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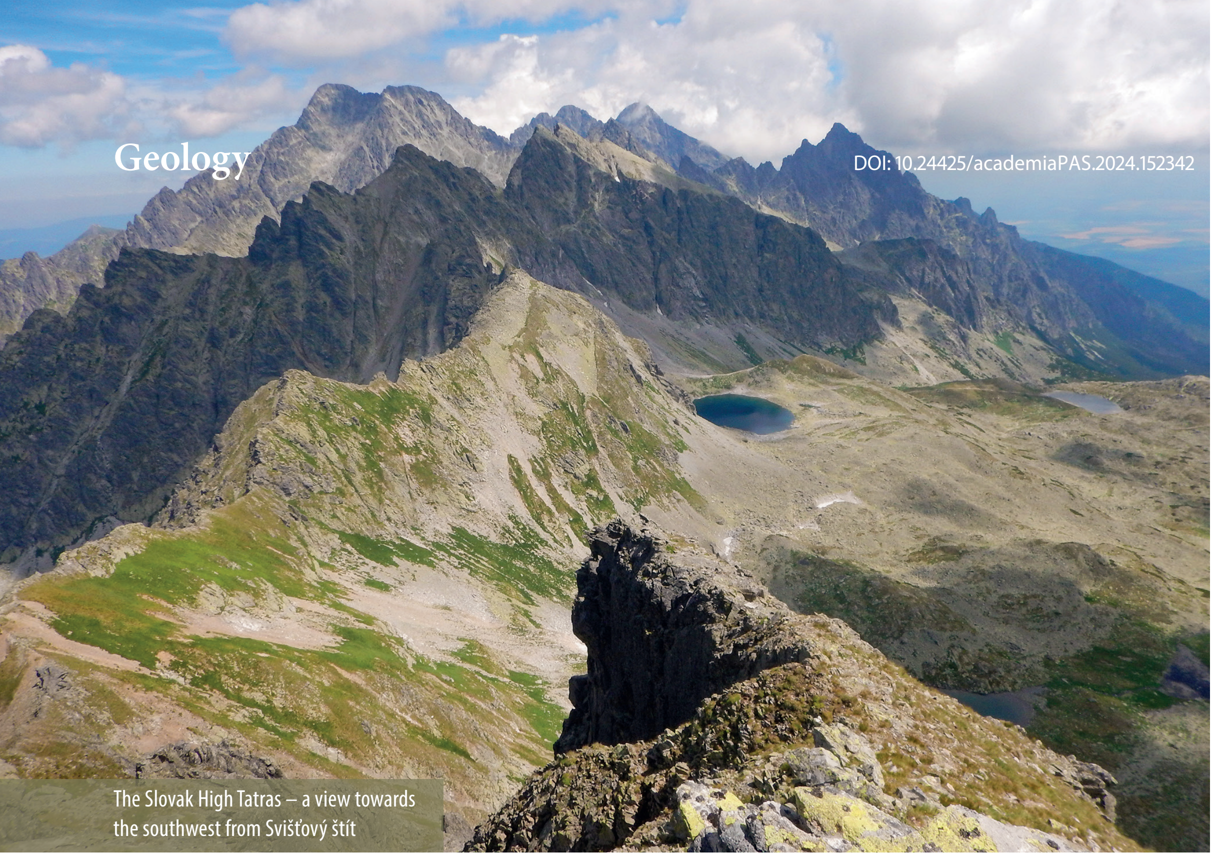

The Slovak High Tatras – a view towards the southwest from Svišťový štít

ECHOES FROM THE CARPATHIANS

Seismic waves are being used to explore deep beneath the Carpathians, unravelling some of the Earth's well-kept secrets.

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The Carpathian Mountains, stretching across Central and Eastern Europe, are a significant geological feature that plays a crucial role in the region's landscape, biodiversity, and cultural history. The mountain range spans over 1,500 km and covers territories in eight countries: the Czech Republic, Slovakia, Poland, Hungary, Ukraine, Romania, Serbia, and Austria. The Carpathians are an extension of the Alpine mountain belt, and their geology is complex, reflecting a long history of tectonic activity, sedimentation, and erosion.

Although the Carpathians have been studied for over 150 years and their surface geology is well known, their deep structure remains the subject of various hypotheses. Only geophysical research can support the surface geology in discovering what lies beneath the surface of this picturesque chain.

Geological formation

The Carpathians are part of the larger Alpine-Himalayan Mountain belt, which was formed due to the collision of the African and Eurasian tectonic plates.

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The formation of the Carpathians began back in the Mesozoic era, particularly during the Cretaceous period (~145–66 million years ago), and continued through the Cenozoic era, particularly during the Paleogene (~66–23 million years ago) and Neogene periods (23–2.5 million years ago). The creation of the Carpathian Mountains is closely linked with the closure of the historical Tethys Ocean and the subsequent collision of the European continent with small continental fragments and volcanic islands as early arrivals of the approaching African plate. The Carpathian Mountain range can be divided into three main segments: the Western, Eastern, and Southern Carpathians. Each of these segments has distinct geological features and histories.

The Western Carpathians include mountains in the Czech Republic, Slovakia, and Poland. This segment is characterized by a complex fold belt consisting of numerous *nappes*, which are large sheets of rock that have been pushed over one another due to the tectonic forces. The Western Carpathians also exhibit significant successions of Mesozoic sedimentary rocks, including limestones and dolomites, which are remnants of ancient shallow seas. The Tatra Mountains, part of the Western Carpathians, are notable for their granitic core, which is exposed due to land uplift and rock erosion.

The contemporary landscape of the Carpathians is diverse and reflects the underlying geological structure and the effects of erosion, glaciation, and tectonic activity. The highest peaks in the Carpathians are found in the Tatra Mountains, where Mount Gerlach in Slovakia reaches 2,655 meters. These peaks are the result of both tectonic uplift and glacial erosion, which have shaped the sharp ridges, U-shaped valleys and *cirques* (circular valleys) typical of the Tatra landscape (Fig. 1).

Tectonic evolution

The Carpathian Mountains are situated at the collision zone of the Eurasian plate and several smaller tectonic units, including the Adriatic plate and the ALCAPA (Alps-Carpathians-Pannonian) microplate. The tectonic and geological evolution of the Carpathians is closely related to the Alpine Mountains, which occurred due to the collision of the African and Eurasian plates and the subduction of the Tethys Ocean. The Carpathians began to form as the Tethys Ocean started to close during the Late Jurassic period (~150 million years ago). The subduction of oceanic crust beneath the Eurasian plate led to the accretion of sedimentary rocks, which later became incorporated into the Carpathian Mountains.

During the Late Cretaceous period (~100–66 million years ago) the region experienced significant compressional forces, leading to the development of faults and the stacking of nappes. These processes were particularly intense in the Western Carpathians, where the collision of the European plate with the Africa-derived ALCAPA led to significant shortening and thickening of the crust. The most significant phase of Carpathian tectonic evolution occurred during the Paleogene and Early Neogene periods (~66–15 million years ago). As the Tethys Ocean continued to close, the European continental margin collided with small continental fragments and island chains associated with the African plate. This collision caused significant crustal shortening, leading to the formation of the mountain belt, being pushed over the European plate. During this period, the Carpathian arc began to form as a distinct, regional geological feature.

The tectonic regime of the Carpathians shifted again during the Middle to Late Miocene (~15–5 million years), when the subducting European plate beneath the Carpathians began to *roll back*. *Slab rollback* is a process where the descending tectonic plate pulls back, causing extension in the overriding plate. In the case of the Carpathians, this led to the formation of the Pannonian Basin, an area of thinned crust and thick sedimentary rock layers that lies to the west of the Carpathians. This rollback of the subducting slab also led to volcanic activity in the inner parts of the Eastern Carpathians, where volcanic rocks support

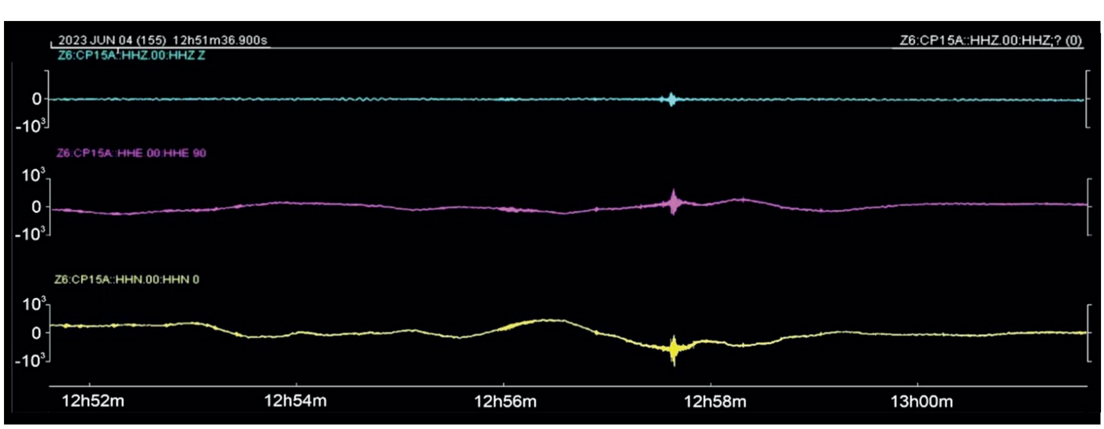


Fig. 2
Raw data from station CP15A

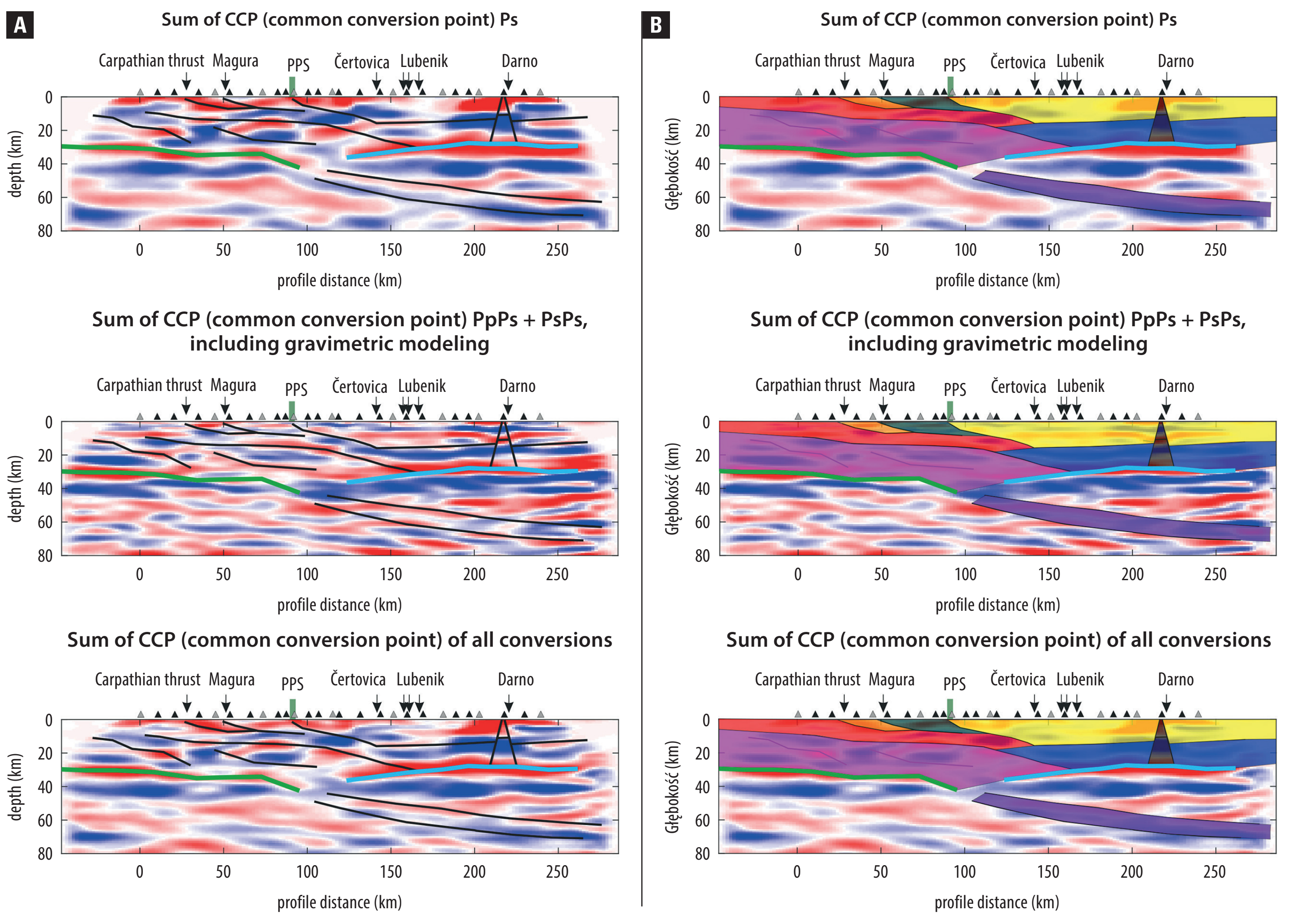


Fig. 3. Seismic results and interpretation: (A) CCP stacks with observed structures, (B) CCP stacks with interpretation of the observed structures

LEGEND

- "European" Moho
- "ALCAPA" Moho
- Observed structures
- "European" middle/lower crust
- "European" lower crust
- ALCAPA lower crust
- "European" upper crust
- Outer Carpathians fold-and-thrust belt
- Magura unit
- ALCAPA nappes units
- Darno fault

this tectonic setup. This phase of extension and volcanism is a key aspect of the tectonic evolution of the region, highlighting the dynamic interplay between compressional and extensional forces.

Geological insight

The Western Carpathians are geologically complex, comprising several distinct units (Fig. 4). To the north lies the Outer Western Carpathians, characterized by a mountain belt involving mostly Cretaceous to Paleogene sedimentary rocks. Moving southward, the mountains transition into the Central and Inner Western Carpathians, which include older, crystalline rock formations originating from the older Variscan orogeny (~370–290 million years), as well as sedimentary cover. Two significant geological structures, the Meliata zone and the Pieniny Klippen Belt (PKB), mark the boundaries between these units – so called *sutures*.

The PKB suture (Fig. 4), formed by the closure of the Alpine-Tethys Ocean, is distinct in its composition, consisting mainly of shallow marine rocks. Unlike typical suture zones, the PKB lacks certain expected geological features, which has led to the hypothesis of a continental sliver known as the Czorsztyn Ridge that is now thought to be deeply buried in the crust of the Central Western Carpathians. The Czorsztyn Ridge is believed to have divided the Alpine-Tethys Ocean into two smaller oceanic basins, the northern Magura and southern Vahic oceans.

Probing the subsurface

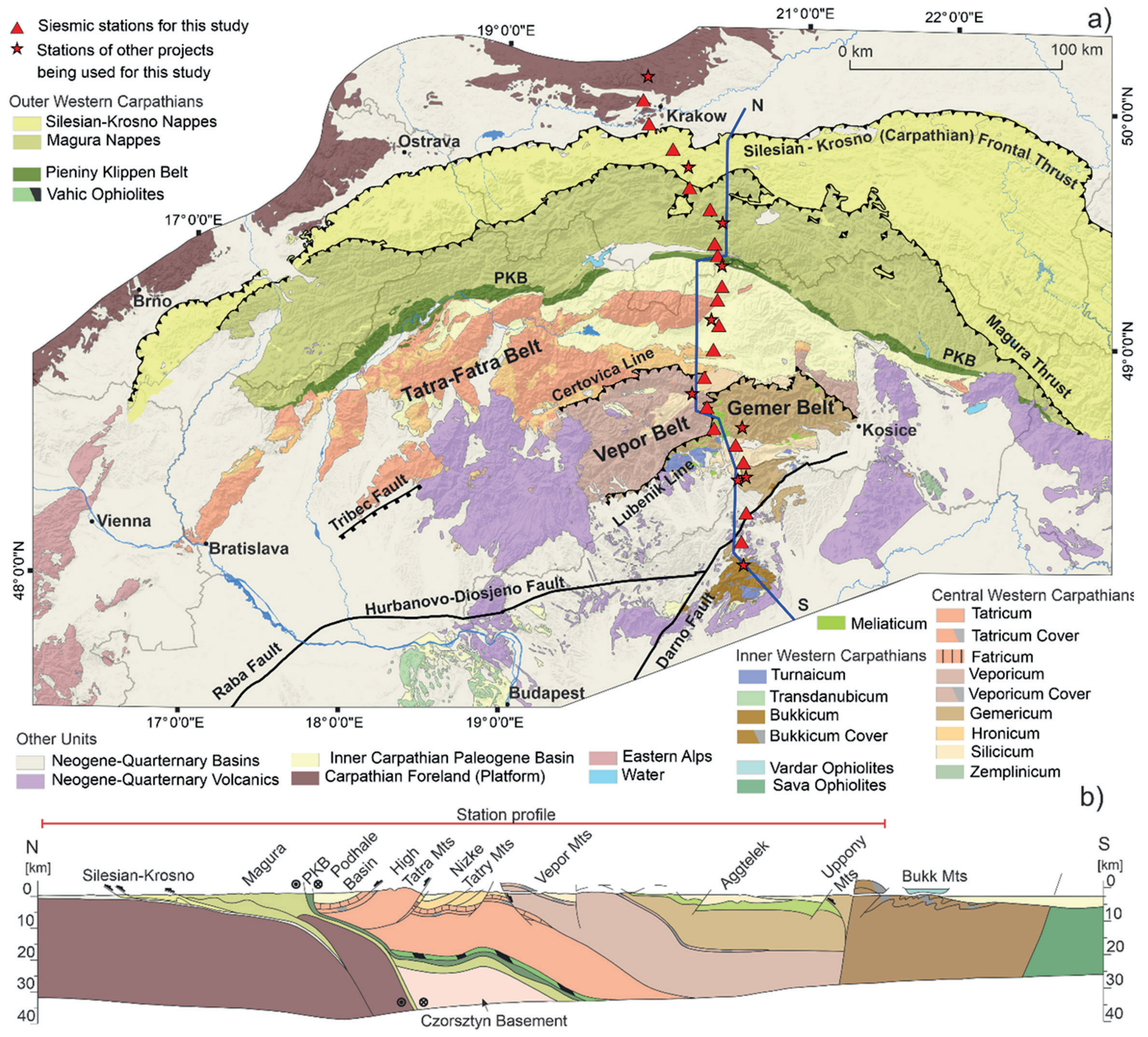
This study aims to explore the existence of a tectonic suture associated with the PKB and the potential existence of the Czorsztyn Ridge using passive seismic methods. Unlike active seismic methods, where artificial sources (e.g. explosions, vibrations) generate seismic waves, passive seismic experiments rely on detecting natural seismic waves generated by earthquakes from around the world.

The first step in the project involved setting up seismic stations across the study area (Fig. 5). In April 2023, a total of 18 seismic stations were assembled, with 12 provided by GFZ Potsdam and 6 from Friedrich Schiller University in Jena, Germany. These stations were deployed during fieldwork in May 2023, with careful selection of the station locations to minimize human-induced noise and ensure reliable data collection. The stations were strategically placed in remote areas, often in abandoned or small schools, to ensure they were in mobile network range and had access to electricity. Once deployed, these stations continuously monitor any ground shaking, including earthquakes. The recorded data that is stored on SSDs or SD cards and is also transmitted to an online server situated in Jena (Fig. 2). This data is used to create so-called *receiver functions*, which are mathematical transformations of the recorded seismic waveforms of incoming earthquakes. These receiver functions visualize the geological structures in the subsurface by analyzing how the incoming earthquake waves interact with different layers in the subsurface, including reflections, refractions and wave conversions.

Building a subsurface model

Using the data collected over the past year, the processed receiver functions were used to generate structural images of the subsurface using the so-called Common Conversion Point (CCP) method (Fig. 3). These images are created by summarizing all structural information in the receiver functions, from all recorded

Fig. 4
Geological map of the Western Carpathians



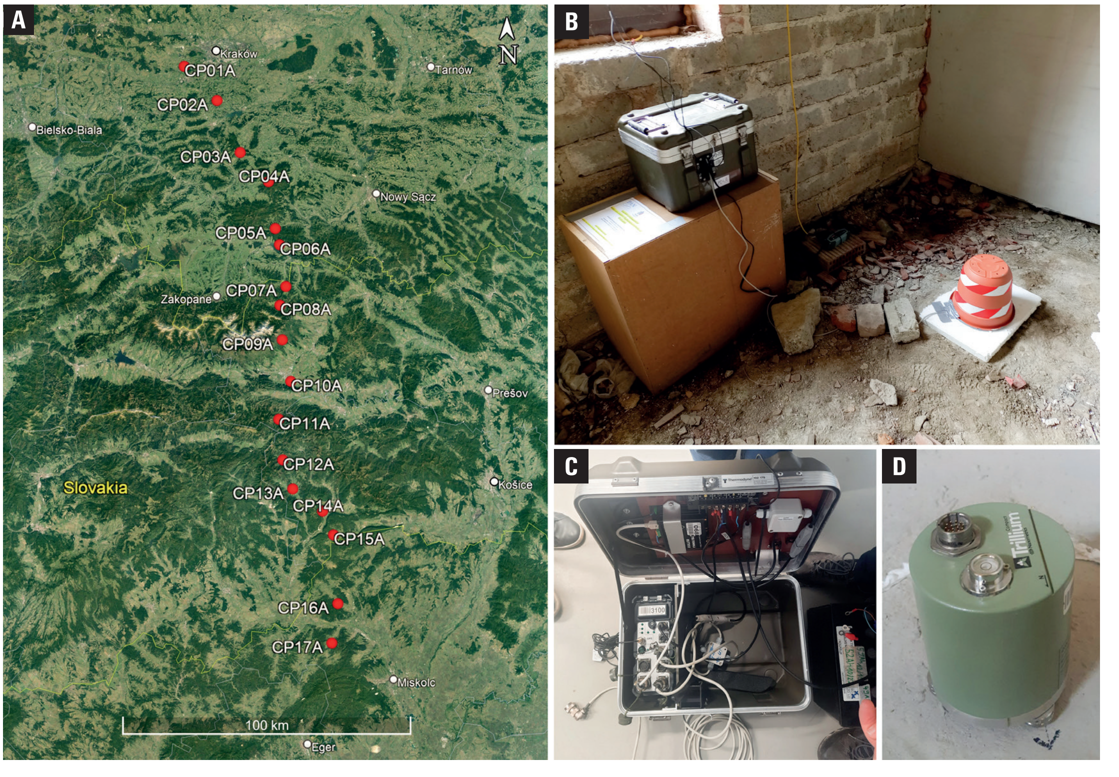


Fig. 5
Location and setup of seismic stations:
(A) station locations,
(B) station at a location after deployment,
(C) parts of the station such as the digitizer and router,
(D) sensor

earthquakes at every station, into a common model. This method offers a detailed picture of the subsurface, highlighting variations in seismic wave velocities that correspond to different geological layers. The results are compared to the existing geophysical and geological literature to build a coherent model of the region.

The CCP stacks reveal several important features of the subsurface structure:

1. The boundary between Earth's crust and mantle was identified at a depth of approximately 30 km across most of the study area. However, a notable thickening of the crust by ~10 km was observed around 100 km into the section, before returning to its typical depth. There is also a southward dipping mantle discontinuity under the Central Carpathian Moho (Fig. 3).
2. Several southward dipping structures were identified within the crust, beneath the Outer Carpathians. These structures originate near the Carpathian Frontal Thrust and Magura Thrust and extend towards the PKB.
3. The PKB (Fig. 3) is almost vertical at shallow depths, but then dips southward flattens out at greater depth, and seems to continue until the end of the section.

Conclusions

Although our results are preliminary and the experiment will continue for another two years, its key findings so far can be summarized as follows.

- First, the step and associated gap in the crust-mantle boundary between km 100 and 140 of the section correspond to the tectonic suture between the European plate in the north and the ALCAPA microplate in the south. The subducted European plate is dipping southward at a low angle into the mantle beneath ALCAPA.
- Second, the deformation of the Outer Western Carpathians is not restricted to sedimentary units as previously believed. There are deep structures within the European crust beneath the sedimentary nappes of the Outer Carpathians. A similar feature has been described from the basement of the Vienna basin at that of Alpine-Carpathian connection.
- Third, the PKB appears to extend to a depth of ~15 km and may act as a basal detachment of the Central Carpathian nappes.

Lastly, the ALCAPA middle-lower crust is wedged into the European slab. No remnants of the Czorsztyn Ridge are observed at the contact between the European and ALCAPA plates.

In summary, this study offers new insights into the complex geology of the Western Carpathians, challenging previous theories and providing a more detailed understanding of the region's tectonic history. As the seismic experiment continues over the next few years, further data will help to refine this model and uncover more about the deep structures that have shaped this fascinating part of the Earth's crust. ■

Further reading:

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