 2014).

In this study, we suggest that the secular subsidence of the Cheb Basin due to the long-term and extensive CO_2 degassing from the underlying mantle decarbonation, in combination with the regional stress field, might be the responsible driving force for the earthquake swarms. We also develop a new model using the local geological setting and

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petrophysical parameters of the seismoactive volume to explain the concentration of seismic activity by local rheological variations, the strength and friction of the paleoplate boundary and its upper-crustal expression.

2. Geological setting

The Western part of the Bohemian Massif represents a junction of three lithospheric domains—Saxothuringian, Teplá–Barrandian, and Moldanubian, which comprise Proterozoic and Paleozoic metamorphic and magmatic rocks, partly covered by sediments of Mesozoic and Cenozoic shallow-marine or freshwater sediments (Franke, 2000; Fig. 1C). The triple junction of the lithosphere domains is characterized by thinning of the crust to 27–28 km (Geissler et al., 2005; Heuer et al., 2006), by a laminated structure of the lower crust (Hrubcová et al., 2005), as well as by thinning of the whole lithosphere (Plomerová et al., 1998; 2003) to a depth of ~80 km (Fig. 2). A detailed analysis of anisotropy of both P- and S-wave velocities using self-consistent 3D anisotropic models of the three lithosphere domains indicates that the changes in the lithosphere anisotropy due to different orientation of olivine fabrics are related to the deep boundaries separating the units (Plomerová et al., 2007; Babuška et al., 2008; Fig. 1C). The domain boundaries are shifted to the southeast relative to their mantle counterparts projected to the Earth's surface. This is due to the detachment of the Saxothuringian upper crust, the Cadomian basement, and its cover from the underlying mantle lithosphere during the Variscan collision, and thrusting over the triple junction of the mantle domains (Babuška et al., 2007).

During Cretaceous and Cenozoic, the area was affected by incipient extension marked by the formation of the Ohře/Eger Rift, with its distinct graben morphology, an elevated heat flow and magmatic activity (Ulrych et al., 2000), developed above the Variscan tectonic suture (Fig. 2). The seismically most active region is located above a broad transition of the mantle lithosphere domains and near the intersection of two major fault systems—the Krušné Hory/Erzgebirge Fault and the Mariánské Lázně Fault. All seismic events recorded in the Nový Kostel and Lazy focal zones are located within this allochtonous Saxothuringian crust that is underlain by the weakened mantle lithosphere of the triple junction (Fig. 1C).

Subsiding area of the Cheb Basin westward of the Mariánské Lázně Fault hosts numerous outlets of mantle-derived CO_2-rich fluids. The spatial configuration of the geological units and CO_2-rich fluid emanations suggests that the domain boundaries act as pathways for mantle-derived volatiles. Such a complex lithosphere structure of the mantle triple junction is independently supported by three Moho reflective interfaces modeled beneath the major focal zone (Hrubcová et al., 2013). Fluid migration through the ductile and partly laminated lower crust was further facilitated by crust-mantle detachments (Babuška and Plomerová, 2008; Figs. 1C and 2). Mlčoch and Skácelová (2009) recognized in the crystalline basement of the basin two synsedimentary fault systems that are oriented along the two perpendicular structures—the Eger Rift and the Mariánské Lázně Fault. The faults cutting the basin basement delineate depressions and horsts of irregular shapes and lateral dimensions ranging from several hundred meters to several kilometers (Dobeš et al., 1986).

The regional gas flux, estimated to exceed 500 $m^3\ h^{-1}$ (Geissler et al., 2005; Weinlich et al., 1999), is spatially focused to the Cheb Basin, and it is located directly above the mantle triple junction (Fig. 2). Other localities in the vicinity of Karlovy Vary and Mariánské Lázně, situated above the western Ohře/Eger Rift and the Mariánské Lázně Fault (Fig. 1), show smaller amounts of the observed gas flux (Babuška and Plomerová, 2008). The monitoring network CarbonNet, located in the Cheb Basin, provides degassing rates at the Hartoušov and Soos stations (Fig. 3), the former yielding an average flow of 30 $l\ min^{-1}$, that is, ~85 kg $CO_2\ d^{-1}$. Kämpf et al. (2013) estimate fault-related discharge of 3.75 t $CO_2\ d^{-1}$ at 27 wet mofettes in the Cheb Basin and its vicinity. Besides the discharge at mofettes, their surface survey revealed diffuse soil flux ~1.556 t $CO_2\ m^{-2}\ d^{-1}$ within the two prominent mofette fields in the basin. Detailed local measurements revealed even higher discharge rates, 23–97 t $CO_2\ d^{-1}$ over an area of ~350,000 m^2 in the Hartoušov mofette field (Nickschick et al., 2015).

3. Mass balance model for the decarbonation and origin and release of CO_2 fluids

We suggest that the massive and long-lasting degassing of mantle CO_2 fluids, situated mainly above the mantle boundaries of the triple junction beneath the Cheb Basin, is the direct principal cause of the basin subsidence and a significant contributor to the stress forces producing the earthquake swarms. The lithospheric geothermal regime may be used to constrain the presence of carbonate minerals, carbonate-rich melts, or CO_2-rich fluids using phase equilibria in the system peridotite-H_2O-CO_2 (Fig. 4). The present geotherm (Goes et al., 2000) intersects Moho at ~610 °C and enters the stability field of dolomite in the peridotite assemblage (Fig. 4a). At a depth of ~93 km and ~1150 °C, it intersects hypothetical solidus of the carbonated peridotite, which implies that the asthenospheric mantle is lubricated by a small fraction of silicate-poor carbonatitic melt (e.g., Lee et al., 2000; Wyllie and Lee, 1998). When these melts buoyantly rise, their behavior is dictated by the efficiency of thermal exchange with the surrounding peridotite. Small, distributed bodies of carbonatitic melts are likely to be in thermal equilibrium with the silicate minerals and rise along the geotherm, intersecting the solidus of the carbonated peridotite and precipitating dolomite, thus becoming immobile (path 1 in Fig. 4b). By contrast, large segregations of carbonatitic mantle may rise adiabatically, and upon intersecting the solidus at a depth of 91–85 km, decompose to a CO_2-rich freely mobile fluid (path 2 in Fig. 4b). The presence of H_2O, as an additional component in the melt-bearing carbonated peridotite, will shift the locus of the fluid release to lower pressures (shallower depths) and the fluids will progressively become H_2O-rich (Fig. 4b). The current upper boundary of the asthenosphere is interpreted to occur at a depth as shallow as 80–65 km (Heuer et al., 2006; Plomerová et al., 2007). This may be used as an indirect evidence for H_2O-bearing but CO_2-rich nature of the present-day peridotitic mantle. The close approach of the present-day geotherm to the dolomite–CO_2 reaction, 4 $MgSiO_3$ (enstatite) + $CaMg(CO_3)_2$ (dolomite) = 2 Mg_2SiO_4 (forsterite) + $CaMgSi_2O_6$ (diopside) + $2CO_2$ (fluid), indicates that both scenarios (paths 1 and 2 in Fig. 4b) are plausible and subtly depend on slight thermal perturbations in the asthenospheric mantle.

The Tertiary and Quaternary volcanics in the Western Bohemia and Bavaria host numerous mantle peridotite xenoliths, which can constrain the incorporation or release mechanisms of carbonates in the upper mantle. Geissler et al. (2007) described wehrlites and hornblende peridotite among xenoliths from Quaternary tephra deposit and interpreted them as fragments of a metasomatized upper mantle (cf. Kogarko et al., 2001; Lee et al., 2000). Wehrlitization is the process of interaction between a sodic carbonatitic melt and orthopyroxene-olivine assemblage (Dalton and Wood, 1993; Kogarko et al., 2001). Extensive studies of xenolith suites in Ohře/Eger Rift extension in the northern Bavaria, near the Saxothuringian–Moldanubian boundary, provided multiple geochemical evidence for alkali-rich carbonate mantle metasomatism (Ackerman et al., 2013; Špaček et al., 2013). Based on this evidence, we propose that the carbonate-rich melts ascending along the geotherm thus entered the stability field of dolomite. The geotherm is located very close (~50 °C) to the dolomite–CO_2 reaction, where dolomite will decompose and release gaseous CO_2. This process can be triggered by local thermal perturbations, which may represent spatial or temporal variations, or be related to repeating arrival or migration of partial melts. The fluid phase, generated by the dolomite breakdown will be a pure CO_2, unlike the magmatic fluids, which are becoming progressively H_2O-rich with decreasing depth (Fig. 4b). We suggest that this scenario of dolomite breakdown at its reaction boundary (path 3