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Seismic imaging of the geodynamic activity at the western Eger rift in central Europe

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ABSTRACT

The western Eger rift at the Czech–German border in central Europe is an important geodynamically active area within the European Cenzoic rift system (ECRS) in the forelands of the Alps. Along with two other active areas of the ECRS, the French Massif Central and the east and west Eifel volcanic fields, it is characterized by numerous CO_2-rich fluid emission points and frequent micro-seismicity. Existence of a plume(s) is indicated in the upper mantle which may be responsible for these observations. Here we reprocess a pre-existing deep seismic reflection profile '9HR' and interpret the subsurface structures as mapped by seismic reflectivity with previous findings, mainly from seismological and geochemical studies, to investigate the geodynamic activity in the subsurface. We find prominent hints of pathways which may allow magmatic fluids originating in the upper mantle to rise through the crust and cause the observed fluid emanations and earthquake activity.

1. Introduction

The Alpine foreland hosts a series of rift zones stretching over a length of over 1000 km, collectively known as European Cenozoic Rift System (ECRS). Graben structures formed on top of massifs originated during the European Variscan orogeny in the late Paleozoic with traces of Tertiary and Quarternary intraplate volcanism (primarily alkaline). Surface expressions of present day magmatic activity can be found at the French Massif Central (Matthews et al., 1987), the east and west Eifel volcanic fields in the Rhenish Massif, Germany (Griesshaber, 1992) and the western Eger rift in the Bohemian Massif located at the Czech Republic–German border (Weinlich et al., 1999) in the form of CO_2 degassing fields. The rifting and volcanism have been modeled mostly as the effect of the Alpine orogene. However, geochemical and geophysical studies suggest that a single or a series of small-scale mantle plumes originating from a thermally and geochemically anomalous layer beneath the European lithosphere may be responsible (Goes et al., 1999; Granet et al., 1995). We present here an investigation into the subsurface of one of these geodynamically active zones within ECRS, the western Eger rift area located at the Czech–German border, using seismic imaging.

Along with CO_2-rich fluid emission fields commonly observed with the other two active parts of ECRS, at the French Massif and Rhenish Massif, the western Eger rift area at the Bohemian Massif is characterized by frequent small-magnitude earthquakes often in large swarms. The seismic activity is sensitive to the fluid activity and may have a possible connection (Bräuer et al., 2008). Isotopic analysis of the emitted fluids shows that they have a significant portion of the upper mantle derived components. In addition, high gas flux and high crustal transport velocity suggest direct degassing channels along deep-reaching faults. Based on these observations, the existence of a magmatic fluid source in the upper mantle has been suggested (Weinlich et al., 1999). The majority of the seismicity in the region is concentrated to an area at the Czech village Nový Kostel close to the Czech–German border (enclosed in the ellipse in Fig. 1) where intermittent swarms of earthquakes with magnitude below 3.5 occur. An earthquake swarm is a series of a large number of relatively comparable, small-magnitude earthquakes with a short time interval between consecutive events, and with no main shock–aftershock sequence as usually observed with fault displacement earthquakes. Documented changes in the regional fluid activity during and after the swarms (Bräuer et al., 2008), seismological studies of the spatiotemporal evolution of the swarm activity (Fischer et al., 2014) and also numerical modeling of the recent swarms in 2000 and 2008 (Hainzl and Ogata, 2005; Parotidis et al., 2003) point to pressurized fluids as being responsible for the seismicity.

Receiver function imaging of the area reveals an updoming of the Moho up to a depth of 27 km with an average depth of 31 km in the

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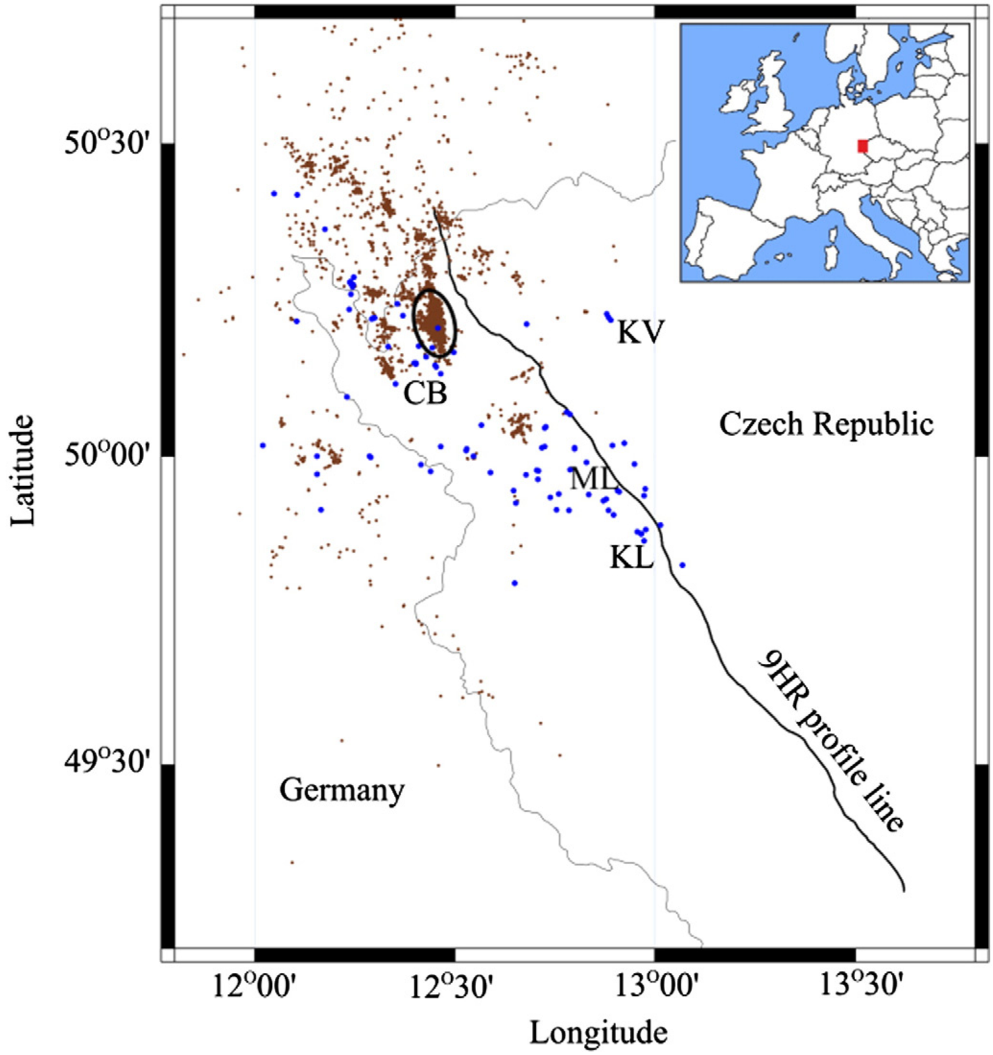

Fig. 1. (a) Map of the study area showing the 9HR profile line along with the regional seismicity during 1991–2011 (brown dots) and fluid escape points (blue dots) in West-Bohemia/Vogtland. Black ellipse represents the swarm area where the majority of the seismicity is concentrated; major gas escape centers are marked as CB (Cheb Basin), ML (Mariánské Lázně), KV (Karlovy Vary), and KL (Konstantinovy Lázně).

surrounding region (Geissler et al., 2005). Anomalies in the receiver functions and also high resolution teleseismic travel time tomography of the upper mantle suggest a velocity increase at 50 km depth followed by a decrease at 65 km depth (Heuer et al., 2006; Plomerová et al., 2007). This has been interpreted as either local updoming of the lithosphere–asthenosphere boundary (LAB), the existence of confined partial melt, or a combination of both.

Based on the above studies, the geodynamic activity of the area has been hypothesized to be caused by magma from a source in the upper mantle which rises to the bottom of the crust (Geissler et al., 2005). At a depth 21–31 km, CO_2-rich fluid separates out and reaches the surface via a number of direct paths. The ascent of the fluid through the crust generates the observed micro-seismicity. We image the subsurface of the region by reprocessing an already existing deep reflection seismic profile '9HR' (Tomek et al., 1997) with advanced imaging techniques in order to find traces of magma bodies, rising fluids and assess the circumstances under which they may produce earthquakes.

2. Geological setting

The Bohemian massif is a large massif occupying parts of Czech Republic, Germany, Poland and Austria. It originated in the Late Paleozoic during the collision between the paleocontinents Gondwana and Laurassia (European Variscan orogeny) and consists of four major geological units: the Saxothuringian zone, the Teplá-Barrandian zone, the Moldanubian zone and the microcontinent Bruno-Vistulian (Kossmat, 1927). The western part of the massif, which is the transition zone of the first three of the above units, is affected by rifting (Eger rift) as part of the European Cenzoic Rifting System. This is where the study area is located.

The crust of the region is composed of magmatic and metamorphic rocks overlayed by unconsolidated sediments of Permo-Carboniferous, Jurassic, Cretaceous and Cenozoic ages. It has been affected by alkaline magmatism/volcanism since the Upper Cretaceous. Active volcanism, which is commonly associated with earthquake swarm activity in other parts of the world, is not present. However, Quaternary-aged volcanoes, Komorní hůrka (0.45–0.9 Ma) and Železna Hůrka (0.17–0.4 Ma), and Mýtina Maar are situated within 15 and 25 km from the swarm earthquake area, respectively (Wagner et al., 2002; Mrlina et al., 2009). Two tectonic faults, the morphologically prominent Mariánské-Lázně fault zone and the Počátky-Plesná fault zone exist within the study area (Bankwitz et al., 2003). Although they intersect each other at the main focal zone of regional seismicity, no direct relationship to the swarm activity has been proven so far.

3. Fluid and earthquake observations and 9HR profile

The CO_2-rich fluid is released in free or dissolved state through eight moffette fields (dry gas vents) and more than 100 mineral springs spread over the region (blue dots in Fig. 1). The fluid emanation points can be grouped into four major gas escape centers (Weinlich et al., 1999): Cheb Basin, Mariánské Lázně, Konstantinovy Lázně, and Karlovy Vary (Fig. 1). The gas emitted at all these centers consists primarily of CO_2 (99%), N_2, He and CH_4. The air corrected $^3He/^4He$ ratio varies across different centers over a range between 2.4 and 6.1 with a maximum at the Cheb Basin center. These values are very high compared to a typical crustal value of less than 0.1, which points to the mantle origin of the fluids (Bräuer et al., 2008).

Systematic monitoring of the regional seismicity shows that for the period 1991–2011 it spreads over an area of approximately 40 × 60 km (brown dots in Fig. 1) with the majority of the earthquakes occurring within a 12 × 15 km area and down to a depth of 15 km. During this time span, three massive earthquake swarms took place in the years 2000, 2008 and 2011 with more than 5000 located events that reached magnitudes of up to 3.5. The swarm earthquake hypocenters cluster on a near-vertical plane between depths of 7 and 11 km (Horálek and Fischer, 2008).

The 9HR profile (Tomek et al., 1997) is approximately 200 km long, starting at the Czech–German border in the north-west and stretching to southern Bohemia in the south-east (Black line in Fig. 1). It passes by the main focal zone of the regional swarm seismicity at a distance of about 4 km; then it runs directly through two of the four major degassing fields, the Mariánské Lázně and Konstantinovy Lázně gas escape centers. The location of the profile is therefore well-suited to study the geodynamically active subsurface below these observations. The profile was acquired in the early 1990s and was then processed with post-stack migration technique to study the tectonics of the greater region. The migrated section (Tomek et al., 1997) did not present any significant feature(s) that may relate to the fluid activity or the earthquake observations. We reprocess 150 km of this profile starting from its north-western end, which is close to the fluid and earthquake observations, with a pre-stack migration technique (Kirchhoff pre-stack depth migration). Since pre-stack migration is more appropriate for the crystalline crust in the area, it is expected to reveal new features over the post-stack method used previously.

4. Data and methodology

The 9HR profile was acquired by employing dynamite sources at 20 m deep drillholes with a split-spread geometry, a maximum offset of 5 km on each side of the shot point, and with a shot and geophone spacing of 200 m and 50 m, respectively. A total recording length of 24 s with a sampling interval of 4 ms was used. The data quality is in general very good; we preprocessed it only minimally by trace normalization, automatic gain control (window length 0.4 s), band-pass filtering (15–20–35–40 Hz, dominant signal frequency is 25 Hz) and first-arrival muting (Fig. 2).

Kirchhoff prestack depth migration (Buske, 1999) was implemented as a weighted stack along diffraction surfaces for each shot gather and the absolute values of these migrated shot gathers were subsequently stacked to obtain the final image. The required diffraction travel times were computed using an Eikonal solver. For this step, we used the same 1D velocity model that is employed by the local seismological network (WEBNET) to locate the swarm seismicity (Málek et al., 2005). Then, a direct comparison of the reflectivity and the seismicity is justified because the same velocity model is used for reflection imaging and locating the earthquakes.

5. Subsurface reflectivity along 9HR profile

The reprocessed seismic reflectivity image from 9HR profile (Fig. 3a) reveals a strongly reflective upper and lower crust with a number of distinct reflective zones. The Moho can be identified as the bottom of the reflective lower crust at depths of about 29–40 km which agrees with the reflective lower crust obtained by Hrubcová et al. (2005, 2013)

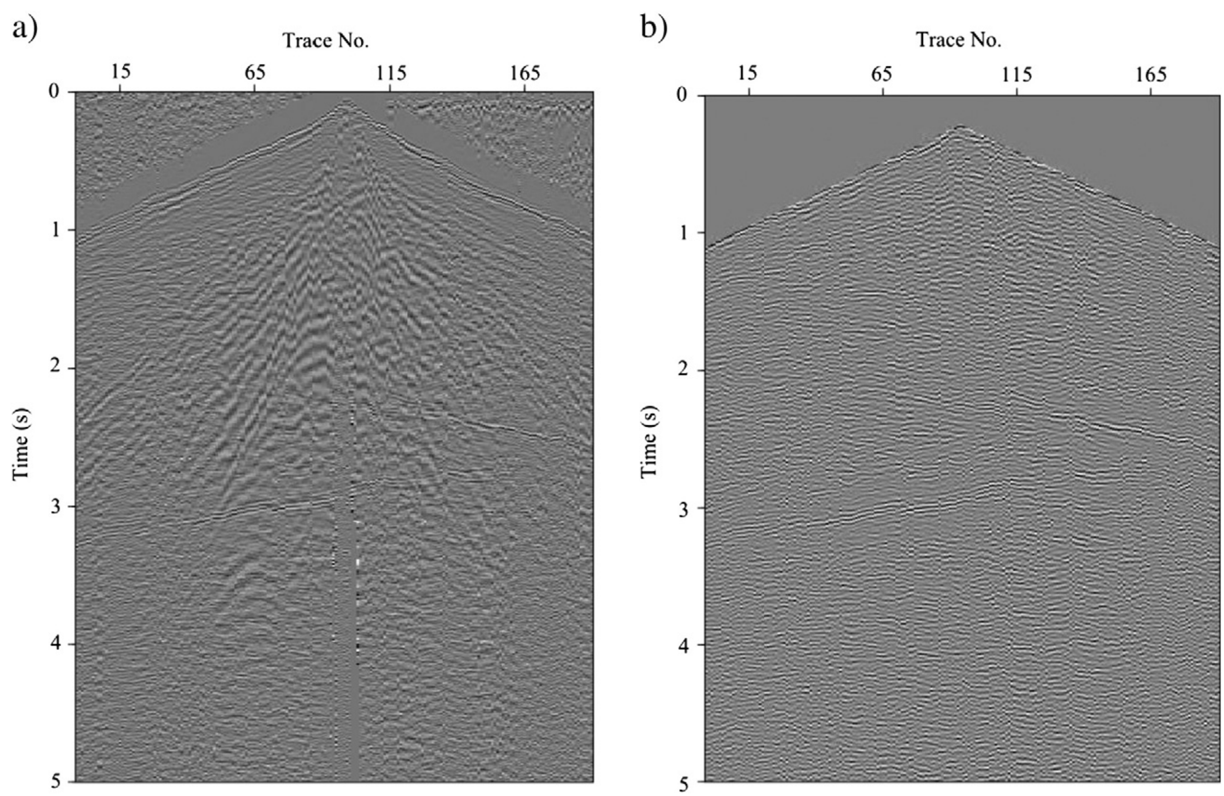

Fig. 2. (a) A raw shot gather of 9HR profile (automatic gain control applied). (b) The same shot gather after trace normalization, band-pass filtering and first arrival muting.

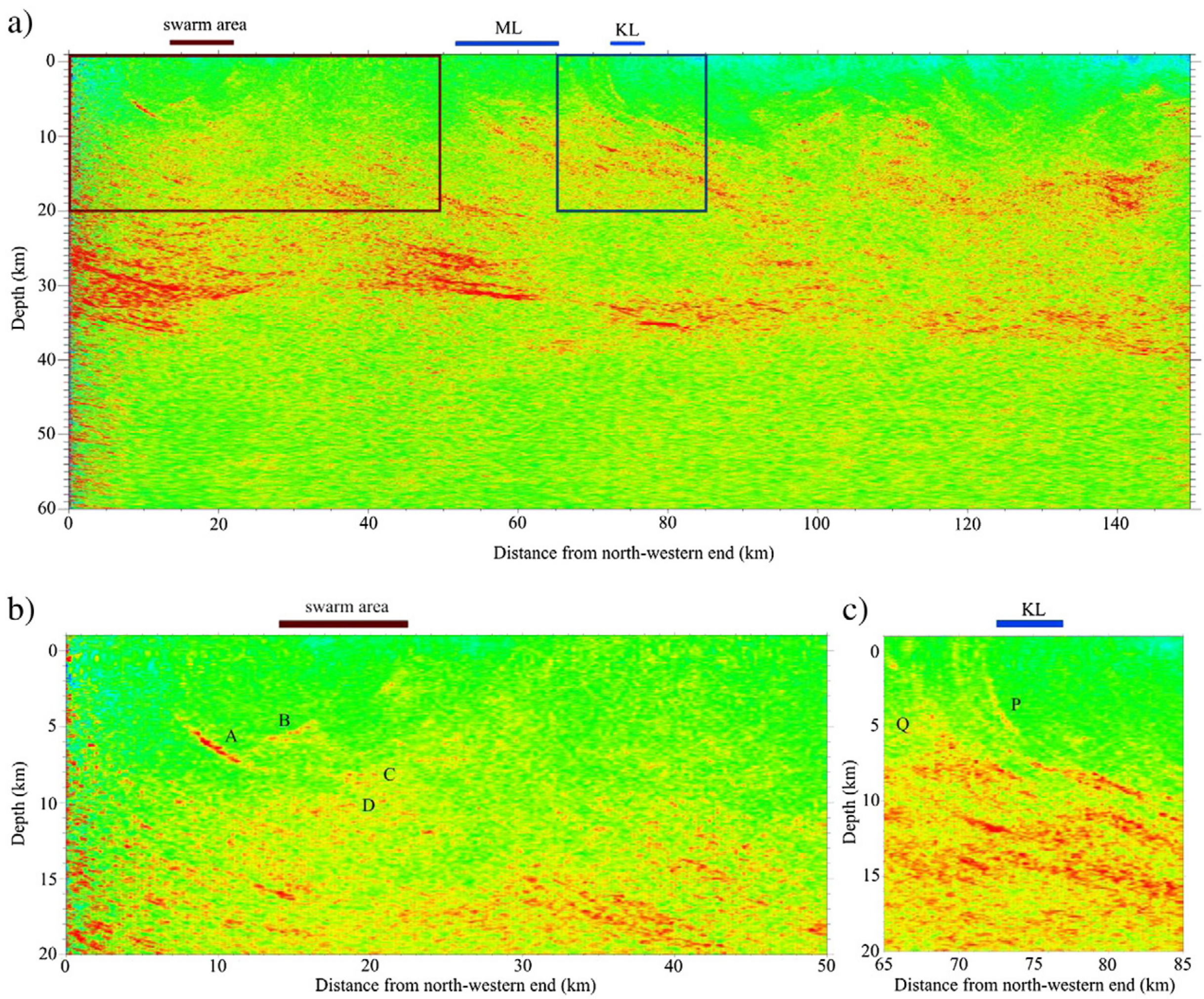

Fig. 3. (a) Kirchhoff-prestack depth migrated section of the 9HR profile. (b) Enlarged NW part of the profile close to the swarm area (brown rectangle in (a)). (c) Enlarged part near the Konstantinovy Lázně (KL) gas center (blue rectangle in (a)).

from refraction and micro-earthquake waveform modeling studies. The shallower Moho is observed at a distance between 20 and 40 km along the profile with an updoming to a depth of around 29 km. This is in good agreement with the results obtained from receiver functions (Geissler et al., 2005). No prominent reflector can be observed in the upper mantle as well as in most parts of the profile from the surface down to a depth of approximately 3–4 km. However, the latter is caused by the generous muting of the first arrivals and lack of a reliable and detailed near-surface velocity model.

Directly below the main focal zone of regional seismicity, two distinct reflectors dipping at -45^0 and 40^0 from horizontal (bright spots A and B) are visible at a distance of 7–18 km along the profile at a depth of about 7 km (Fig. 3b). Another less pronounced reflector (bright spot C) is visible at a distance of about 17 km along the profile at a depth of 8 km. Furthermore, significant but more diffuse crustal reflectivity dominates the area at depths greater than 10 km along with occasional strong sub-horizontal reflectors at various depths. The upper edge of this diffuse reflectivity zone below the bright spots A, B, and C is indicated as D.

Similar to that below the earthquake area, a diffusely reflective zone appears at a depth of 5 km immediately below the Mariánské Lázně and Konstantinovy Lázně gas escape centers (Fig. 3a, c) with frequent strong reflectors. Its upper boundary is marked as Q. Also, beneath the Konstantinovy Lázně gas escape center, a prominent near-vertical reflector P can be observed dipping at 10^0 from vertical (Fig. 3c).

In comparison to the post-stack migrated image by Tomek et al. (1997), the reprocessed image shows a significant amount of new structural information. None of the features described above are traceable in the former image. In fact, such high resolution is rarely achieved in the crystalline crust. In this regard the reprocessing was highly successful and provides ample scope for investigating the geodynamic activity in the study area in relation to the newly imaged reflectors.

6. Subsurface reflectivity and the geodynamic activity

Below the imaging depth of 60 km, no reflection is detected from the mantle that may hint towards the existence of a magma body. However, Moho updoming is clearly observed in accordance with other imaging studies directly below the area where the majority of the regional seismicity is confined. The prominent multiple sub-horizontal reflectors at the upwelled Moho, together with the highly diffuse reflectivity arranged in an anticline structure immediately above it (Fig. 3a), possibly relate to the crustal deformation caused by the tectonic forces generated by the Moho updoming.

6.1. Subsurface reflectivity vs earthquake observations

Down to a depth of 10 km below the main focal zone of the regional seismicity, the crust is characterized by diffuse reflectivity with many strong sub-horizontal reflectors appearing at various depths (Fig. 4a). We interpret the reflectivity as a highly fragmented permeable middle and lower crust below a rather intact and less-permeable upper crust. If a fluid reservoir exists in the lower crust or upper mantle, then the

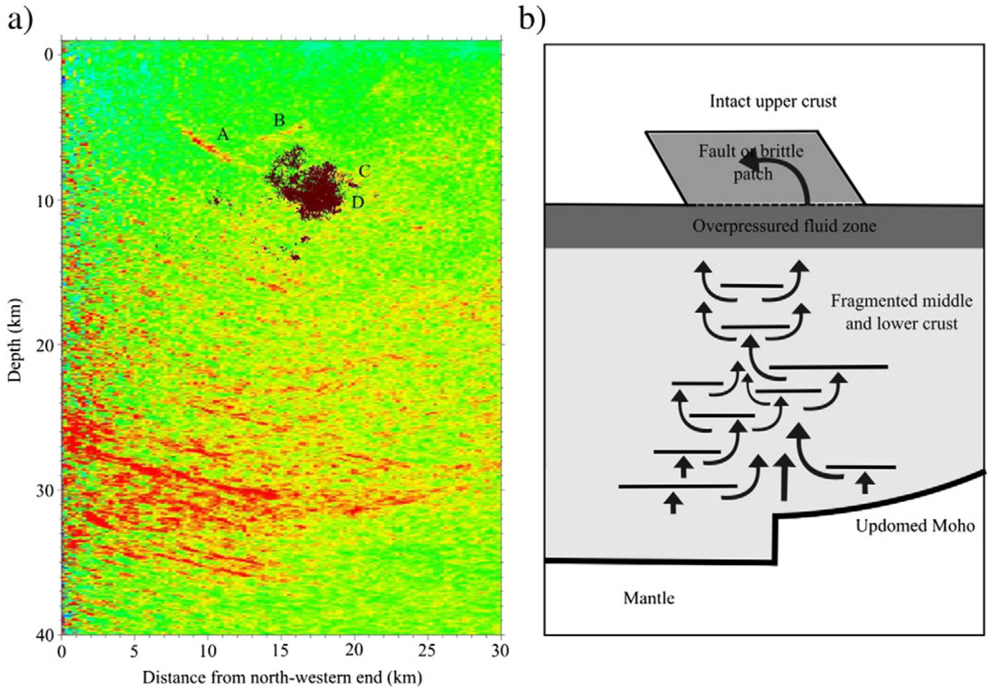

Fig. 4. (a) Swarm area from year 1991 to 2011 (brown dots) projected onto the migrated section. (b) Schematic sketch with the main interpreted features.

fluids can rise up through such a strongly fragmented crust producing even more diffuse reflectivity, accumulate at some discontinuity at depth of 10 km (bright spot D in Fig. 4a) and develop a zone of overpressured fluid (Fig. 4a, b). The presence of such a fluid trap is supported by the occurrence of many gas escape points adjacent to the swarm area, which confirms active fluid flux below but none directly above it. We further interpret the sub-horizontal reflectors within the diffusely reflective crust as local interruptions of the ascending fluid at different tectonic fractures or lineaments, thereby producing higher reflectivity due to the presence of high-pressure fluid.

The hypocenters recorded during the recent massive earthquake swarms in the years 2000 and 2008 against the seismic reflectivity image show that the swarm activity initiates at bright spot D with a sudden spontaneous upward movement of a large number of hypocenters (magenta dots in Fig. 5a, e). Although the foci migration is rather complex in detail, a prevailing upward spreading is observed in both swarms (Fischer et al., 2014). Considering a supposed existence of an over-pressured fluid zone immediately below bright spot D, it gives the impression of a sudden release of critically-pressurized trapped fluids into less permeable rocks above it by simultaneously fracturing

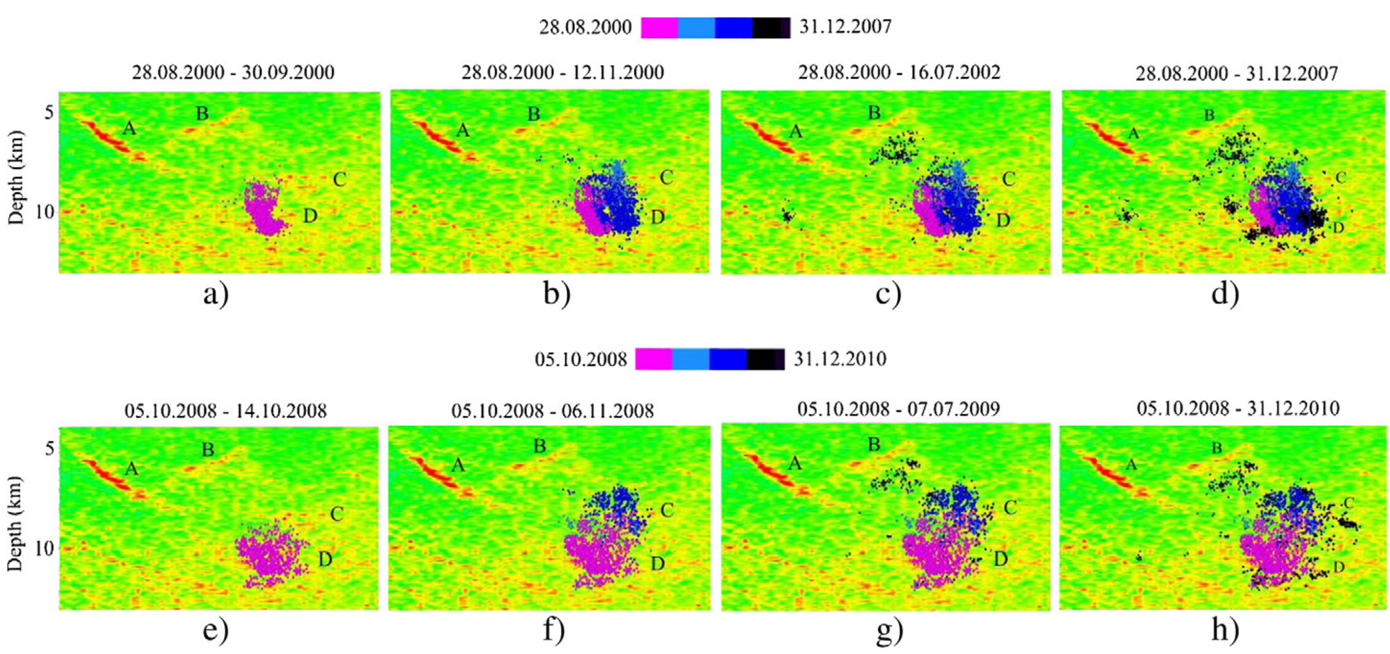

Fig. 5. Spatiotemporal evolution of the swarms (pink to blue symbols) in year 2000 (top) and 2008 (bottom) with respective subsequent seismicity (black) projected onto the reflectivity image. Events plotted in a cumulative manner.

and intruding into an overlying zone of weakness and redistributing the local stresses in the zone. Such a hypothesis linking pressurized fluids with the micro-earthquakes is in accordance with the observed influence of swarm activity on the fluid activity (Bräuer et al., 2008), models of swarm hypocenter migration in terms of fluid movement (Fischer et al., 2014) and numerical modeling of the swarms as diffusion of a pressurized fluid injected into a poroelastic medium (Hainzl and Ogata, 2005; Parotidis et al., 2003). The further evolutions of the two swarms are also similar and can be explained by the fluid migration concept. After the initial sudden upward movement, the hypocenters ascend further with another sudden large number of events occurring at bright spot C (blue dots in Fig. 5b, f) followed by an immediate downward movement in the case of year-2000 swarm (dark blue dots in Fig. 5b). This may indicate the existence of a relatively strong barrier that obstructs the ascent of the fluids. In the later periods of both swarms (since the second half of November 2000 and 2008, respectively), the upward hypocenter migration is stopped beneath bright spot B and it then spreads in a cluster aligned with the local inclination of the bright spot (black dots in Fig. 5c,g). This may be interpreted as the ascending highly-pressurized fluids being blocked by a non-permeable boundary above and having no alternative but to turn and follow the boundary, further generating earthquakes until losing all of its energy. After the termination of both swarms, the seismicity appears randomly throughout the swarm volume (black dots in Fig. 5d, h). Such additional earthquakes should naturally be generated as the system returns slowly to equilibrium.

While the above hypocenter migration pattern is prominent for the massive swarms of year 2000/2008, it however may not be clearly observed for every other swarm that took place in the area. This could be due to reshaping of the fault/brittle zone following a swarm (due to new fractures introduced) or fluid intrusion through different fault(s)/brittle zone(s) for different swarms or simply absence of sufficient energy of the intruding fluid to cause enough seismicity so that the complete pattern is visible.

Furthermore, the main cluster of the regional seismicity (including the swarms of years 2000 and 2008) is restricted primarily along a sub-vertical plane (Horálek and Fischer, 2008). Therefore, the intrusion of the fluids from the over-pressured fluid zone could possibly have taken place along a relatively permeable planar zone such as a fault or a brittle patch that extends from the fragmented permeable middle crust into the less-permeable units above it (Fig. 4b). Bright spot (A) and the adjacent reflector (B) define the upper boundary of the seismicity and may then be identified as the upper edge of this semi-permeable zone. Existence of such a zone is also supported by the observation that the ascending swarm activity in both years 2000 and 2008 could not penetrate above the bright spots and instead spreads along them (Fig. 5c and g) suggesting a blockage of the earthquake-producing ascending fluids by a non-permeable boundary overhead. Particularly, the highly reflective and laterally-limited bright spot A can be well explained by entrapment of highly pressurized fluid.

Based on the above arguments the following driving mechanism for the frequent swarm earthquakes at the western Eger rift area may be hypothesized (Fig. 4b). Fluids from a reservoir in the upper mantle rise through fragmented lower crust and are blocked by less-permeable units in the upper crust developing an over-pressured fluid zone. After a critical pressure state is reached, fluid from this zone forces its way into a semi-permeable fault zone above. This alters the stress distribution in the zone and produces swarms of micro-earthquakes. After relieving the critical energy this way, the system then returns to equilibrium until the critical pressure state is reached again due to the continuous ascent of fluid from the reservoir below. A similar concept of swarm-generating fluid migration has been proposed recently by Shelly et al. (2013) at the Yellowstone caldera.

A stress analysis using events from the year 2008 swarm shows that the events can be assigned to two principle fault planes (Vavryčuk et al., 2013). The seismicity distribution can be divided into two interconnected major segments that are located along these planes. This result agrees well with the above hypothesis of fluid intrusion through a fault zone causing the earthquakes.

6.2. Subsurface reflectivity vs fluid observations

The diffusely reflective crust from a depth of 5 km directly below the Mariánské Lázně and Konstantinovy Lázně gas centers (upper edge marked by Q) hosts characteristic strong reflector segments dipping at -40^0 to -45^0 from horizontal (Fig. 6a). The overall reflectivity pattern is similar to that observed at the earthquake area (below 10 km depth) and we can again interpret the diffuse reflectivity as fragmented permeable crust through which fluid can migrate and the reflector segments as local interruptions of the ascending fluid at small-scale discontinuities. Considering the alignment of the reflectors, they may represent parts of tunnel-like structures that can act as fluid conduits and allow for the direct transport of fluids as was indicated by the fluid studies (Weinlich et al., 1999). The region continues down to Moho with the reflector segments now oriented sub-horizontally, and has a connection to the updomed part of Moho. Fluids from a reservoir in the upper

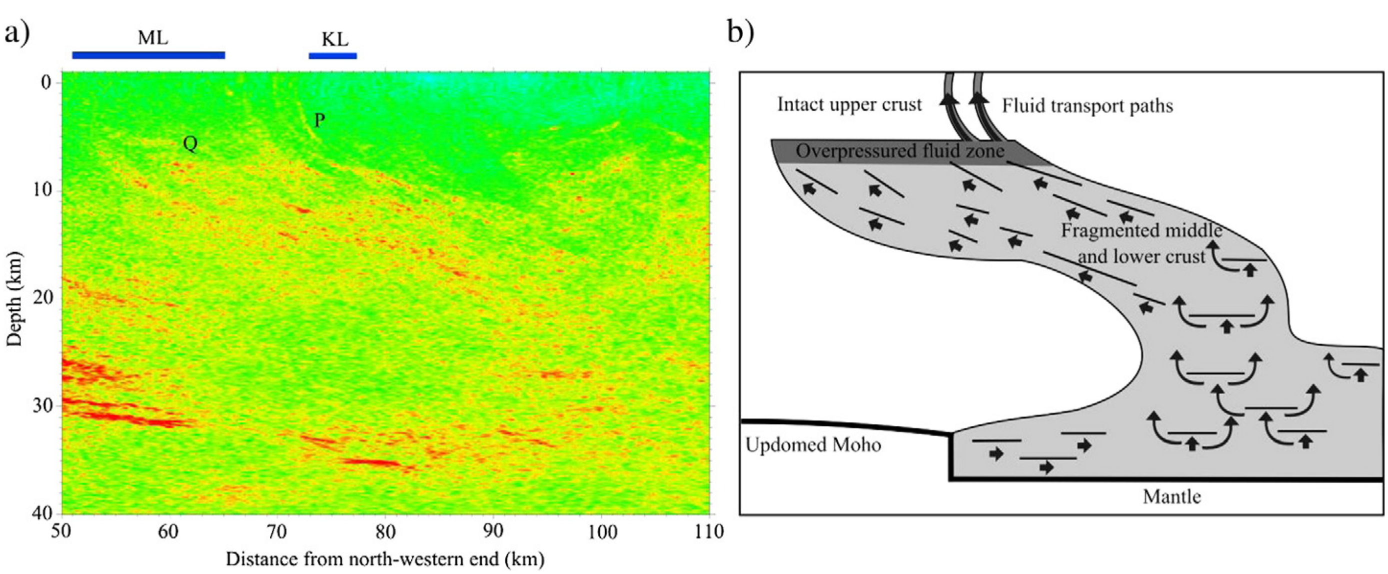

Fig. 6. (a) Reflectivity image below Mariánské Lázně (ML) and Konstantinovy Lázně (KL) gas escape center. (b) Schematic sketch with the main interpreted features.

mantle can rise along such fragmented crust and accumulate and possibly produce an over-pressured zone similarly as at the earthquake area, at a depth of 5 km below the gas escape centers (Fig. 6b).

Immediately below Konstantinovy Lázně degassing center, which has several degassing points directly on the 9HR profile (Fig. 1), some indications of sub-vertical fault-like structures can be identified (e.g. bright spot P in Fig. 3c, a), which appear to merge at greater depths into the underlaying region of diffuse reflectivity (upper edge marked by Q). Such features may represent local near-surface channels that can transport accumulated fluid from an over-pressured fluid zone below to the surface (Fig. 6b). Unfortunately, due to the large-scale nature of the 9HR survey, the resolution in the shallow subsurface is limited and only some hint of these fluid transport features can be seen here. Directly below the Mariánské Lázně degassing center, any near-surface features similar to the bright spot P are absent. However, its fluid emission points are widely distributed over a large area. Therefore, the corresponding near-surface transport channels may not reflect seismic energy detectable by the 9HR source-receiver geometry.

7. Conclusions

The seismic reflectivity image of the western Eger rift obtained by reprocessing the deep seismic reflection profile '9HR' reveals a number of new and significant subsurface features apparently related to the geodynamic activity at the area. While the reprocessed profile imaged structures down to a depth of 60 km, it did not directly image any magma body in the upper mantle or lower crust. However, it does show structures that may indicate that magmatic fluids from a common root, possibly corresponding to the upwelled Moho, ascend through regions of fragmented crust and accumulate at a depth of 10 km below the main earthquake zone and 5 km below the major degassing fields and form over-pressured fluid zones. Below the earthquake area, a semi-permeable zone may exist into which critically over-pressured fluids intrude and produce the observed micro-seismicity. Below the degassing fields, the over-pressured fluid may further rise along near-surface channels and cause the observed fluid emissions. A mantle plume(s) below the western Eger rift, as suggested by receiver functions and tomography studies, may act as the source for these magmatic fluids.

Despite the fact that the reprocessed 9HR profile sheds considerable light on the crustal structure beneath the study area, it is only a 2D line. Therefore, it does not represent the 3D situation beneath the area (e.g. the swarm area has a lateral offset of several kilometers from it). New reflection seismic studies could be useful in this regard, in particular to see how the structures imaged by the 9HR profile extend laterally and how they agree with the conclusions drawn here.

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