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RESEARCH ARTICLE

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Miocene tectonic activity at the boundary between NE Pannonian and NW Transylvanian basins (Romania): Insight from new seismic data

Ionelia Panea[1] | **Ioan Munteanu**[1] | **Carmen Gaina**[2] | **Victor Mocanu**[1] | **Relu Dumitru Roban**[1] | **Catalin Florin Bouaru**[1] | **Geysir-BaiaMare Working Group**

[1]Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania

[2]Centre for Earth Evolution and Dynamics, Department of Geosciences, University of Oslo, Oslo, Norway

Correspondence
Ionelia Panea, Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania.
Email: ionelia.panea@gmail.com

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Abstract

Situated at the junction between the Eastern Carpathians Mountains, the Pannonian and the Transylvanian basins, the Baia Mare region (Romania) has a complex geological history that witnessed the interaction among the three main tectonic provinces. Here, we report results from new seismic reflection measurements that provide modern information about the subsurface geological structure. The integrated analysis of the newly acquired and vintage seismic reflection data from the study area reveals details about the architecture of the Palaeogene and the Neogene deposits at the contact between the northeastern Pannonian and northwestern Transylvanian basins. In particular, it unveils a fault zone that most probably controlled the tectonic evolution of the eastern Pannonian and Transylvanian basins. A better understanding of the crustal structure and tectonic features in the study area is a first step into evaluating the geothermal potential of the region.

KEYWORDS
seismic reflection measurements, structural interpretation, subsurface geology, tectonic

1 | INTRODUCTION

The Pannonian and Transylvanian basins formed to the west of the Carpathian arc (Figure 1). Their formation and evolution are thought to be driven by the Miocene subduction retreat of a slab attached to the European continent into the Carpathians embayment (e.g. Balla, 1987; Horváth et al., 2006; Tiliţă et al., 2013). At the contact between the northeastern Pannonian Basin (NE-PB) and the northwestern Transylvanian Basin (NW-TB) sits the Baia Mare region (black square in Figure 1), not only well known for its mineral resources but also for its geothermal potential demonstrated by high heat flow values and the presence of hot springs (e.g. Demetrescu, 1982; Roşca et al., 2016).

To date, geological and tectonic knowledge about this region has been documented by sparse geophysical data only (vintage seismic reflection and well data) and surface geology collected at the margins of the Baia Mare junction region (e.g. Ciulavu et al., 2002; Krészek & Bally, 2006; Răbăgia, 2009; Săndulescu, 1984; Săndulescu et al., 1993; Tiliţă et al., 2013; Tischler et al., 2008).

The lack of local geophysical data in the Baia Mare region led to coarse geological models of the Neogene to Quaternary deposits which were constructed on limited data to the east and west of

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For further information regarding the Geysir-BaiaMare Working Group, please see the Acknowledgements section.

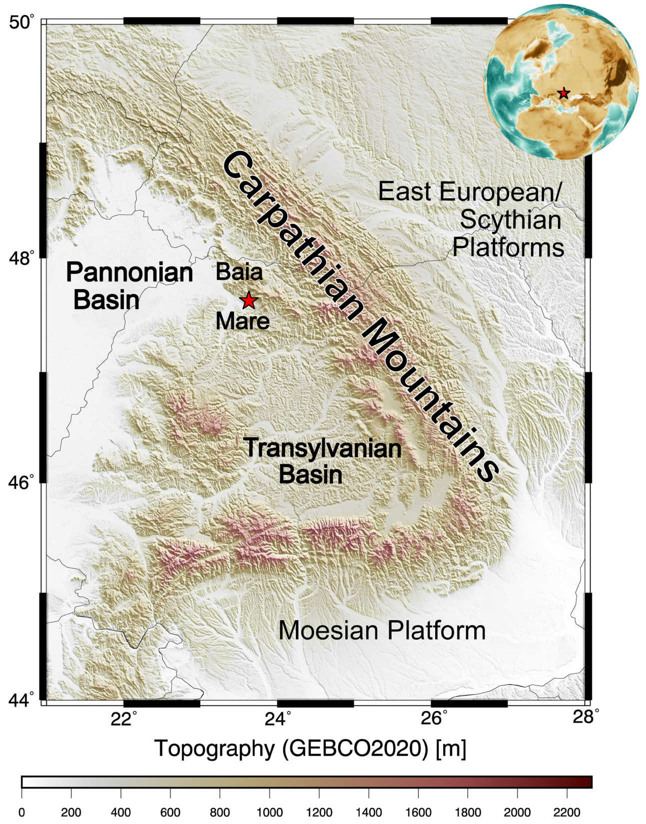

FIGURE 1 Topographic map (GEBCO 2020, https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2020/) of the Carpathian arc and surrounding sedimentary basins. The study area is the Baia Mare region (the red star indicates the location of the Baia Mare city).

the region. Our seismic reflection measurements using explosive sources were designed to fill this information gap that will help unravel the crustal and sedimentary architecture and how different tectonic blocks interacted for the last 50 million years.

2 | GEOLOGICAL SETTING OF THE BAIA MARE REGION

Tectonically, the Baia Mare region belongs to the Baia Mare Depression, which is an eastward extension of Pannonian Basin developed on the southern side of the volcanic Gutâi-Oaş mountains (Figure 2). This basin is bounded by three isolated islands of metamorphic basement known as the Codru, the Țicău and the Preluca uplifts (C, T and P in Figure 2) and it is floored by pre-Neogene basement that sits under the Neogene sedimentary cover and Neogene magmatites.

The pre-Neogene basement contains metamorphic rocks of Precambrian and Precambrian-Palaeozoic ages and sedimentary rocks of Jurassic, Late Cretaceous and Palaeogene ages. The basement crops out in green schist facies in the Codru, Ţicău and Preluca areas.

Significance Statement

The Baia Mare region, situated at the junction between three main tectonic units, is known for its mineral resources and the highest heat flow values recorded to date in Romania. So far, the tectonic evolution of this region was inferred from the neighbouring NE Pannonian basin data due to the lack of local geophysical information. In this study, we report results of new seismic reflection measurements performed along two perpendicular lines located SW of Baia Mare. Both seismic sections display evidence for the uplift of the NE Pannonian basin starting from Late Miocene. The interpretation of the newly acquired and vintage seismic data reveals similarities and differences between the architecture of the Palaeogene and Neogene formations and clear evidence for a fault zone that controlled the tectonic evolution of both parts of basins.

Palaeogene and/or Neogene sedimentary formations directly cover the crystalline basement in the Codru and Ţicău areas (e.g. Munteanu et al., 2021; Popescu, 1984; Rusu et al., 1983). In the Preluca area, the crystalline basement is covered by Upper Cretaceous marls and sandstones (Rusu et al., 1983). The Palaeocene-Lower Eocene continental deposits, conglomerates, shales and sandstones of the Jibou formation are covered unconformably by Middle Eocene deposits of sandstones and shales which grades up into nummulitic limestones (Popescu, 1984; Rusu et al., 1983). The sedimentary deposits of Oligocene-Early Miocene ages mainly occur nearby the Preluca area and appear as small patches towards west, where these deposits were removed before the deposition of the middle Miocene sedimentary deposits and volcanic related products such as andesite, granites and tuffs (Munteanu et al., 2021). The sedimentary succession continues with an alternation of conglomerates, sands, marls and tuffs of Upper Miocene–Pliocene followed by fluvial Quaternary deposits (Rusu et al., 1983).

The calc-alkaline Neogene volcanism is thought to be a consequence of the European lower plate westward subduction and slab break-off along the Carpathians (e.g. Pécskay et al., 1995; Seghedi et al., 1998). Magmatic activity started in the Badenian age being followed by extrusion of basaltic and andesite of the Sarmatian and Pannonian ages. The volcanic chain cuts and interbeds with Neogene sedimentary deposits (Săndulescu, 1984).

Two strike-slip crustal faults, the North Transylvanian (NT) and the Bogdan-Dragoş Vodă faults, have been interpreted on vintage seismic reflection data recorded along lines from the NE-PB and the NW-TB following various paths and being crosscut or not by northwest-striking dextral and northeast-striking sinistral strike-slip faults (e.g. Ciulavu et al., 2002; Krészek & Bally, 2006;

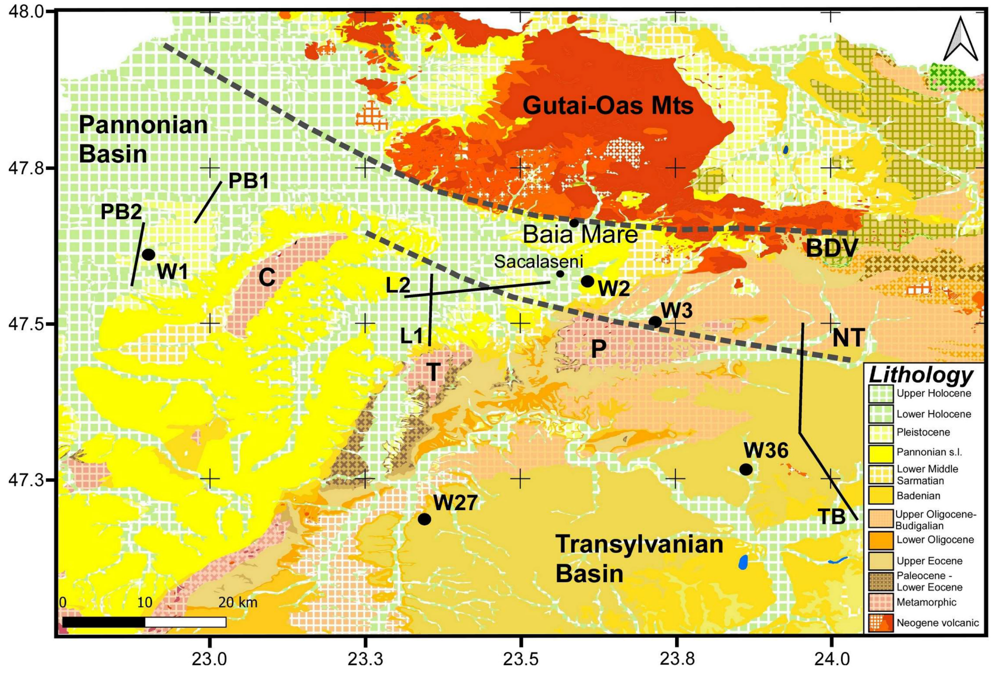

FIGURE 2 Geological map of the study area (source of the map—portal of the Geological Institute of Romania). C, T and P—Codru, Ţicău and Preluca isolated islands of metamorphic basement, faults—dashed lines, seismic lines—black lines, NT—North Transylvanian fault, BDV–Bogdan-Dragoş-Vodă fault, L1 and L2—seismic lines acquired in July 2021 as part of this study, Transylvanian Basin, PB1 and PB2—vintage seismic lines, W1, W2, W3, W27 and W36—wells intercepting the crystalline basement.

Răbăgia, 2009; Săndulescu, 1984; Săndulescu et al., 1993; Tiliţă et al., 2013). Figure 2 displays their locations as in Ciulavu et al. (2002). The NT fault (or fault zone) crosses the Baia Mare region with a trajectory not well documented given the lack of seismic information. It crops out on the northern border of the Preluca uplift, where it is known as the Preluca fault (Săndulescu, 1984). The main movement along this fault took place during the Burdigalian times (Săndulescu et al., 1993).

3 | SEISMIC PROFILES AND INTERPRETATION

The seismic reflection data were recorded along two perpendicular lines located SW of Baia Mare (L1 and L2 in Figure 2). The main goal of the survey was to image the contact between the sedimentary and basement formations, assumed to be at depths shallower than 3 km.

The line L1 has a length of 13 km with a north–south orientation. The seismic energy was generated using explosive charges detonated in 41 individual holes with depths of 8 m, 88 groups with two holes of 5 m depth and 2 groups with four holes of 3 m depth. The dataset contains 131 shot gathers. Each shot gather has traces coming from a fixed spread of 1045 individual wireless receivers spaced at 12.5 m.

The line L2 is 17.6 km long and a west–east orientation. The dataset contains 188 shot gathers. The seismic energy was generated in 136 individual holes with depths of 8 m and 52 groups with two holes of 5 m depth. The measurements were performed using a fixed spread of 1411 wireless receivers spaced at 12.5 m.

For both lines, the time sampling interval was 1 ms and the record length was 10 s.

The analysis of raw shot gathers displayed in the time domain provided preliminary information about the subsurface geological structure. Clear reflected waves can be seen on the shot gather from Figure 3a up to about 1.3 s measured at zero offset. Their presence indicates a thick sedimentary cover with layers separated by interfaces characterized by significant contrast in acoustic impedance. Reflected waves coming from dipping interfaces were seen on several records; an example is given in Figure 3b.

Standard processing steps were applied to the acquired seismic data (Table 1). The uninterpreted and interpreted seismic sections are displayed in Figures 4 and 5.

The seismic section along line L1 shows significant thinning of the sedimentary cover from north to south (Figure 4). The top of the Pre-Badenian deposits is marked by an unconformity. Reflectors with onlap-type terminations were interpreted inside the Badenian sequence (black arrows in Figure 4b). The sedimentary and volcanic deposits of the middle to Late Miocene and Pliocene age are imaged by continuous reflectors. The high-amplitude reflectors might indicate the presence of tuff deposits and/or unconformities. The ages are inferred from rock samples collected from various outcrops. The metamorphic basement made of folded and faulted deposits was observed in outcrops situated in the Ţicău area and formations with

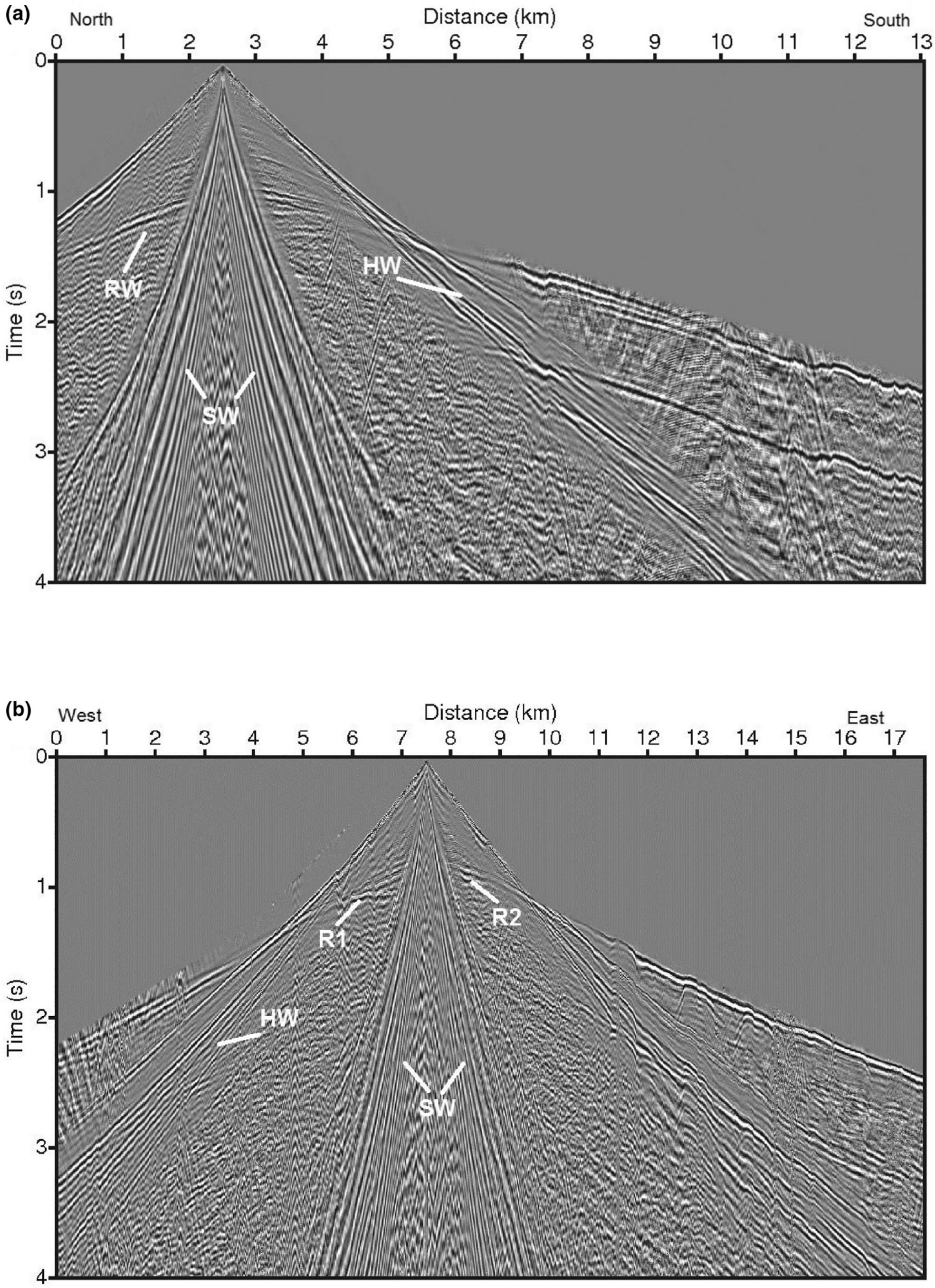

FIGURE 3 Raw shot gathers with shot points along the two seismic lines (see locations in Figure 2): (a) Line L1 with shot point distance of 2.5 km and (b) Line L2 with shot point distance of 7.5 km. Amplitude corrections have been applied for better display. RW—reflected waves, R1 and R2—reflected waves from dipping interfaces, SW—surface waves, HW—head waves.

middle to Late Miocene and Pliocene age were found in outcrops placed in the vicinity of the line L1. The seismic sequences of the Pannonian and Pliocene age contain reflectors with erosional-type terminations (dashed black arrows in Figure 4b). The Quaternary deposits, interpreted on top of the Pliocene ones, have thicknesses of tens of metres. Normal faults of Palaeogene age reactivated during the Miocene times cut the deposits of the Pre-Badenian age (Fn in Figure 4b). The reverse fault is interpreted to be a response of the Sarmatian compression (Fi_Mi in Figure 4b).

For the line L2, the seismic section displays the middle to Upper Miocene deposits without significant lateral variations in their thicknesses (Figure 5b). Reflectors with onlap-type terminations were interpreted inside the Badenian deposits and reflectors with erosional-type terminations for the Sarmatian and Pannonian ones (black and dashed black arrows in Figure 5b). The Pliocene deposits, covered by thin Quaternary ones, show a decreasing thickness from west to east and reflectors with erosional-type terminations on top.

TABLE 1 The processing sequence used to produce the seismic sections L1 and L2.

Processing sequence	Parameters
Input seismic data	SEG-Y format, 10 s length Time sampling interval—1 ms
2D line geometry	Receiver spacing—12.5 m Source spacing—approx. 100 m
Static corrections	Final datum—300 m Replacement velocity—2000 m/s
Trace editing	Kill trace, top muting
Amplitude corrections	Time window—0.5 s
Frequency filtering	Frequency-wavenumber (reject type) Spiking deconvolution (decon operator length—120 ms) Band-pass (12–72 Hz)
Velocity analysis	Stacking velocities
Normal Move-Out correction	Stacking velocities
Stacking	Yes
Time migration	Kirchhoff method
Time-to-depth conversion	Yes

A series of normal faults of Pre-Badenian age reactivated during the Miocene times were interpreted (Fn in Figure 5b). A fault zone is interpreted on the central part of the seismic section. Knowing that the static shifts are small, this interpretation seems genuine. The reflectors corresponding to the Pre-Badenian (Oligocene) age are characterized by strong amplitudes after faulting compared to those seen above them, which appear with low amplitude and interrupted continuity. The deformation of the Pre-Badenian deposits could be related to the activity of the NT fault (or fault zone) during Burdigalian. Seismological measurements proved that this fault is still active, which might explain the strong attenuation in amplitude of the reflectors seen inside the fault zone (Polonic, 1980; Săndulescu et al., 1993).

4 | DISCUSSION

The interpretation of the newly acquired seismic reflection data was guided by information provided by surface geological mapping in the Baia Mare region, vintage seismic reflection and borehole data recorded to the west and to the east of it.

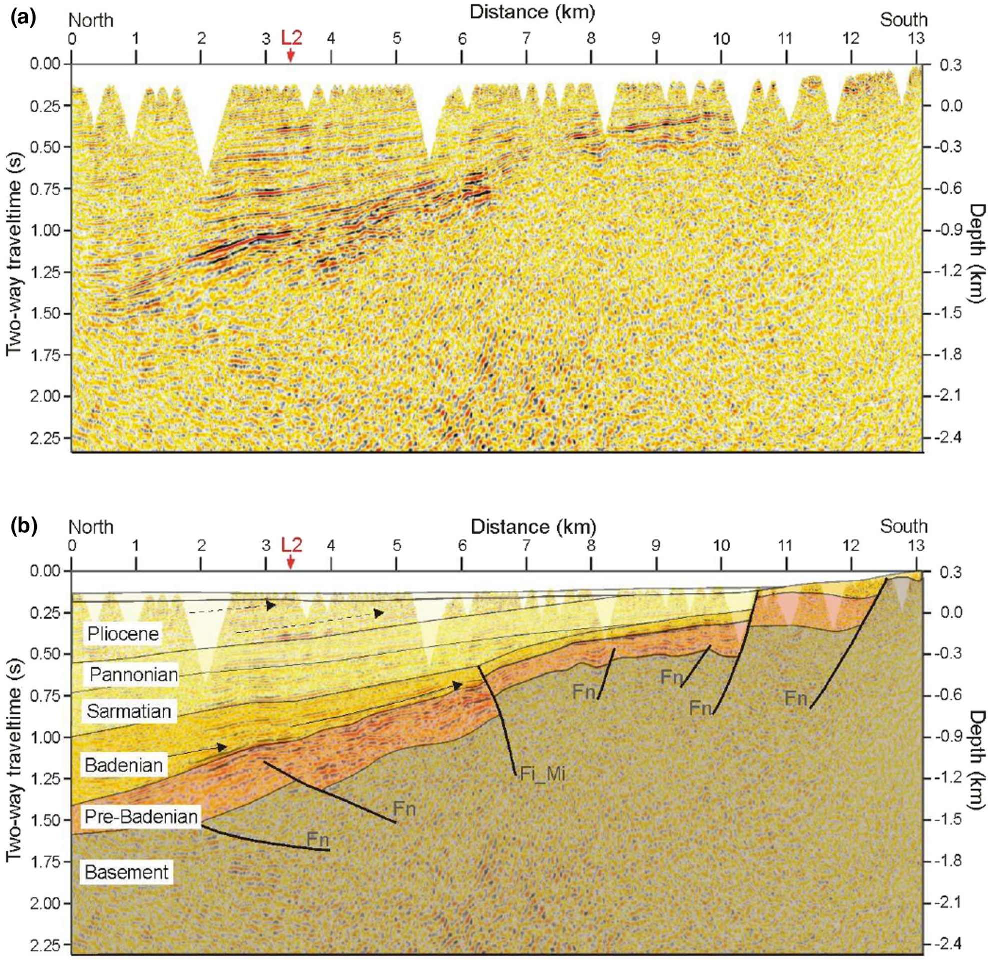

FIGURE 4 Seismic section along the line L1 before (a) and after (b) interpretation (see its location in Figure 2). Fn—normal faults, Fi_Mi—reverse fault, onlap-type terminations—black arrows, erosional-type terminations—dashed black arrows.

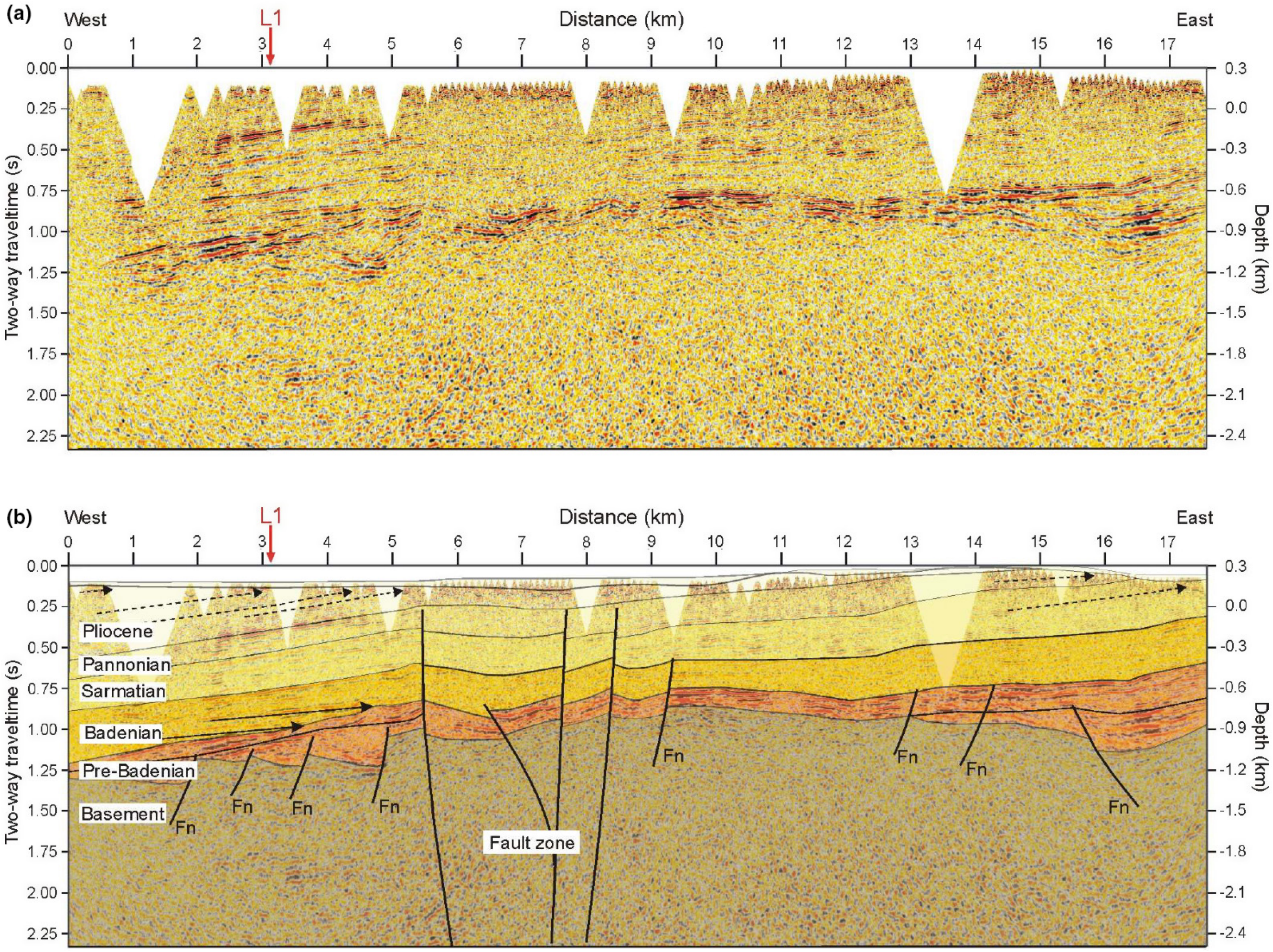

FIGURE 5 Seismic section along the line L2 before (a) and after (b) interpretation (see its location in Figure 2). Fn—normal faults, onlap-type terminations—black arrows, erosional-type terminations—dashed black arrows.

The vintage seismic data used in our interpretation were recorded along two lines from the NE-PB (PB1 and PB2) and on the line TB from the NW-TB (see Figure 2 for their locations). For the lines PB1 and the PB2, our structural interpretation is based on information taken from existing literature (e.g. Ciulavu et al., 2002; Răbăgia, 2009). The geological model built along the line TB is based on the interpretation presented in Krézsek and Bally (2006). Locations of wells which crossed the sedimentary cover and intercepted the crystalline basement are shown in Figure 2.

The seismic sections for the lines PB1 and PB2 are displayed in Figures 6 and 7. We interpreted Pre-Badenian (Oligocene) and basement formations cut by normal faults of Pre-Badenian age reactivated during the middle Miocene (black lines in Figures 6b and 7b). The Badenian-Sarmatian formations are imaged by reflectors characterized by good amplitudes (Figures 6b and 7b).

Pre-Badenian formations were also identified on the new seismic reflection lines (Figures 4b and 5b). The well W2 drilled in the Săcălăşeni area crossed siliciclastic carbonate deposits of the Oligocene age (see its location in Figure 2). The missing Eocene and Lower Miocene deposits, documented by seismic and well data recorded to the west and the east of the Codru uplift, might be the response of the compressional movements and erosion from Eocene and of the movements along the NT fault from Burdigalian (Ciulavu et al., 2002; Săndulescu, 1984).

The architecture of the Middle and Upper Miocene formations developed to the west and to the east of the Codru uplift changes from curved structures in the west to monocline ones in the east (compare Figures 4b and 6b). The bending of those from the western part might be a response of the compressional tectonic regime which affected the entire PB during the Pliocene (Horváth & Cloetingh, 1996).

The uplift of the NE-PB starting from the Early Miocene was interpreted by Ciupagea et al. (1970) based on geological observations and by Sanders (1998) using fission-track analysis. This uplift is for the first time confirmed by our new seismic data. On both seismic lines L1 and L2, reflectors with erosional-type terminations were interpreted inside sequences of middle to Late Miocene and Pliocene ages (Figures 4b and 5b).

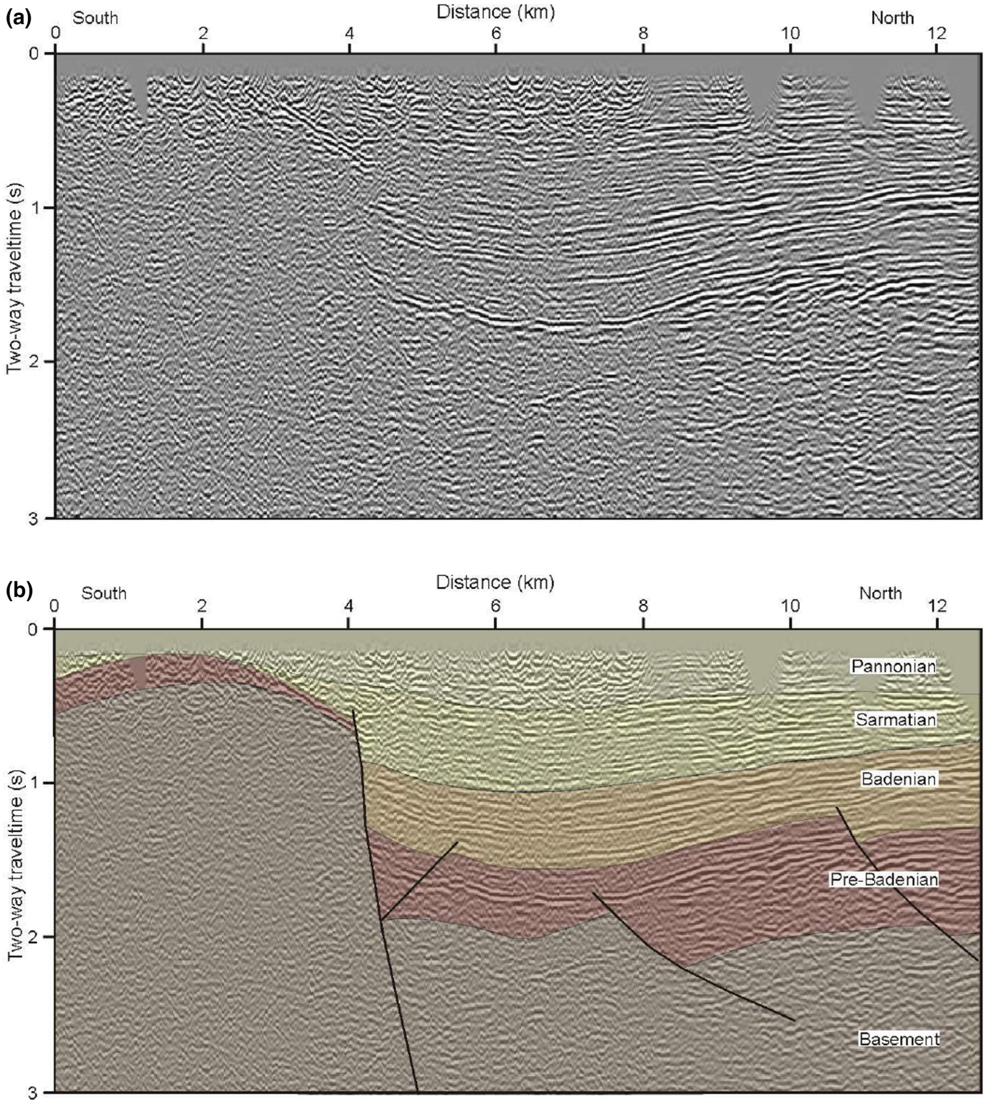

FIGURE 6 Seismic section along the line PB1 before (a) and after (b) interpretation (see its location in Figure 2); thick black lines—reactivated Miocene faults. [Colour figure can be viewed at wileyonlinelibrary.com]

The fault zone on the seismic line L2 correlates well with the NT fault zone interpreted on vintage seismic data recorded on the NW-TB (NTFZ in Figure 8) and with the NT fault drawn on tectonic sketches of the Romanian northern sector of the PB (Ciulavu et al., 2002; Săndulescu et al., 1993; Visarion et al., 1979); see Figure 2 for the location of the NT fault. The vintage seismic reflection and well data recorded on the NW-TB proved the presence of the Lower Miocene and salt deposits. These deposits were not intercepted by wells drilled on the NE-PB, such as the wells W1 and W2, or found in outcrops. An example of vintage seismic reflection data from the NW-TB is the line TB (Figure 8a). The geological model from Figure 8b has been drawn using the interpretation performed by Krészek and Bally (2006). The wells drilled to west and to south of the line TB intercepted crystalline basement rocks (the wells W3, W27 and W36 in Figure 2). The pre-Neogene, Lower Miocene, salt and Middle to Upper Miocene formations crop out to surface towards the central part of TB. Outcrops of the Oligocene age were mapped to east of Baia Mare, the Lower Miocene ones towards south (Krészek & Bally, 2006, and references therein).

5 | SUMMARY

The seismic reflection survey performed in the Baia Mare region in July 2021 provides useful information constraining the tectonic and stratigraphic evolution of the NE-PB. The interpretation of the newly acquired and vintage seismic reflection data indicates similarities and differences between the architecture of the sedimentary and volcanic formations up to Late Miocene age. Deposits of Pre-Badenian (Oligocene), middle to Late Miocene age were interpreted on the NE-PB and the NW-TB. Borehole data show the absence of Lower Miocene formations on the NE-PB, including the Baia Mare region,

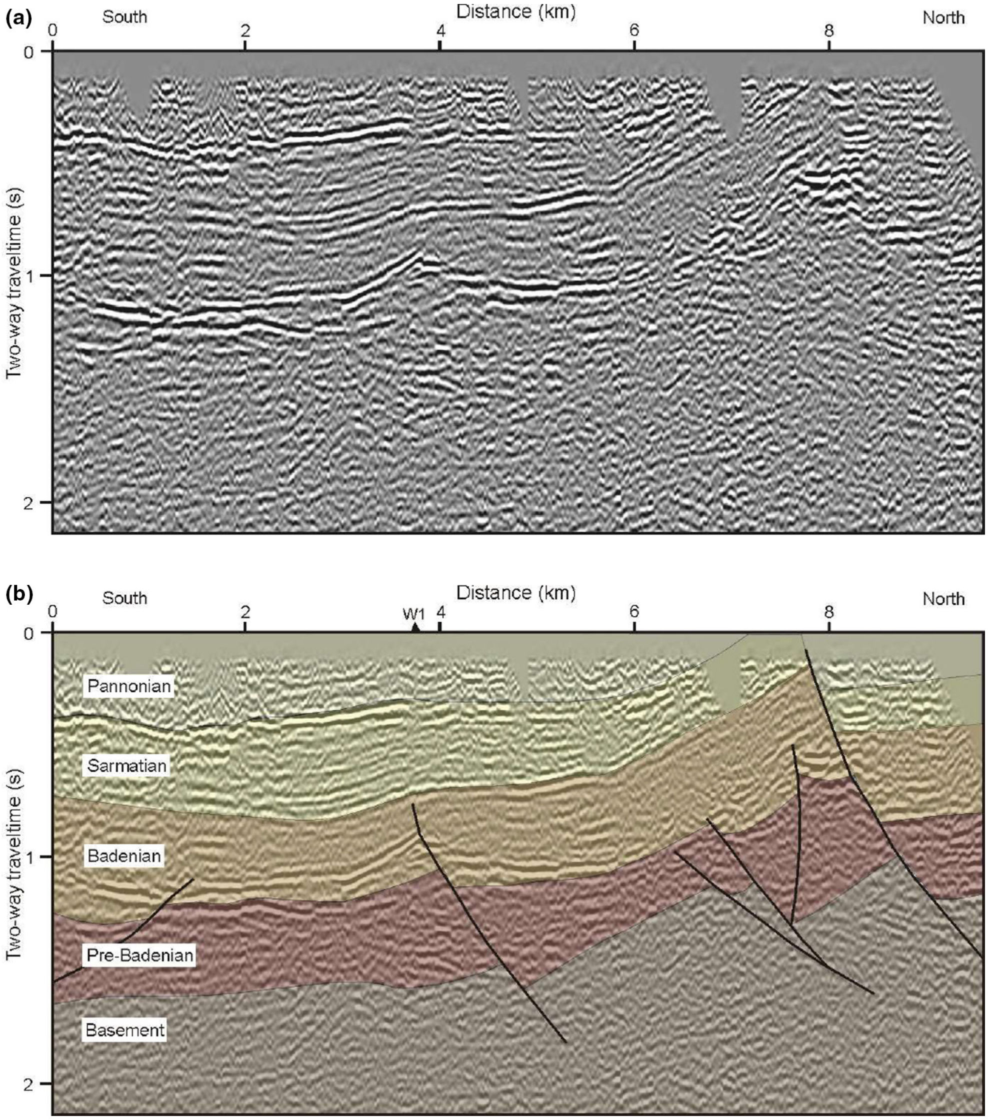

FIGURE 7 Seismic section along the line PB2 before (a) and after (b) interpretation (see its location in Figure 2); thick black lines—reactivated Miocene faults, W1—well. [Colour figure can be viewed at wileyonlinelibrary.com]

and their presence on the NW-TB. Our newly acquired data show for the first-time subsurface evidence of the most recent uplift of the NE-PB starting from the Late Miocene. This is demonstrated by clear reflectors with erosional-type terminations which were interpreted inside the seismic sequences of Late Miocene and Pliocene age. The east–west seismic line images provide reliable evidence for a fault zone that may be the continuation of the North Transylvanian fault zone interpreted on the vintage seismic data from the NW-TB. The tectonic features revealed by the new data may be important structures to be considered in future basin evaluation for geothermal potential in this area. The interpreted faults can represent possible pathways for the water movement and for the heat transfer towards surface.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

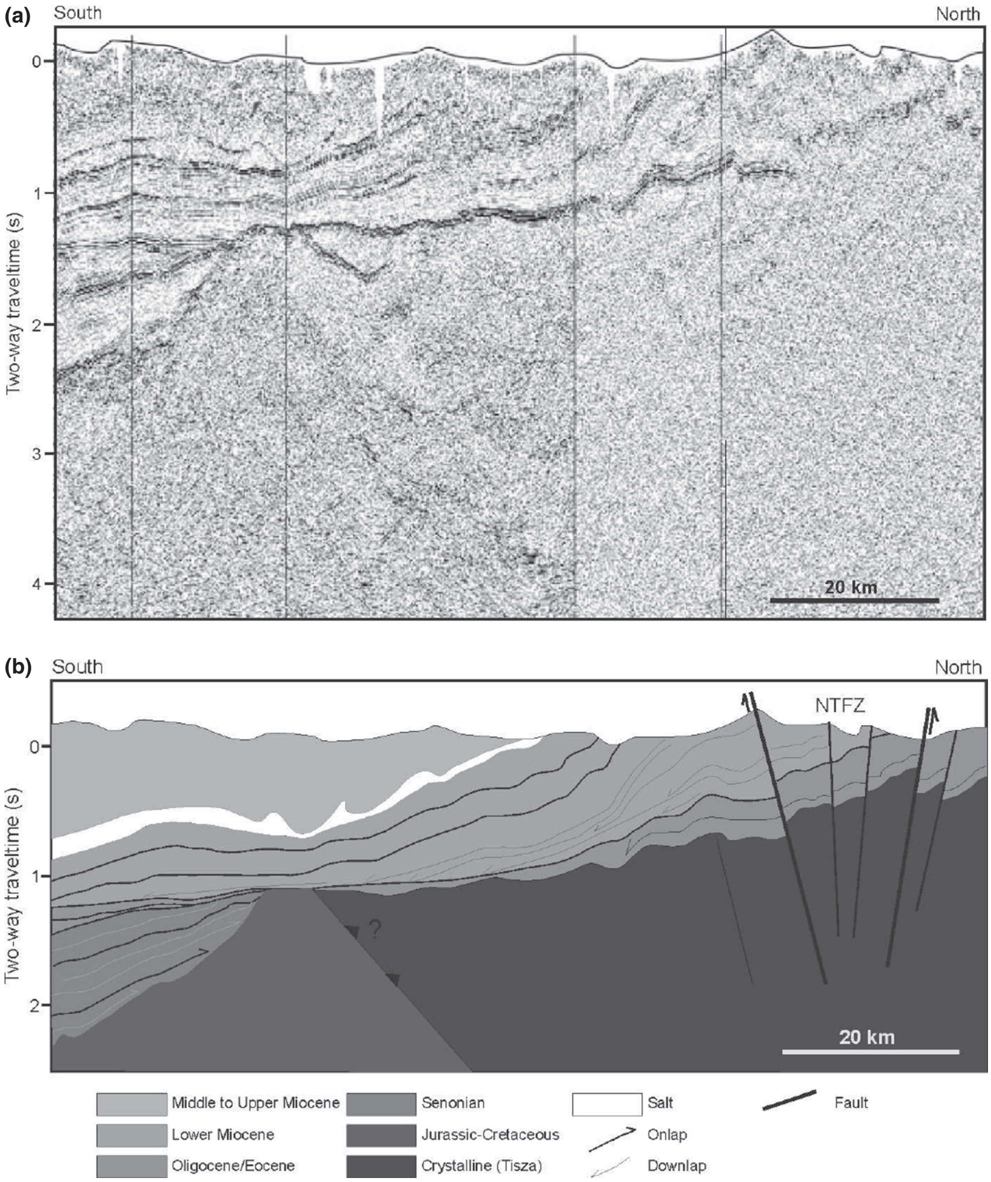

FIGURE 8 Seismic section along the line Transylvanian Basin (TB) before (a) and after (b) interpretation (crops edited after Krészek & Bally, 2006). The location of the line TB is indicated in Figure 2. The depth is in time (s).

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