Western Eger Rift in Central Europe: active magmatic emplacement from combined seismological and isotope studies

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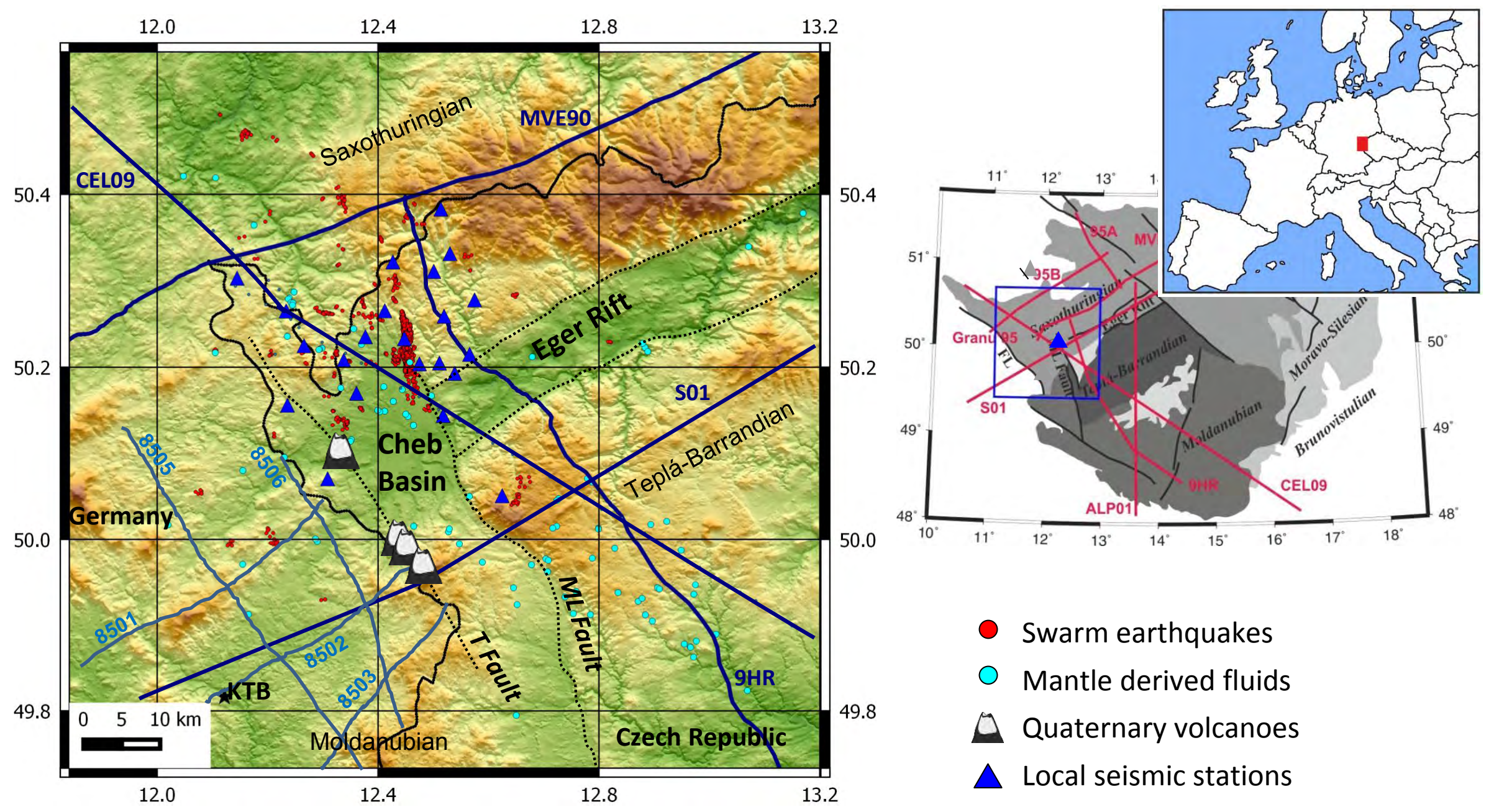
Western Eger Rift intracontinental geodynamic region



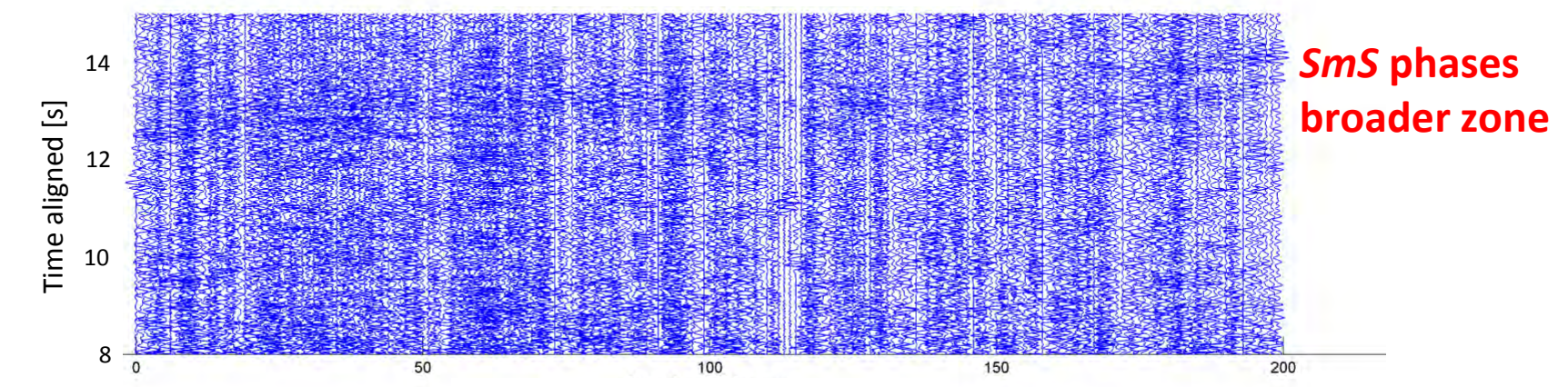
Seismicity at lithospheric plate boundaries can be accompanied by magmatic processes, which play fundamental role in formation and differentiation of the Earth's crust. These processes are connected with magmatic emplacement as a result of an ongoing magmatic activity at the lower crustal level. Though they are usually confined to lithospheric plate boundaries, they can also occur in intraplate setting, however there, they are a rare phenomenon not commonly observed or discussed. Seismic and seismological interpretation must be supplemented by multidisciplinary research helping in detection of such areas and leading to advanced tectonic implications.

The western edge of the Eger Rift in central Europe as a part of the European Cenozoic Rift System represents such a case. It is a geodynamic region abundant of repeated seismic swarms and mantle derived fluids emanating at the surface, Cenozoic volcanism, and neotectonic crustal movements at the intersections of major intraplate faults showing diverse phenomena and representing unique European intracontinental setting. Strong lateral variations of the lower crust documented from wide-angle data, supported by results from local seismicity, indicate two types of magmatic emplacement at the crust-mantle level. Xenoliths from corresponding depths document the origin depths of the magma at the lower crust/upper mantle transition. Increased helium isotope ratios in CO2-rich gases evidence lithospheric mantle origin and can constrain timing of processes. The character of the lower crustal material combined with isotope studies enable to differentiate two episodes of tectonic setting with different times of origin. Spatial and temporal relations to recent geodynamic processes suggest active magmatic processes in the intracontinental setting in this area.

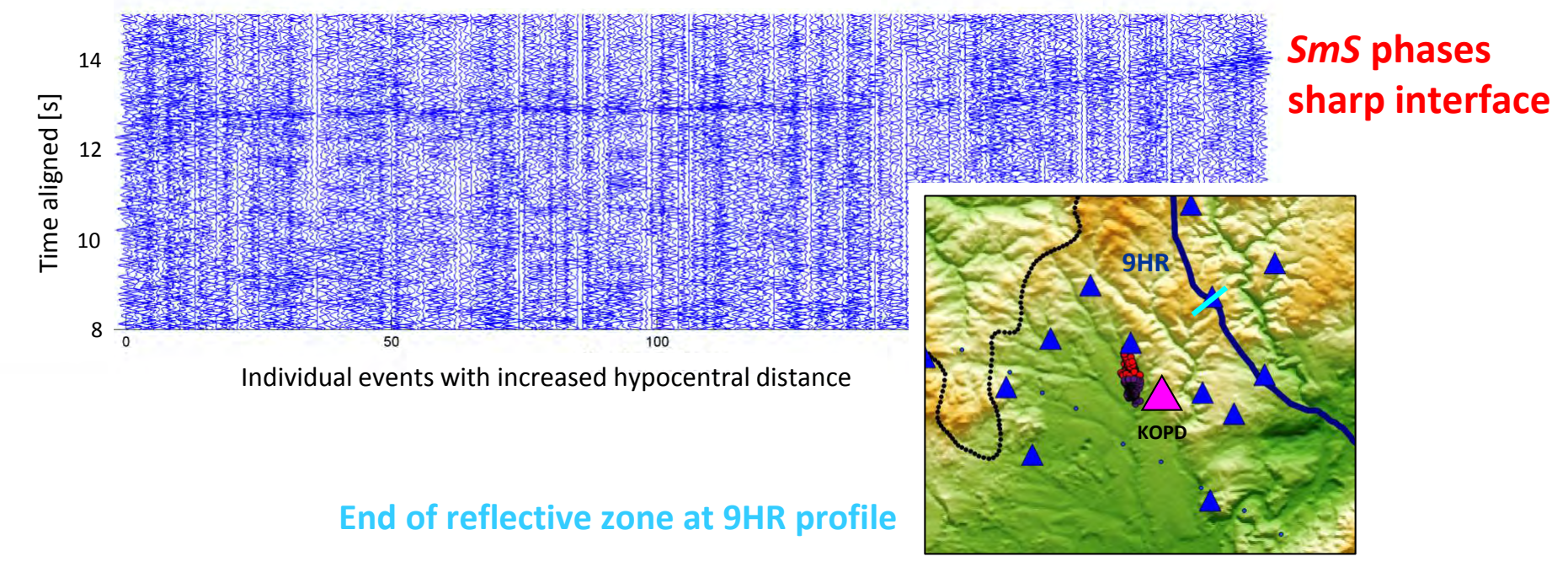
Lower crust from local seismic sources

Reflective zone vs strong-contrast interface from reflected *SmS* Moho phases

Data from northern part of EQ cluster

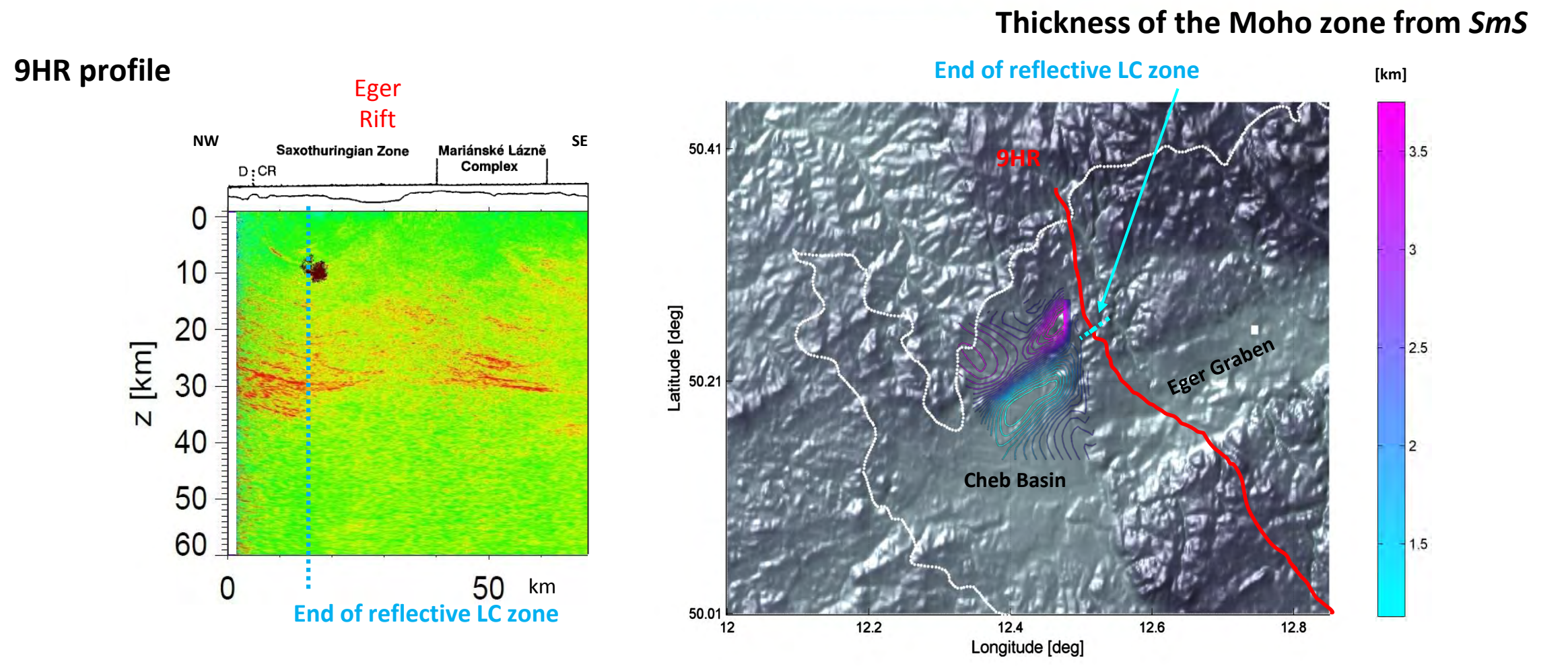


Data from southern part of EQ cluster



The Moho transition from reflected *SmS* Moho phases in waveforms of local seismicity recorded at WEBNET network stations (after *Hrubcová et al.,* 2013). Waveforms are *P*-wave aligned and sorted according to time of the *SmS* phase for each event. Waveforms from the northern part of seismic cluster (red dots) exhibit less pronounced *SmS* phases with more reflectivity indicating broad reflective zone in NW; data from the southern part of this cluster (violet dots) show strong *SmS* phase indicating one sharp interface as the top of the lower crust in SE.

Comparison of lower crust in 9HR reflection profile with results from local seismic sources



Reflection profile 9HR with the projection of swarm earthquakes in the upper crust above sharp changes of lower-crustal reflectivity. Thickness of the Moho reflective zone from interpreted local seismicity.
Note abrupt termination of seismic reflectivity at 9HR profile coinciding with sharp Moho from local earthquakes. Its SW trend is parallel with the prolongation of the NW flank of the Eger Rift zone.

Magmatic emplacement

Origin

- **Occurs when basaltic magma is trapped during its rise at crust/mantle boundary**
- **Due to difference in densities of magma and surrounding rocks**
- **When magma cools, the lower crust thickens**

Characteristics of the lower crust

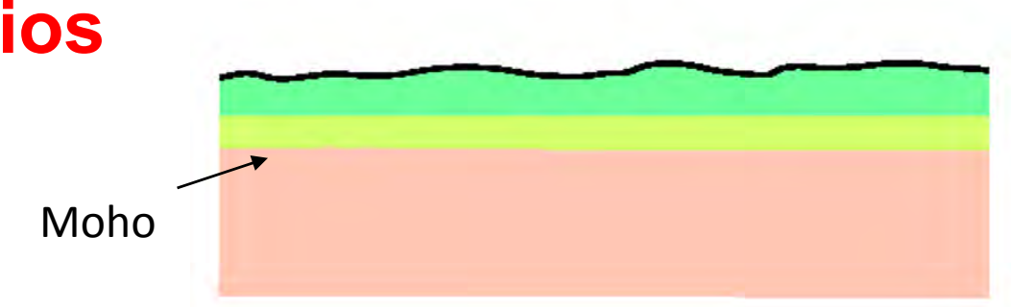
- **High seismic velocities (6.9 – 7.8 km/s)**
- **Increased densities compared to surrounding felsic crustal rocks**
- **Upper and lower boundaries – strong seismic reflectors (despite relatively small velocity contrasts)**
- **Sometimes with seismic reflectivity – sill intrusions**
- **Sometimes reflection-free bodies – massive magma cooling**

Western Eger Rift

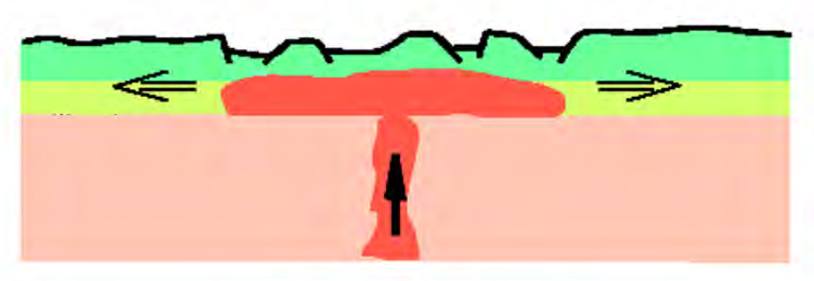
- **High-velocity lower crust – related to magmatic emplacement**
- **Two types of LC**
- **Represent two episodes with different timing and tectonic setting**

Possible scenarios

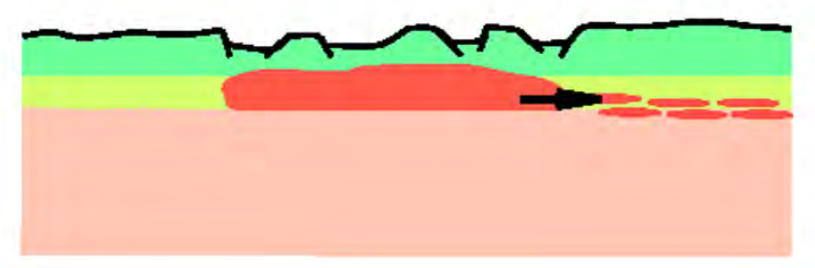
Original model



Crustal stretching with massive mafic intrusion/underplating of crustal batholith



Layered intrusion/emplacement along Moho at late stages of development

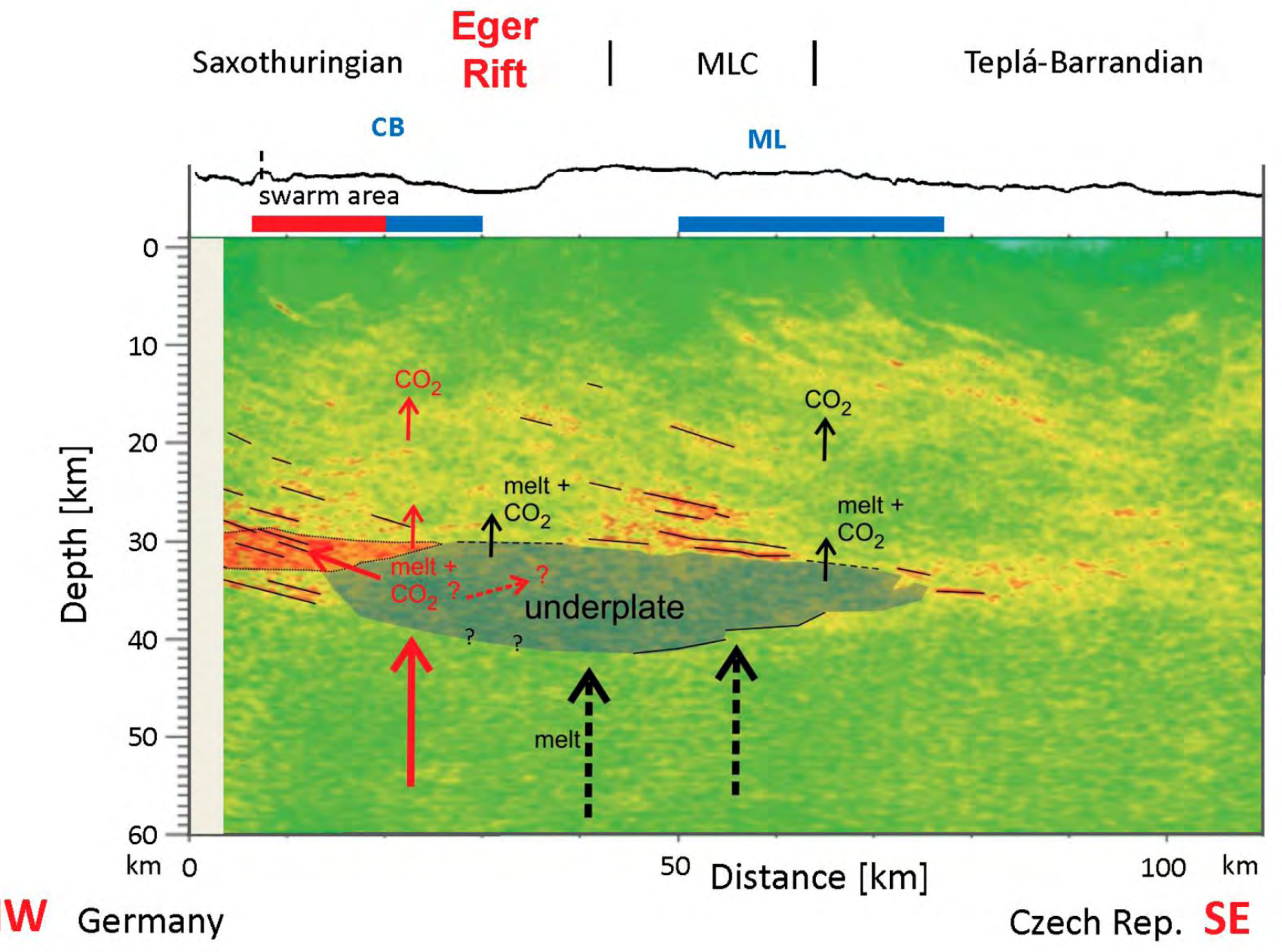


Seismic reflectivity represents elongated "thin" mafic bodies interpreted as sill-like intrusions into pre-existing less mafic continental lower crust. Massive magma chamber cooling results in reflection-free bodies (after *Thybo and Artemieva*, 2013).

Late Cenozoic magmatic body

The western Eger Rift exhibits high-velocity lower crust with both high reflectivity (lamination) lower crust in NW and reflection-free lower crust with strong reflector at its top in SE. Since the character of the seismic lower crustal image differs laterally, the timing and the tectonic setting of the these two types of lower crust differ, too.

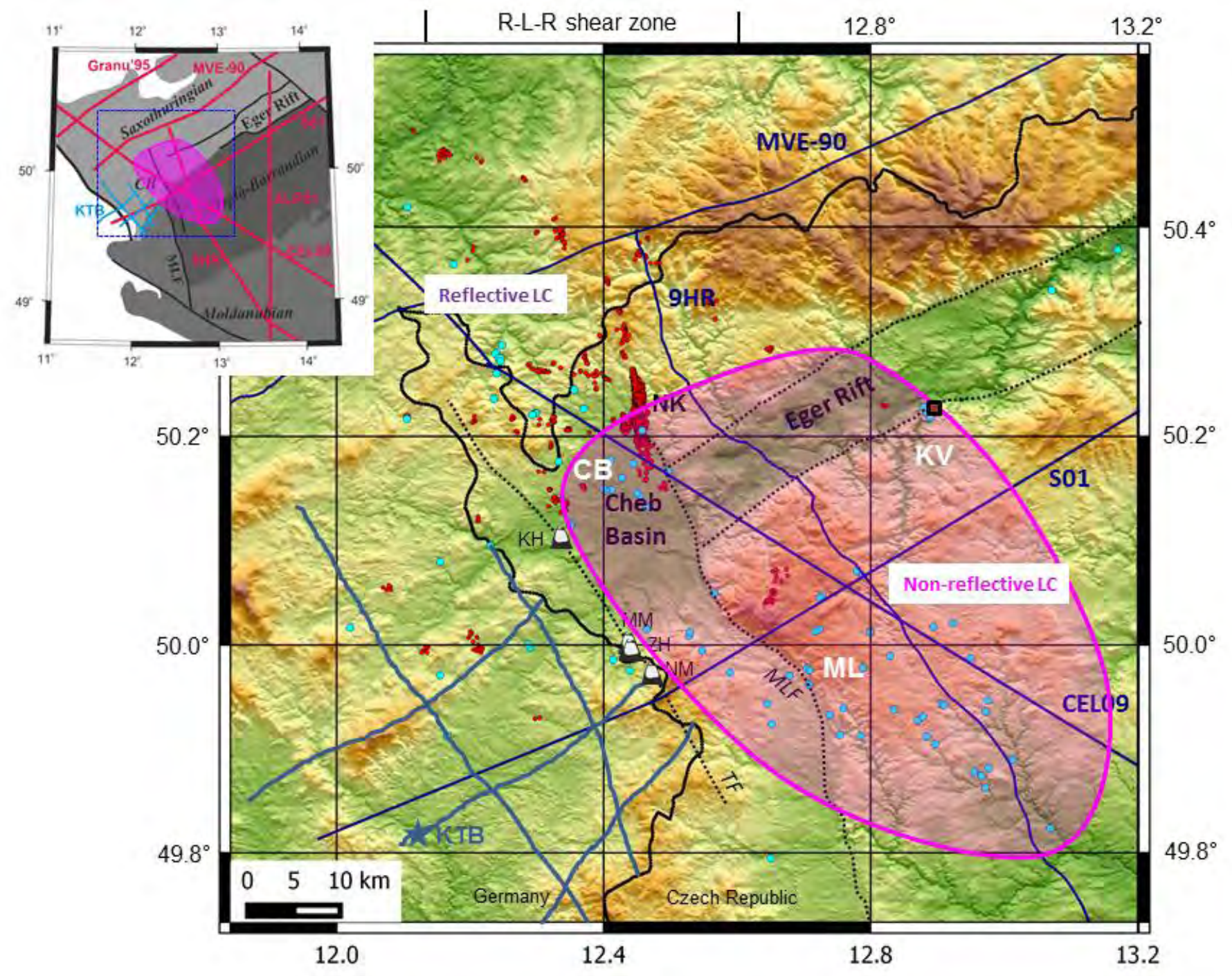
	CB	ML
Gas flow (l/h)	**> 100 000**	**> 100 000**
CO_2 (vol.%)	**> 99**	**> 99**
Highest $^3He/^4He$ (Ra)	**6.3**	**4.6**
ESCM He (%)	●	◕



The schematic cross-section based on pre-stack image of the 9HR reflection profile (after *Mullick et al.,* 2015) indicating presumed shape of non-reflective underplated Late Cenozoic magmatic body and its delimitation from surrounding reflective Variscan lower crust.

The red arrows suggest probable paths for the activity, black arrows indicate steady state activity and if dashed, it indicates activity in the past. Since different datasets are merged, the structure of the lower crust highlights relative differences and lateral changes; absolute depths depend on velocity model applied. The fluid characteristics for CB and ML degassing centers indicated in the upper part. ESCM, European subcontinental mantle; MLC, Mariánské Lázně Complex.

Lateral extent of magmatic body



Lateral extent of Late Cenozoic reflection free magmatic body in the lower crust with strong reflector at its top projected at the surface. Indication according to seismic results complemented by assumed limits according to gas-geochemistry and volcanic activity. Degassing centers Cheb Basin CB, Mariánské Lázně ML, and Karlovy Vary KV indicated. Brown rectangle represents the occurrence of hydrothermal travertine in KV.

Delimitations

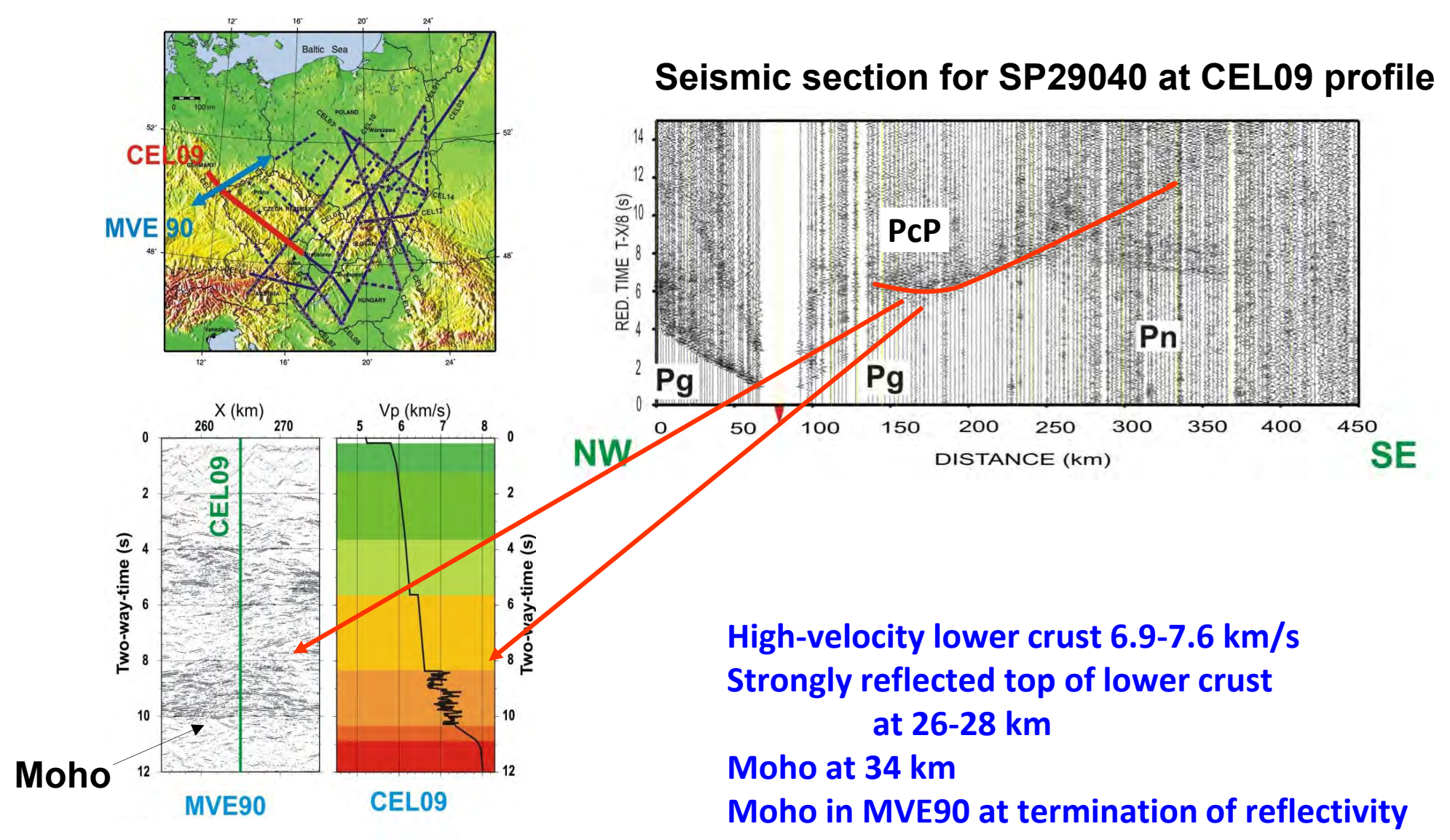
- **Termination of reflectivity at the 9HR profile (15 km and 75 km)**
- **Termination of reflective zone from local seismic sources**
- **Termination of reflectivity of reflection profiles KTB at Tachov Fault**
- **Occurrence of mantle fluids in degassing centers CB and ML**
- **Degassing centre KV with the hydrothermal activity documented by travertine (age 0.23 Ma)**
- **Quaternary volcanics along the Tachov fault**

Seismic characterization of the lower crust – high velocity lower crust with two types of crust/mantle transition

Reflective high-velocity lower crust in NW

Active seismic investigation
Receiver functions

Reflection profile MVE90 & CEL09

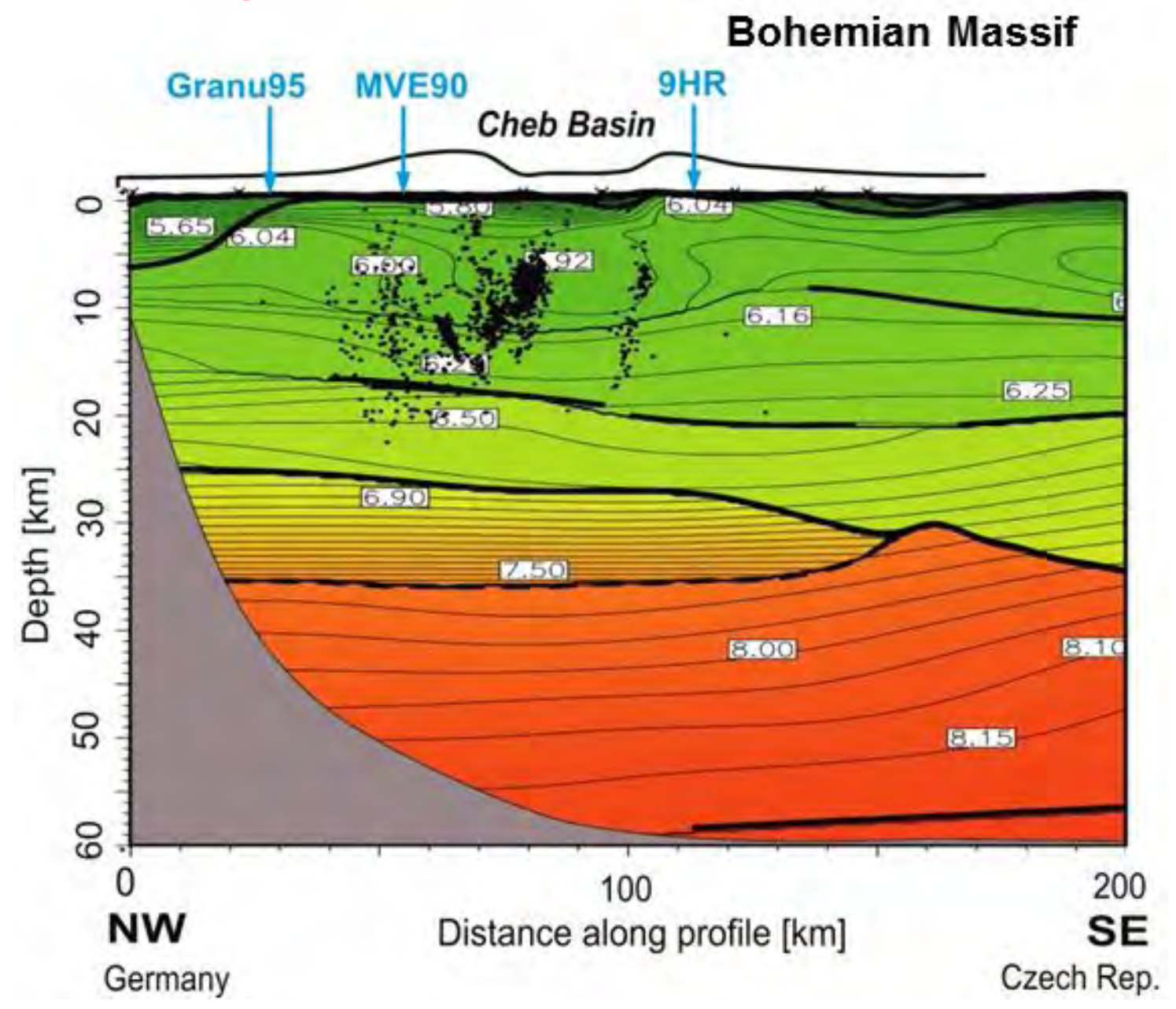


High-velocity lower crust 6.9-7.6 km/s
Strongly reflected top of lower crust at 26-28 km
Moho at 34 km
Moho in MVE90 at termination of reflectivity
Moho reflections not visible in CEL09 refraction data

Increased reflectivity at the base of the crust along the reflection profile MVE90 (*DEKORP Research Group*, 1994) with the 1-D velocity model from the refraction and wide-angle reflection profile CEL09 (converted to two-way traveltime) at the crossing point. High-velocity lower crust interpreted along the profile CEL09 (after *Hrubcová et al.*, 2005) exhibiting highly reflective top of the lower crust at depth of 27-28 km visible also in seismic data (*PcP* phase).

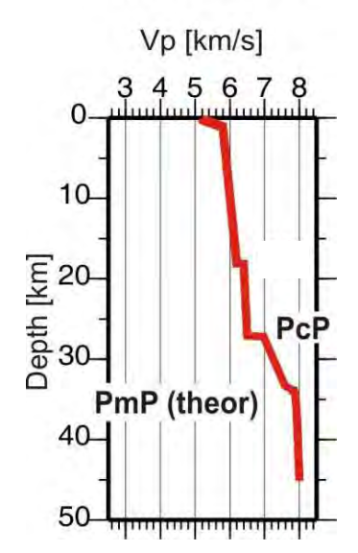
Note band of reflections between 8.2-10s of two-way travel time at the MVE-90 profile corresponding to high-gradient lower crust in the CEL09 profile. Moho is interpreted at 10s two-way-time at the bottom of 5-6 km thick reflective lower crust.

Refraction profile CEL09



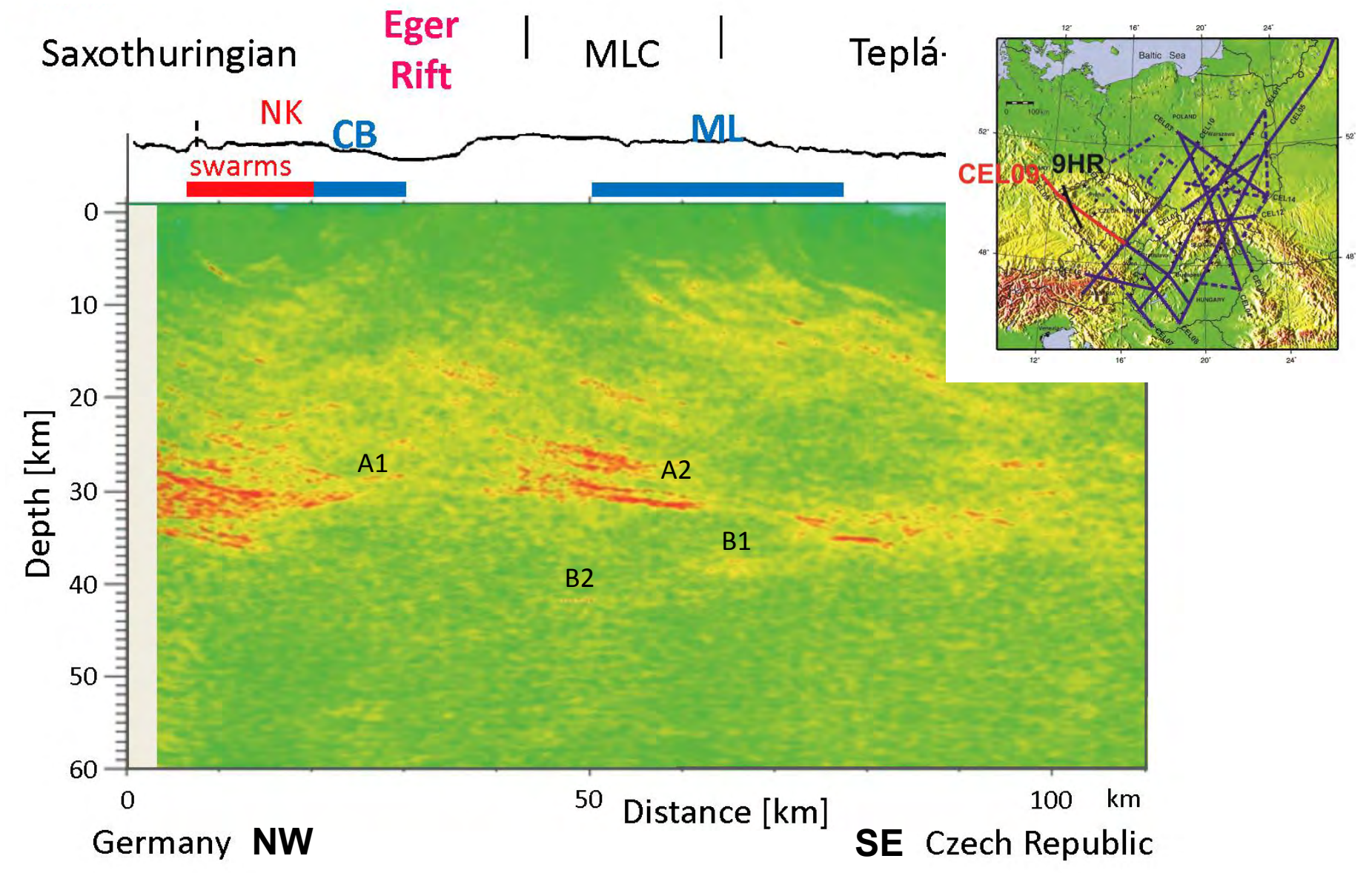
High-velocity lower crust interpreted in the refraction and wide-angle reflection profile CEL09 of the CELEBRATION 2000 experiment (after *Hrubcová et al.*, 2005). Velocities of 6.9-7.6 km/s are at depths of 25-35 km up to 150 km profile distance.

Note high velocity gradient between *PcP* as reflection from the top of the lower crust and the Moho (marked by *PmP* theor), which is not visible in the data.



Non-reflective high-velocity lower crust in SE

Reflection profile 9HR



Reflective lower crust at 0-15 km at depths of 27-35 km
Termination of reflectivity at 15 km distance

High-velocity non-reflective lower crustal body
Strong reflector at top of lower crust at distance 15-75 km, missing reflectivity bellow
Deeper reflectors at distance 45-75 km, dipping NW as Moho transition

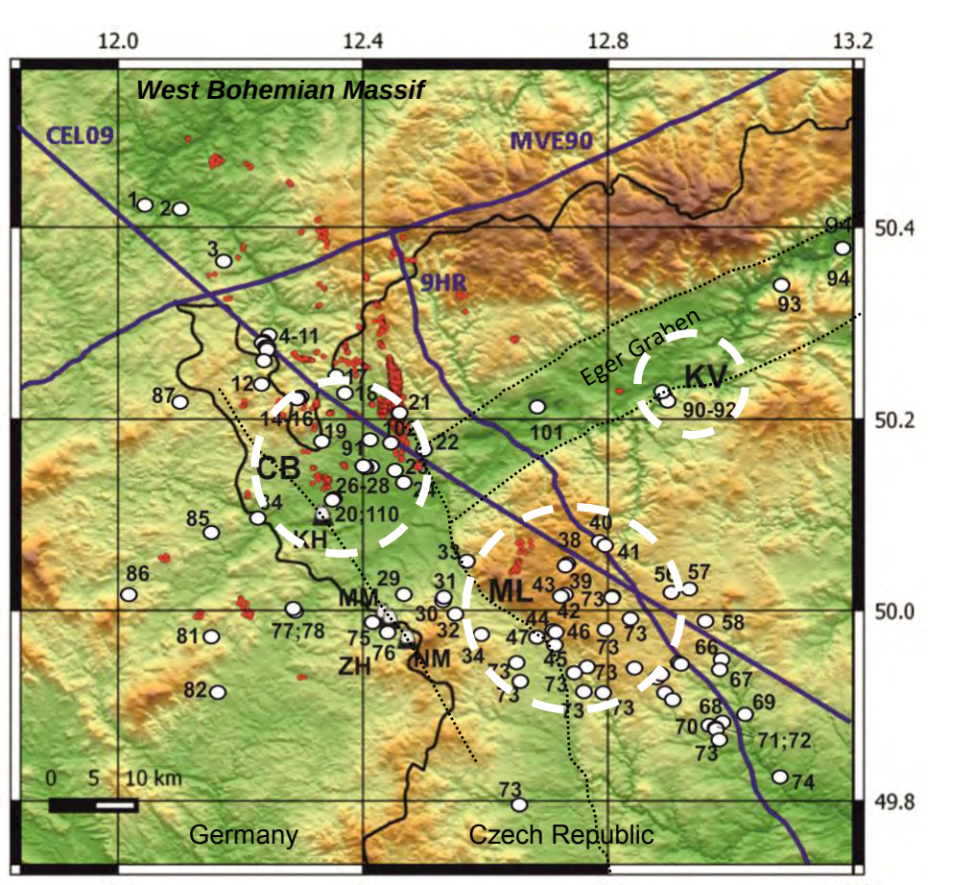
Reprocessed Kirchhoff pre-stack depth migrated NW part of the reflection profile 9HR (after *Mullick et al*., 2015). Degassing fields Cheb Basin, CB and Mariánské Lázně, ML indicated.

Note abrupt termination of seismic reflectivity at ~15 km along profile. Reflector at the top of the lower crust at ~30 km depth with missing reflectivity below is traced at distance of 15-75 km (A1, A2). Deeper reflectors (B1, B2) at 10.9-11.9 s two-way-time at a distance of 45-75 km dip NW and represent bottom delimitation of the lower crust, the Moho.

Timing & tectonic setting of the emplacement

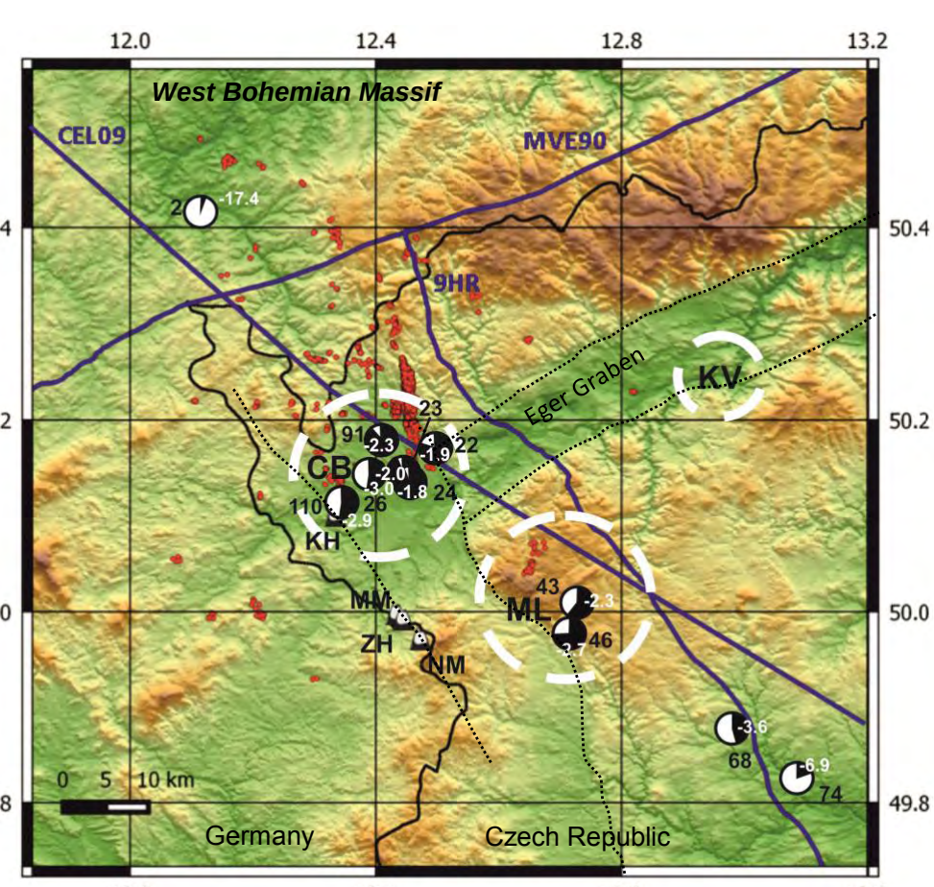
Mantle-derived fluid emanations at surface

Geophysical imaging provides detailed structural information; however, it does not indicate how and when the processes took place. This can be documented by isotope time series studies, which give evidence on still active processes. In the western Eger Rift area, the emanating fluids show high mantle-derived helium fractions with the $^3He/^4He$ ratios ranging between 3.3 and 6.3 Ra at all sites of the degassing centers CB and ML



Distribution of degassing sites

- **Fractions of mantle-derived helium isotope**
- **Lithospheric mantle origin of fluids**
- **Actively degassing magma**

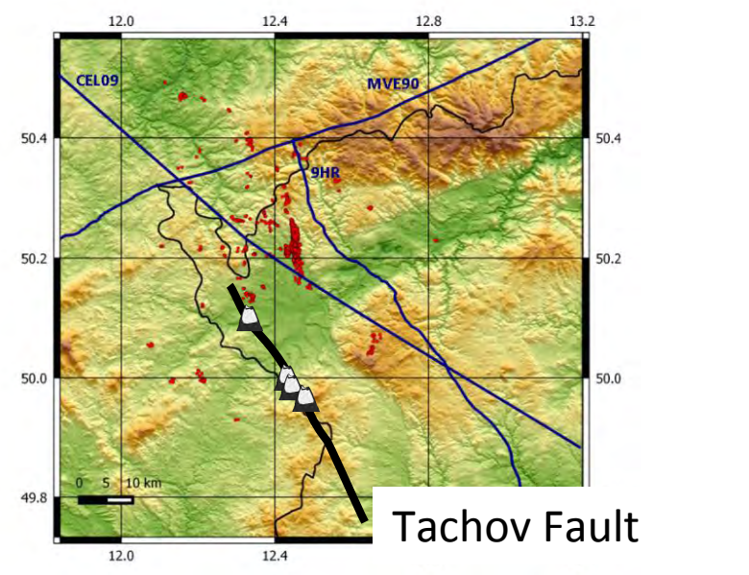


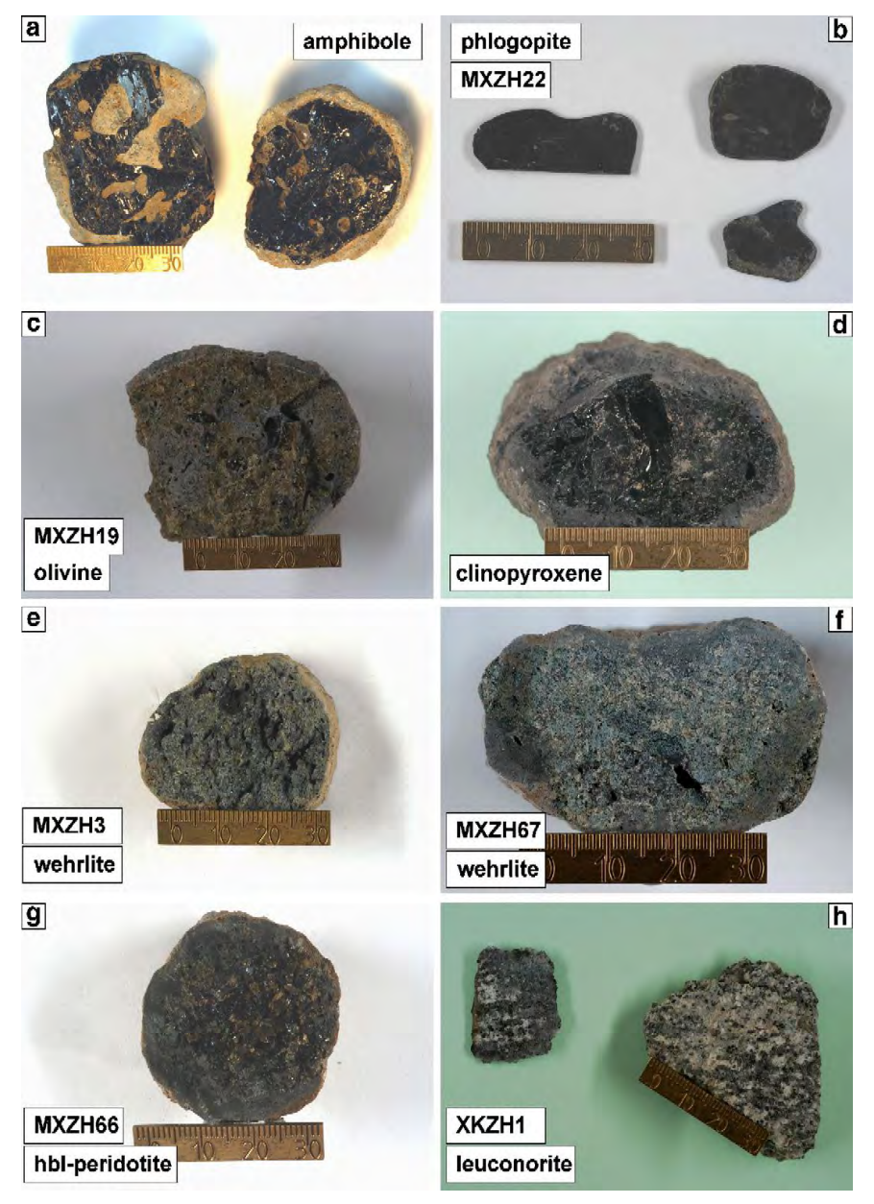
Isotope signature of gas-rich mofettes with mantle-derived He isotopes

Distribution of degassing sites (according to *Geissler et al.*, 2005). Based on high gas flow, three degassing centers (CB, Cheb Basin; ML, Mariánské Lázně; KV, Karlovy Vary) indicated with white dashed circles.

Isotope signatures of eight gas-rich mofettes. Black numbers represent location numbers; white numbers are the $\delta^{13}C$ values. Black quarters of circles correspond to fractions of mantle-derived helium related to the subcontinental mantle reservoir with $^3He/^4He≈6.5$ Ra (after *Bräuer et al.*, 2008). Seismic events and four Quaternary volcanoes indicated; dark blue lines correspond to seismic profiles.

Xenoliths and Quaternary volcanic activity





Source of magma documented by mantle xenolith studies (after *Geissler et al.*, 2005)

- Quaternary volcanoes (maars) at Tachov Fault contain xenoliths of 0.29 Ma age
- Nephelinitic magma from uppermost lithospheric mantle
- Geo-thermobarometry documents depths of 25-40 km
- Werhlites and clinopyroxenites with significant amount of amphibole
- Rock seismic velocities correspond to velocities of 6.9-7.5 km/s from lower crust at CEL09 profile

Active magmatic emplacement

Late Cenozoic to recent magmatic processes
Deep covered magmatic/fluid activity within new continental rift area

Two types of lower crust

- **Laminated/reflectivity in lower crust**
  Late Variscan or pre-Variscan tectonics
  Characteristic for Saxothuringian underthrusting towards SE
- **Reflection-free body in lower crust**
  Late Cenozoic to recent emplacement
  Mantle-derived fluid emanations at surface
  Xenolith studies and Quaternary volcanic activity

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Acknowledgements

This research was supported by Grant Agency of Czech Republic, grant 17-19297S and CzechGeo LM2010008.