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A geophysical model of the Variscan orogenic root (Bohemian Massif): Implications for modern collisional orogens

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A B S T R A C T

A new model of the structure and composition of the Variscan crust in the Bohemian Massif is proposed based on 3D gravity modelling, geological data, seismic refraction (CEL09) and reflection (9HR) sections. The Bohemian Massif crust is characterized by a succession of positive and negative anomalies of about 60–80 km wavelength for nearly constant Moho depths. The south-western part of the Bohemian Massif displays a large negative Bouguer anomaly corresponding to high grade rocks (granulites and migmatites) of the Palaeozoic crustal root represented by the Moldanubian domain. The adjacent Neo-Proterozoic Bruno-Vistulian microcontinent displays an important gravity high reflecting mafic and intermediate medium grade metamorphic and magmatic rocks. The deep crustal boundary between the root domain and the Bruno-Vistulian microcontinent is represented by a strong gradient located 50 to 70 km westwards from the surface boundary between these units indicating that the high density basement rocks are covered by a thin sheet of low density granulites and migmatites. North-west from the Moldanubian domain occurs an important gravity high corresponding to the Neo-Proterozoic basement of the Teplá-Barrandian Unit limited in the north by southeast dipping reflectors of the Teplá suture which is characterized by high density eclogites and ultramafics. The footwall of the suture corresponds to low density felsic crust of the Saxothuringian basement. The reflection and refraction seismics and gravity modelling suggest a complex lithological structure of the Moldanubian domain marked by a low density 5–10 km thick lower crustal layer located above the Moho, a 5–10 km thick heavy mafic layer, a 10 km thick mid-crustal layer of intermediate density and a locally developed 2–5 km thick low density layer at the surface. The low density lower crust correlates well with low P-wave velocities in the range 6.0–6.4 km s^{-1} in the CEL09 section. This complex geophysical structure and surface geology are interpreted as a result of Carboniferous partial overturn of low density lower crust and high and intermediate density crust in the area of central root and by viscous extrusion of low density orogenic lower crust over the high density Bruno-Vistulian continent. Comparison of these data with geophysical profiling of the Andean and the Tibetan plateaus suggests that modern orogenic systems reveal comparable deep crustal geophysical pattern. Based on these similarities we propose that the Variscan root represents a deep crustal section of above mentioned plateaus, which may have develop by the same orogenic process.

1. Introduction

The composition and structure of crustal layers forming thick orogenic roots in collisional orogens remain a matter of discussion thanks to complexity of geophysical data and derived geodynamical models (Rudnick, 1995; Rudnick and Fountain, 1995). Based on the geodynamic context and reflection seismic results, two different types of hot modern orogens are distinguished: (1) the Andean type, where oceanic crust subducts beneath a continental lithosphere. This process creates a Franciscan type accretionary wedge, a magmatic arc established on the continental crust and a large continental plateau; (2) the Tibetan type where continental crust underthrusts another continent following an oceanic subduction stage. This orogen also creates a thick continental plateau and complex metamorphic structures in front of the continental accretionary wedge. These two fundamentally different processes allow explanation of the structure of 300 km of orogen adjacent to the suture but fail to explain the orogenic fabric in more distal parts of a thick orogenic root underneath the plateau.

In the central Andes, the ANCORP'96 seismic reflection profile shows strong reflectors called “bright spots” located at 15–30 km

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depth underneath the surface of Altiplano which coincide with a low velocity zone of 5.9 km/s to 6.1 km/s in seismic refraction profiles (Patzwahl et al., 1999) and a zone of low resistivity located at mid-crustal depths (Schilling and Partzsch, 2001; Oncken et al., 2003). The Andes are also marked by an exceptionally high negative Bouguer anomaly underneath the plateau (~$-300 \cdot 10^{-5}$ mGal) and high heat flow (~100–125 mW/m²) along the ANCORP section (Oncken et al., 2006). All these data indicate that the Altiplano middle crust coincides with a partially molten dominantly felsic zone with up to 30% distributed melt (Schilling and Partzsch, 2001). This means that the important heat flow in the Andes is not associated with underplating of the root by basaltic magmas as is suggested for a range of other orogens (Götze and Kirchner, 1997; Springer, 1999).

The Tibetan Plateau shows similar geophysical features such as bright spots in reflection seismics (Nelson et al., 1996) and a low velocity and resistivity zone at mid-crustal depths (Makovsky and Klemperer, 1999). Gravity surveys of the Himalaya–Tibet orogen show a large scale negative Bouguer anomaly of less than −500 mGal and elevated heat flow reaching, locally, 150 mW/m^2 (Hu et al., 2000). These features indicate that a partially molten mid-crustal layer similar to that proposed for the Andes also exists beneath the southern Tibetan plateau (Schilling and Partzsch, 2001). However, there is no detailed study that shows the relation between the partially molten mid-crustal layer and the composition of rocks located at the bottom of the root, i.e. close to Moho depth. Some studies have suggested that the orogenic lower crustal material has to be felsic to intermediate in composition due to the high gravity potential of rocks underneath the Tibetan plateau (e.g. Le Pichon et al., 1997). In order to solve the problem of exceptionally low density felsic crust at depths of 60 km, Chemenda et al. (2000) proposed a model of underthrusting of Indian continental crust underneath the Tibetan crust, thereby replacing lithospheric mantle with felsic buoyant lower crust. By contrast, for the Andes the problem is solved by the injection of felsic lower crust from the Brasilian shield region (Lamb and Hoke, 1997) into the central parts of the orogen. However, in general, the origin of negative gravity anomalies, the composition of orogenic lower crust and its connection to a partially molten zone at the mid-crustal depths remains unresolved.

The Bohemian Massif represents a deeply eroded section of a large high-T orogen allowing observation of the structure of fossil orogenic root similar to the Tibetan or the Altiplano plateau (Dörr and Zulauf, 2010). In the current outcrops K-feldspar-kyanite bearing granulite massifs (18–20 kbar/800–1000 °C) are common, associated with felsic migmatites of Carboniferous age (Štípská and Powell, 2005; O'Brien, 2008). These HP–HT units are surrounded by middle crustal rocks represented by metagreywackes, amphibolites and subordinate metapelites (8–10 kbar, 650 °C). Locally, these supra-crustal rocks are well preserved being separated from adjacent middle and lower crustal material by crustal scale normal faults (Pitra et al., 1994; Zulauf et al., 2002a, Dörr and Zulauf, 2010). In order to explain the exhumation of Saxonian HP granulites Weber and Behr (1983) proposed a model of 'diapiric folding'. In their model the deep granulitic layer tends to amplify and pierce through the weaker middle crust during crustal shortening, to form a large scale steep fold bringing HP rocks to middle crustal levels. In contrast, several authors have proposed that the HP granulites and associated migmatites were exhumed to supra-crustal depths in the form of "diapiric" extrusions from the depth of the Moho (Štípská et al., 2004; Schulmann et al., 2005; Franěk et al., 2006). Indeed, based on numerical modelling, Gerya et al. (2001) shown that the exhumation of granulites and other felsic lower crustal rocks occur during gravitational redistribution processes. Therefore, it is explicitly inferred that the orogenic lower crust was felsic during Carboniferous times, forming an allochthonous body underneath the Variscan crust (Behr, 1978; Behr et al., 1984; Weber, 1984). Following these postulates two questions arise: where do the felsic granulites come and; is there any correlation between the felsic granulites at the surface and the deep crustal source?

A detailed network of gravimetric data from the Bohemian Massif (Polanský and Škvor, 1975; Ibrmajer, 1981; Plaumann, 1983, 1987) shows an important negative gravimetric anomaly corresponding to the Moldanubian Zone, which is interpreted as a fossil Carboniferous orogenic root (Schulmann et al., 2009). In addition, seismic reflection and refraction studies show unexpectedly inhomogeneous lower crust with low P-wave velocities in this area. In this paper, we interpret the gravimetric data in the light of seismic sections and geological observations. An attempt is made to explain these data in terms of existence of a felsic lower crustal layer which underplated standard mafic lower crust by tectonic process. We propose a connection between this residual felsic lower crust and HP felsic granulite bodies at the surface via a gravity redistribution process which operated during the Carboniferous. Finally, it is proposed that the geophysical structure of the Moldanubian crust can provide a key insight into interpretation of modern collisional orogens such as Tibet and Andes.

2. Geology of the Bohemian Massif

The Bohemian Massif is a large Palaeozoic belt located at the eastern termination of the Variscan belt. It is generally divided into four major tectonic domains (Suess, 1926; Kossmat, 1927): the Saxothuringian, the Teplá-Barrandian, the Moldanubian and the microcontinent Bruno-Vistulian (Fig. 1). The geology of the Bohemian Massif is briefly characterized as follows:

(1) *The Saxothuringian domain* (Fig. 1) contains Neoproterozoic para-autochthonous rocks (~580–550 Ma) and allochthonous Late Ordovician to Devonian distal and proximal margin sequences (Franke, 2000) containing relics of MORB-type Ordovician metabasites eclogitized during the Devonian (~395 Ma; Schmädicke et al., 1995). Later Carboniferous underthrusting of the Saxothuringian continental rocks underneath the Teplá-Barrandian domain to the east was responsible for the eclogitization of continental crust (Massonne, 2006) at ~340 Ma associated with the exhumation of deeply buried rocks in form of crustal scale nappes (Konopásek and Schulmann, 2005).

(2) *The boundary between the Saxothuringian–Teplá-Barrandian* is characterized by a relic Devonian oceanic suture which is well preserved in the Mariánské Lázně Complex (Kastl and Tonika, 1984; Zulauf, 1997). This complex is represented by serpentinites, amphibolites, eclogites and metagabbros of Cambrian (~540 Ma; Timmermann et al., 2004) and Ordovician (~496 Ma; Bowes and Aftalion, 1991) protolith ages metamorphosed at eclogites facies conditions during Devonian (410 and 370 Ma; Beard et al., 1995; Dallmeyer and Urban, 1998). The western boundary of the oceanic suture is marked by the presence of felsic granulites of the Egger graben (Zulauf et al., 2002b).

(3) *The Teplá-Barrandian domain* (Fig. 1) consists of Neoproterozoic arc-related volcano-sedimentary rocks overlain by siliceous black shales and a flyshoid sequence. The Neoproterozoic basement is unconformably overlain by Lower Cambrian clastic sediments, Upper Cambrian volcanic and sediments of the Lower Palaeozoic (Ordovician to Middle Devonian) Prague Basin (Havlíček, 1981). The whole sequence is folded by steep folds presumably of Late Devonian age (Zulauf, 2001).

(4) *The Central Bohemian Plutonic Complex* occurs on the boundary between the Teplá-Barrandian and the Moldanubian domains. It consists of Late Devonian (~354 Ma) calc-alkaline tonalites, granodiorites, trondhjemites, quartz diorites and gabbros in the west (Janoušek et al., 2004) and Early Carboniferous (~349–346 Ma, Holub et al., 1997) high-K calc-alkaline plutonic bodies in the southeast.