Macroseismic Constraints on Deep Crustal Structures in the Bohemian Massif

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Abstract. We analysed two moderate earthquakes that occurred near Mirotice in southern Bohemian Massif (Czechia) in March 2024 (M_L 3.5) and April 2025 (M_L 3.1), integrating seismological analyses with crowdsourced macroseismic observations. Both events originated at unusually large focal depths for the region (23–24 km) and were widely felt across southern and central Bohemia, attracting significant public and scientific attention. Macroseismic effects were documented through extensive citizen participation, with over 1,500 questionnaires for each event collected by the Institute of Geophysics of Czech Academy of Sciences. Maximum macroseismic intensities reached IV–V; however, the spatial distribution of observations was distinctly non–circular, forming a pattern controlled by major tectonic structures. Areas underlain by granitoids of the Central Bohemian Pluton exhibited dense and far reaching macroseismic responses, consistent with low seismic energy attenuation of the Moldanubian, whereas regions dominated by early Palaeozoic sedimentary rocks of the Teplá–Barrandian showed sparse observations, indicating higher attenuation. Focal mechanisms indicated normal faulting on a NW–SE striking fault plane, consistent with regional stress field. The unusually large focal depths may be attributed to low geothermal gradient in the area suggesting deep seated structural controls on earthquake nucleation. The results delineate two subvertical structures within the Bohemian Massif and demonstrate that crowdsourced macroseismic data provide valuable constraints on earthquake effects and deep geological controls on seismic wave propagation, even in regions with low seismicity, and effectively complement instrumental observations.

Short Summary

Two moderate earthquakes near Mirotice (Bohemian Massif) in 2024 and 2025 were analysed using seismological and crowdsourced macroseismic data. Both events occurred at unusually large depths (23–24 km) and were widely felt. Non-circular macroseismic patterns reflect tectonic control and contrasting attenuation between different tectonic units and constrain subvertical structures within the Bohemian Massif. Normal faulting matches the regional stress field, suggesting deep structural control.

Introduction

35 Involving citizens in science related to natural hazards helps people better understand risks and prepare for them. It also supports disaster management and improves decision making. Crowdsourcing makes use of information shared by many individuals, providing valuable ground level insights that strengthen scientific understanding and emergency response. In seismology, citizen involvement has been especially effective in gathering and sharing important information, significantly contributing to seismic risk mitigation (e.g., Guan and Chen, 2014; Hao and Wang, 2020; Kryvasheyeu et al., 2016).

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Macroseismic questionnaires, pivotal in this context, gather information on ground shaking and its effects on buildings, infrastructure, and populations. Online macroseismic questionnaires, supported by widespread internet access, have further enhanced this process by enabling rapid, cost effective, and geographically extensive data collection (e.g., Kankanamge et al., 2019). Compared to traditional paper based methods, online approaches improve the efficiency, accuracy, and

45 comprehensiveness of macroseismic data.

Macroseismic data not only support the assessment of earthquake impacts but also offer valuable constraints on character of geological features. Their applicability to geological investigations depends on data quality, the representativeness of the surveyed population, and the methodologies used for data collection and analysis. Crowdsourcing, facilitated by online

50 platforms, mobile applications, and widespread smartphone use, enables broad public participation and rapid data acquisition. This methodology is particularly effective in regions with sparse seismic instrumentation or low seismicity, where instrumental seismic data are often unavailable. In such settings, crowdsourced macroseismic observations offer a cost effective means of acquiring large volume datasets that reflect geological controls on seismic wave propagation (e.g., Toshinawa et al., 1997; Cifelli et al., 1999).

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This approach is especially relevant for the Bohemian Massif, one of the largest exposures of the European Variscan orogenic belt situated at its eastern periphery (Fig 1). Bohemian Massif developed between ~500 and 250 Ma as a result of convergence between the Gondwana and Baltica (e.g., Edel et al., 2018) and was configured by the Neoproterozoic evolution of the northern Gondwana active margin (e.g., Soejono et al., 2017), Cambro–Ordovician crustal extension (e.g., Soejono et al., 2020) and

60 Late Devonian oceanic subduction followed by Early Carboniferous deep continental underthrusting of Saxothuringian microcontinent (e.g., Schulmann et al., 2014; Žák et al., 2014). Bohemian Massif has been subdivided into four main regional units based on lithology and metamorphic grade. From west to east it comprises Neoproterozoic basement and Palaeozoic cover of the Saxothuringian Domain (e.g., Linnemann et al., 2004), Ediacaran accretionary wedge and Lower Palaeozoic sequences of the Teplá–Barrandian Unit (TBU) (e.g., Hajná et al., 2017), Variscan middle and lower crustal rocks of the

65 Moldanubian Domain (Schulmann et al., 2005) and Neoproterozoic basement with Palaeozoic sedimentary cover of the Brunovistulicum (e.g., Hanžl et al., 2019). Closure of the Saxothuringian ocean by subduction and following deep continental

underthrusting (e.g., Schulmann et al., 2014; Žák et al., 2014) formed the magmatic arc related suites of the Central Bohemian Plutonic Complex (CBPC) at the Teplá–Barrandian/Moldanubian boundary.

70 Present day seismicity within the Bohemian Massif is dominated by weak intraplate earthquakes, mostly confined to upper crust (<12 km), and concentrated mainly along the massif margins. More significant seismic activity is limited to western Bohemia/Vogtland, where earthquake swarms are linked to the ascent of mantle derived fluids migrating along deep crustal structures (Fischer et al., 2014), and to the eastern Sudetes (see CZEQ catalogue). Consequently, large parts of the internal structure of the Bohemian Massif, particularly its deep-seated features, remain seismically inactive and therefore poorly
75 constrained by seismic activity. For this reason, seismic stations within the Bohemian Massif (excluding the above active regions) primarily serve as part of regional seismic monitoring networks.
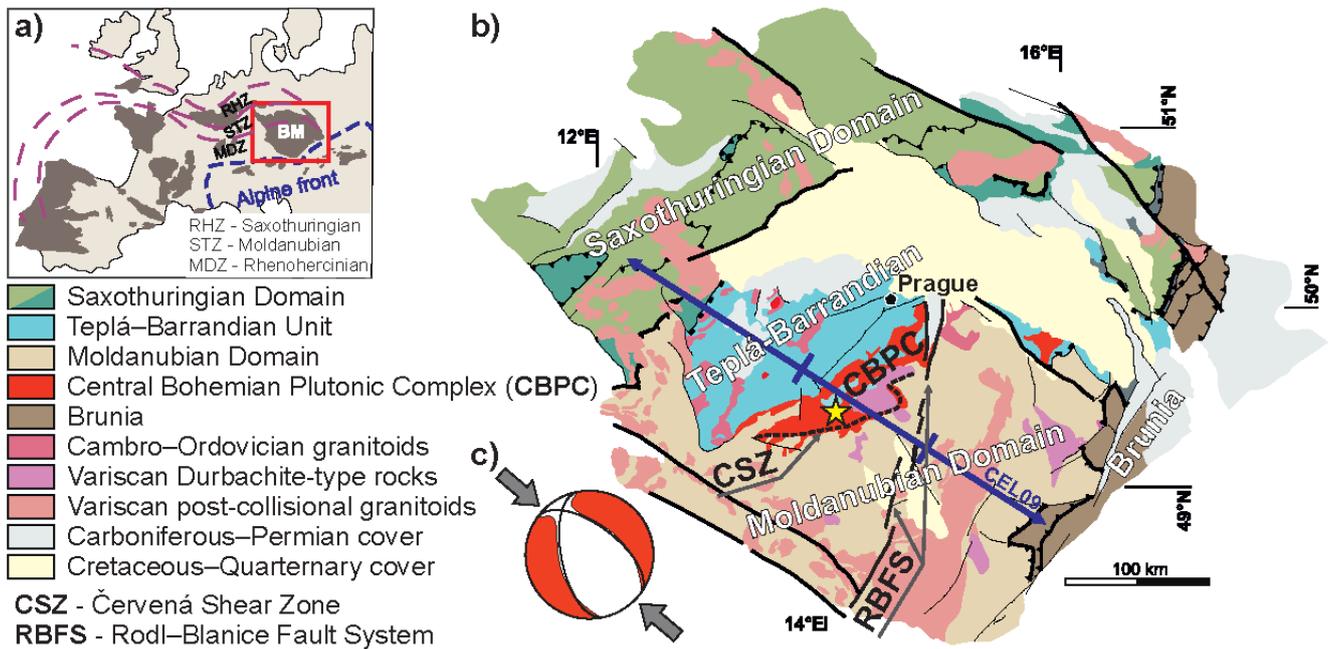
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Figure 1. a) Schematic sketch of the European Variscides with the Bohemian Massif (red box) in the eastern edge. b) Simplified geological map of the Bohemian Massif with individual tectonic units (modified after Machek et al., 2022). The Mirotice earthquakes are marked by yellow star; the violet line marks the CEL09 seismic profile from the CELEBRATION 2000 experiment (Hrubcová et al., 2005). c) Source mechanism of Mirotice earthquakes; the arrows
85 indicate the orientation of the regional maximum horizontal stress (SHmax; Heidbach et al., 2016).

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In regions where seismic station coverage is sparse, macroseismic observations offer a valuable complement to instrumental data. Against this background, this study explores a crowdsourcing based macroseismic analysis of two earthquakes (M_L 3.5 in 2024 and M_L 3.1 in 2025) near Mirotice in southern Bohemian Massif, Czechia. Located in the deep crust, both events were

90 widely felt across southern and central Bohemia, which provided an opportunity to examine macroseismic data, analyse spatial distribution of earthquake impacts, and uncover geological evidence related to seismic phenomena. By assessing impacts on people, buildings, and the environment, the results demonstrate the potential of crowdsourced macroseismic data to reveal deep seated geological structures that control seismic wave propagation within the Bohemian Massif.

95 **2024 and 2025 Mirotice Earthquakes**

On 7 March 2024, shortly before noon local time (10:41:41 GMT), an earthquake of magnitude M_L 3.5 occurred in southern Bohemia (Czechia). The epicentre was located southeast of Mirotice town (49.42° N, 14.05° E) with the hypocentral depth of 24 km ±1.5 km. Subsequent analysis identified four minor aftershocks with M_L ~0.5 occurring within one hour of the main shock, followed by a very weak event (M_L −0.1) about 12 hours later. The latest aftershock (M_L 0.4) was recorded more than

100 three weeks later, on 29 March 2024 at 17:51 GMT.
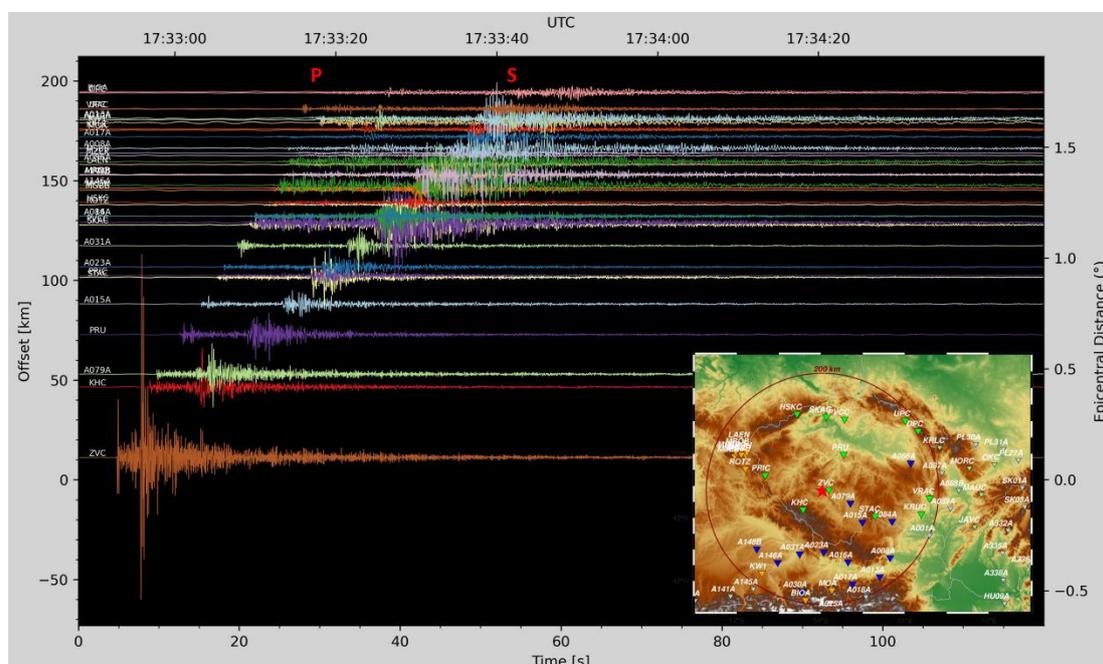
Figure 2. The April 2025 Mirotice earthquake (M_L 3.1) recorded by regional stations (depicted in the inset) with marked P

105 and S waves.

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The second earthquake, with magnitude M_L 3.1, occurred on 24 April 2025 at 17:32:47.3 GMT. This event originated essentially at the same location (49.42° N, 14.04° E) and at a comparable hypocentral depth of ~24 km ±1.5 km. The main shock was followed by four weak aftershocks (maximum M_L 0.3), two occurring immediately after the main shock and two 110 recorded one day later. Example waveforms are presented in Fig. 2.

Such earthquakes are rare in this region. Moreover, the Mirotice earthquakes were unusually deep for the Bohemian Massif with depths of 23–24 km, which ensured that the effects were felt over wide area.
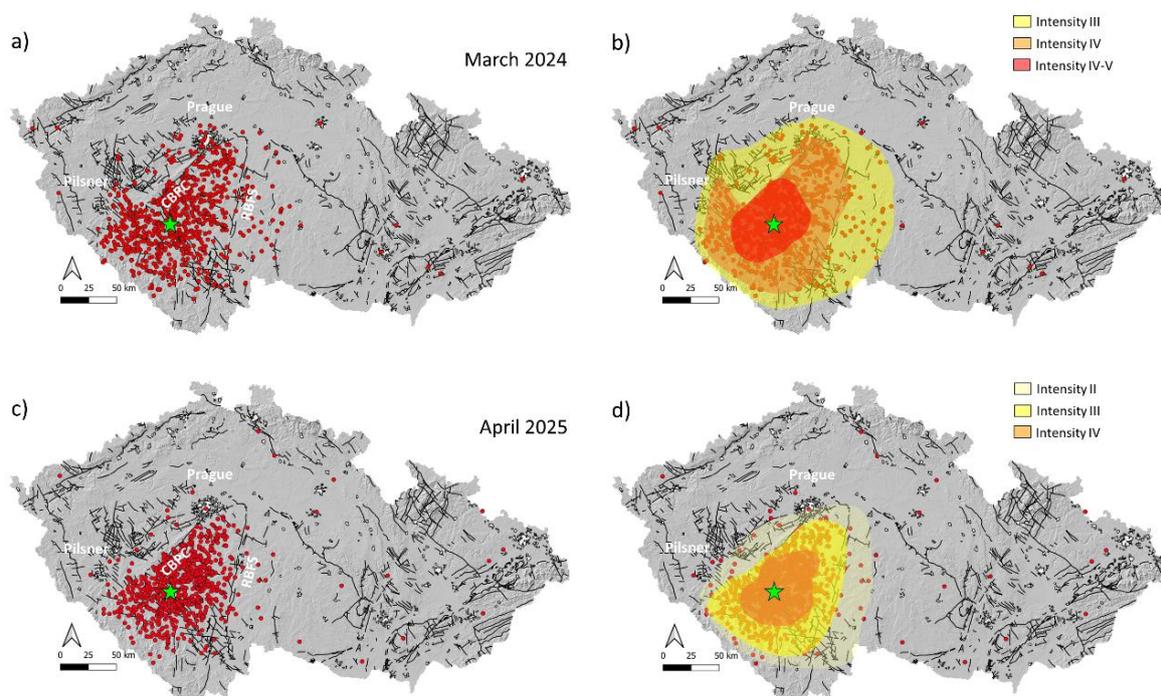
Figure 3. The Mirotice earthquakes. (a,b) The M_L 3.5 event in March 2024; (c,d) the M_L 3.1 event in April 2025. (a,c) Spatial distribution of macroseismic observations (red dots) collected at the Institute of Geophysics of the Czech Academy of Sciences. (b,d) macroseismic intensity according to the EMS–98 scale. The epicentres are marked in green; CBPC, 120 Central Bohemian Plutonic Complex; RBFS, Rödl–Blanice Fault System.

Focal mechanisms were determined through full waveform moment tensor inversion using the Bayesian ISOLA method (Vackář et al., 2017), based on waveform data from 11 broadband seismic stations at epicentral distances of 11–70 km. The inversion employed velocity model derived from nearby CEL09 refraction and wide–angle reflection profile (Fig. 1) of the 125 CELEBRATION experiment (Hrubcová et al., 2005), which improved the waveform fit. The results indicate that both events

were characterized by normal faulting on a NW–SE striking fault plane with strike 160° and dip 59° (Fig. 1). Similar focal mechanisms were obtained from 47 P–wave first–motion polarities with slightly different more regional velocity model (strike 164°, dip 51°).

130 **Macroseismic Observations**

The earthquakes that occurred near Mirotice in 2024 and 2025 were unusual for the region in terms of their location, depth, and felt intensity, and therefore attracted considerable scientific interest as well as public attention. Macroseismic effects were documented through 1,512 questionnaires for the 2024 event and 1,679 questionnaires for the 2025 event, collected via online forms and smartphone applications by the Institute of Geophysics of the Czech Academy of Sciences

135 (*https://www.ig.cas.cz/makroseismicky-dotaznik/*).

The shaking was reported over distances of several tens of kilometres. Responses were collected from distances of up to 70–100 km from the epicentre, including the Písek, Strakonice, and Tábor regions, as well as the Šumava Mountains (Fig. 3a,c). Respondents reported ground shaking of varying intensity (strong shaking in 17% of cases and light shaking in 66% for the

140 2024 event; light shaking in 58% of cases for the 2025 event), swaying of lightweight objects and clinking of dishes (30% in 2024; 18% in 2025), and, in some cases, hairline cracks in walls or plaster, particularly near the epicentre (2.5% in 2024; <1% in 2025). The shaking, which lasted several seconds, was commonly accompanied by window vibrations and by rumbling to booming sounds that often preceded ground motion. Many residents also reported sounds resembling the passage of heavy vehicles or an explosion (92% in 2024; 95% in 2025).

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Individual questionnaire responses were converted to macroseismic intensities following the criteria of the EMS–98 scale (Grünthal, 1998). Questionnaires lacking sufficient diagnostic information, containing inconsistent timing, duplicates, or those reporting effects not clearly attributable to the earthquake were excluded from the analysis. Reports indicating shaking felt by a few persons at rest, without movement of objects, were assigned intensity III ("weak"). Reports of shaking felt by many

150 indoors, accompanied by rattling of windows, doors, or dishes and slight movement of lightweight objects, were assigned intensity IV ("largely observed"). An intensity of IV–V was assigned in areas with numerous reports indicating clear movement of unsecured objects, overturning of small items, or rare non-structural damage (e.g. hairline cracks in plaster), but without fully satisfying the criteria for intensity V ("strong"). When multiple effects were reported, intensities were assigned conservatively based on object or damage related indicators, and the final locality intensity was taken as the modal value of

155 all retained responses.

The maximum macroseismic intensity, assessed according to the EMS–98 scale (Grünthal, 1998), reached IV–V for the stronger 2024 earthquake and IV for the weaker 2025 event. The spatial distribution of macroseismic intensities is illustrated in the corresponding intensity maps (Fig. 3b,d). However, the most notable feature was not the intensity level itself but the

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160 spatial pattern of the reported observations. The stronger 2024 event was observed farther to the west than the 2025 earthquakes; nevertheless, in both cases the distribution of observations was distinctly non–circular. Importantly, the uneven spatial pattern was not controlled by population density (Fig. 4). Notably, the weaker 2025 event was reported more frequently, and in addition, both events were widely accompanied by reported sound effects.
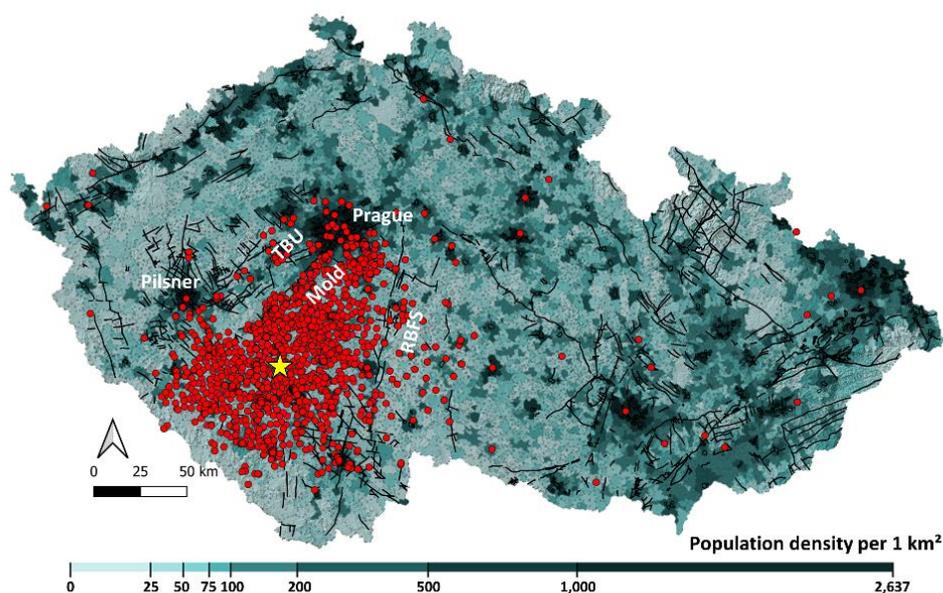
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Figure 4. Spatial distribution of macroseismic observations (red dots) for both 2024 and 2025 Mirotice earthquakes (yellow star), superimposed on map of population density (people per km²; *https://geoportal.gov.cz/*). Note trapezoidal patter of the observations delimited from the west by the Teplá–Barrandian (TBU) / Moldanubian (Mold) boundary and from the east by the Rödl–Blanice Fault System (RBFS).

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Tectonic and Structural Context

The earthquake epicentral area (Fig. 1) is located within the Central Bohemian Plutonic Complex (CBPC), specifically in the Mirotice complex, near the NE–SW trending boundary between the Teplá–Barrandian Unit and the Moldanubian Domain. The evolution of CBPC is characterized by the intrusion of Late Devonian plutons of magmatic arc affinity (Staré Sedlo and

175 Mirotice complexes) into Neoproterozoic and Early Palaeozoic metasedimentary successions of subhorizontal structural record (Žák et al., 2014; Tomek et al., 2015). Later, this boundary was intruded by voluminous syntectonic early Carboniferous arc plutons during regional vertical transpression associated with WNW–ESE arc perpendicular shortening (Žák et al., 2005, 2014). This tectonomagmatic evolution resulted in deep seated steeply dipping NE–SW oriented boundary separating CBPC in the east from contrasting lithologies of the Teplá–Barrandian Unit in the west.

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The transpression regime was later replaced by ductile normal shearing along the Červená Shear Zone, which facilitated exhumation of high grade Moldanubian Domain and formed the inclined eastern boundary between CBPC and Moldanubian Domain (Žák et al., 2012; 2014; Fig. 1). In the study area, the Moldanubian is characterized by mostly shallow to subhorizontal structures and lithological contacts formed during late Variscan orogenic collapse in the central Bohemian Massif (Schulmann et al., 2014; Verner et al., 2014). The eastern margin of the region is further disrupted by the large scale, NNE–SSW trending Rödl–Blanice Fault System, which developed during late Variscan tectonic evolution and was subsequently reactivated during the Cretaceous and Miocene (Prachař, 2022).

Studies of the deep European Variscan crust show that pre–Permian thrusts exposed at the surface are rooted in the lower crust, at the Moho or within the upper mantle (Meissner and Wever, 1986). These observations highlight the importance of investigating the deep structure of the Bohemian Massif to constrain subduction / collision processes and delineate deep sub–vertical tectonic boundaries. The deep crustal structure of the Bohemian Massif has been investigated by several active seismic profiling (e.g., Tomek et al., 1997; Růžek et al., 2003, 2007; Hrubcová et al., 2005; Vavryčuk et al., 2004), which revealed higher P-wave velocities with lower vertical gradient in the Moldanubian crust due to its crystalline rocks exposed at the surface. The Moho beneath this unit forms sharp first–order discontinuity reaching maximum depths to 39 km (Hrubcová et al., 2005), coinciding with minimum surface heat flow (< 50 mW m^{-2}; Čermák, 1977) and suggesting cold and mechanically strong Moldanubian lithosphere (Babuška and Plomerová, 2000).

In contrast, the Teplá–Barrandian Unit is characterized by higher near surface velocity gradients, consistent with its Palaeozoic volcano–sedimentary sequences. The Moho beneath this unit is shallower as documented along the refraction CEL09 profile (Hrubcová et al., 2005, 2017). In addition, two middle crustal reflectors, characterized by modest velocity contrasts (~0.15–0.3 km s^{-1}), are identified along CEL09 at depths of ~7–13 km and 17–20 km across much of the region.

The 2024 and 2025 Mirotice earthquakes occurred within the Moldanubian crystalline basement, slightly west of the deepest Moldanubian root. They were located in the Central Bohemian Plutonic Complex, ~25 km from its contact with the Palaeozoic sedimentary sequences of the Teplá–Barrandian Unit (Fig. 1).

Discussion

When interpreted in a geological framework, the spatial distribution of macroseismic observations from the 2024 and 2025 earthquakes provides insight into deep structure of the Moldanubian and its contact with Teplá–Barrandian (Fig. 1). Macroseismic observations were unevenly distributed around the epicentre, forming a trapezoidal pattern (Fig. 3) bounded by the boundary between the Teplá–Barrandian Unit and the Moldanubian Domain to the west and the Rödl–Blanice Fault System to the east. The enclosed area is dominated by intrusive felsic rocks, mainly granites and granodiorites of the Central Bohemian

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Plutonic Complex and high grade metamorphic Moldanubian rocks, which are characterized by low seismic energy attenuation
215   and thus enable efficient seismic wave propagation.

In contrast, areas located west of the contact exhibit a markedly low density of macroseismic observations. This corresponds
to the geological character of the Teplá–Barrandian Unit, which is dominated by early Palaeozoic sedimentary formations.
Moreover, at the boundary with the Central Bohemian Plutonic Complex, the Teplá–Barrandian Unit is characterized by
220   steeply oriented highly anisotropic deformation structures (Fig. 5). The reduced number of observations suggests increased
seismic energy attenuation within this geological unit. The contrasting lithologies along the NW–SE trending contact are also
expressed in gravity and particularly in geomagnetic data pointing to deep character of this zone (Bucha and Blížkovský, 1994;
Švancara et al., 2021). The Rödl–Blanice Fault System is a N–S trending structure extending across the Moldanubian Domain,
and the observed attenuation of seismic energy along this zone suggests the presence of a deep crustal fault (Fig. 5). In this
225   way, macroseismic observations delineate subvertical features within the Bohemian Massif that are not otherwise detected by
seismic methods.
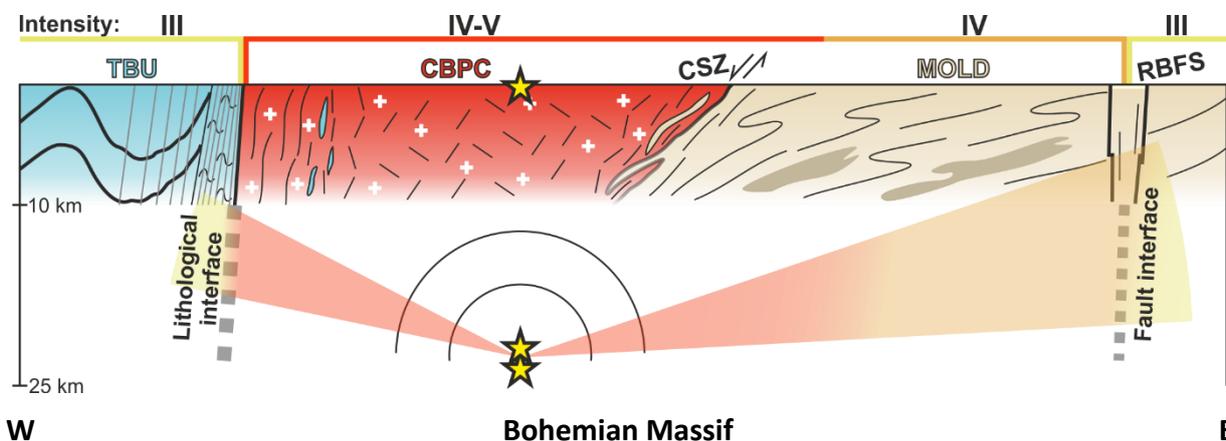
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Figure 5. Schematic cross–section along a segment of the CEL09 profile (see Fig. 1) showing principal geological structures
of the Bohemian Massif (modified after Deiller et al., 2021; Verner et al., 2014; Žák et al., 2005, 2012, 2014) with
spatial distribution of 2024 macroseismic intensity (on top) of the Mirotice earthquakes (yellow stars). Note two
235   interpreted subvertical, crustal scale tectonic boundaries affecting seismic-wave propagation and attenuation: the
lithological contact between the Teplá–Barrandian Unit (TBU) and Moldanubian Domain (Mold) in the west, and the
deep Rödl–Blanice Fault System (RBFS) in the east. CBPC, Central Bohemian Plutonic Complex; CSZ, Červená Shear
Zone.

240 Interpreting the contrasting macroseismic characteristics across the Teplá–Barrandian/Moldanubian contact as a consequence of wave reflections from this zone is unlikely given the geometric constraints. The earthquakes nucleated at depths of 23–24 km, with the horizontal distance to the contact of ~25 km. The subvertical geometry of the contact is unfavourable for generating strong shear-wave reflections back to the surface from such nearby sources. Instead, the non-circular distribution of macroseismic observations outlines major crustal structures: the Teplá–Barrandian/Moldanubian contact in the west is

245 expressed as a deep-seated lithological boundary, whereas the Rödl–Blanice Fault System in the east represents a crustal-scale fault zone (Fig. 5). Finally, the observed pattern cannot be attributed to the source radiation, as the macroseismic field is markedly asymmetric, whereas reverse faulting is characterized by a quadrupolar radiation symmetry.

The Mirotice earthquakes, with focal depths of ~23–24 km, are unusually deep for the region, likely reflecting the low

250 geothermal gradient (Čermák, 1977). Their hypocentres coincide with a reflective interface imaged along the CEL09 seismic profile of the CELEBRATION 2000 experiment, located near the epicentral area (Fig. 1). This interface (Hrubcová et al., 2005) may represent a structural feature that influences earthquake nucleation.

Although smaller in magnitude, the 2025 earthquake (M_L 3.1) was reported more frequently than the 2024 event (M_L 3.5).

255 Together with frequently reported acoustic phenomena for both earthquakes, this indicates efficient seismic wave transmission from depth. Such behaviour supports deep–seated origin of the activated structures and implies a relatively homogeneous crustal medium in the Moldanubian that facilitates both propagation of seismic waves and generation of acoustic signals.

Both focal mechanism solutions are identical, as confirmed by shape identical waveform recordings on nearby stations, and

260 indicate normal faulting on a NW–SE striking plane (Fig. 1; Table 1). The region is influenced by far–field stresses from the ongoing Africa–Eurasia convergence, which transmit compressional stresses from the Alpine belt into the Bohemian Massif. Despite local stress heterogeneity, the maximum horizontal compressive stress (SHmax) is consistently oriented NW–SE in central Europe (Heidbach et al., 2016; Müller et al., 1992). The focal mechanisms reflect a normal faulting stress regime, with a vertical maximum principal stress, a NW–SE oriented intermediate horizontal stress, and a minimum horizontal stress

265 perpendicular to the fault strike. This faulting geometry is consistent with the regional stress field, in which the maximum principal stress in vertical direction is dominated by lithostatic pressure at focal depth and horizontal stress retains the regional NW–SE orientation.

Conclusions

270 The 2024 and 2025 Mirotice earthquakes provide valuable insight into the deep structure of the Bohemian Massif. By integrating seismological analyses with crowdsourced macroseismic observations, this study demonstrates that citizen reported data can effectively capture spatial variations in seismic wave propagation and reveal geological controls on earthquake effects. The unusually large focal depths of earthquakes, normal faulting mechanisms, and efficient wave transmission are consistent

275   with a low geothermal gradient and the presence of deep–seated crustal structures identified by seismic profiling. The non–circular pattern of macroseismic observations delineates deep crustal Teplá–Barrandian/Moldanubian contact as a lithological boundary west of the epicentral area, while to the east, it outlines the crustal scale Rödl–Blanice Fault System. Together, these observations highlight the sub–vertical features within the Bohemian Massif that are not otherwise resolved by seismic methods. The results demonstrate the influence of major sub–vertical crustal scale tectonic boundaries on seismic wave propagation and attenuation. They also underline the value of crowdsourced macroseismic data as a complementary source for

280   investigating deep crustal processes in regions with sparse intraplate seismicity.

Table 1: Focal mechanisms of the 2024 and 2025 Mirotice earthquakes

Earthquake	Strike 1	Dip 1	Rake 1	Strike 2	Dip 2	Rake 2
2024/03	169°	50°	-60°	307°	49°	-121°
2025/04	169°	67°	-55°	288°	42°	-144°

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2 Appendices

Earthquake magnitude and macroseismic intensity

Earthquakes are sudden dislocations within the Earth's crust caused by a release of accumulated stress. They are characterized by the energy discharged during the event. Two main parameters describe earthquake strength: magnitude and macroseismic

290   intensity.

- Earthquake magnitude quantifies the ground displacement recorded by seismic instruments and correlates directly with the energy released at the earthquake source. A single magnitude value characterizes the overall strength of an earthquake. Because magnitude is defined on a logarithmic scale, an increase of one unit corresponds to a tenfold increase in ground–

295   motion amplitude and approximately a thirtyfold increase in released energy. The M_L scale refers to local magnitude, commonly used for small to moderate earthquakes in local and regional studies.

- Macroseismic intensity describes the effects of an earthquake at the Earth's surface at specific locations. It depends on factors such as distance from the epicentre, hypocentral depth, and local geological conditions. Intensity is typically

300   evaluated using macroseismic scales and represented on intensity maps. It generally decreases with increasing distance from the epicentre and is strongly influenced by near–surface geological structures. This parameter is essential for seismic hazard assessment, historical earthquake analysis, and applications in structural engineering and insurance.

The European Macroseismic Scale (EMS–98; Grünthal, 1998), developed by the European Seismological Commission, is used

305 in Europe. It is a twelve–degree scale that evaluates the state of buildings, structural types, age, height, and damage extent. Macroseismic intensity is determined through statistical analysis of data collected from macroseismic questionnaires.

Author contributions

PH: Conceptualization; JV, AP, HKE, PS, and JZ: Data curation; PH, JV, AP, and PS: Formal analysis; PH: Funding

310 acquisition; PH and MM: Writing original draft and visualisation; PH, MM, JV, HKE, PS, and JZ: Writing review and editing.

Competing interests

We declare no potential conflicts of interest.

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