



# Deep structure of the Pieniny Klippen Belt in Poland

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## Abstract

An interpretation of the deep structure of the Pieniny Klippen Belt in Poland is presented, utilizing a high-resolution deep seismic reflection survey. The studied profiles reach a depth of around 23 km. The seismic lines depict the structure and mutual relationships between the main domains analyzed—the Central Carpathians (CC), the Pieniny Klippen Belt (PKB) and the Outer Carpathians. The seismic lines show the Central Carpathian Paleogene (CCP) sediments covering the Tatric units and overlying Križna and Choč nappes of the CC south of the PKB. The entire nappe pile comprising the CC units is thrust over sedimentary rocks that probably derived from the European Plate, representing a mixture of autochthonous platform Paleozoic to Neogene sediments and slices of Outer Carpathian and PKB rocks. The older crystalline basement of the European Plate is suspected to be below these sedimentary rocks. The reflections below 20 km depth show a possible boundary between different crustal elements within this plate. The PKB is part of a 3–5 km wide flower structure, limited by fault zones that include faults cutting across sediments of the CCP and the Magura Nappe. The fault marking the southern limit of the PKB is particularly well visible in the seismic sections. The Albian–Lower Miocene flysch sequences, constituting the main components of the PKB, form north-vergent thrust-sheets. During the Albian to Miocene the PKB originated as an accretionary prism in front of the moving CC Plate, followed by plate rotation and strike-slip processes. The entire CC nappe pile is thrust over the Precambrian and Lower Paleozoic crystalline basement of the European Plate and probably slices of the PKB. The Outer Carpathians display an allochthonous character above the European Plate and comprise several north-verging imbricated nappes (thrust-sheets). The European plate dips gently southwards below the PKB and the CC Plate, cut by several deep-reaching faults.

**Keywords** Pieniny Klippen Belt · Central Carpathians · Outer Carpathians · Reflection seismics · Tectonics · Olistoliths

## 1 Introduction

The goal of this research was the interpretation of the deep structure of the Pieniny Klippen Belt (PKB) in Poland and mutual relationships between the main analyzed domains: Central Carpathians, Pieniny Klippen Belt (PKB) and Outer (Flysch) Carpathians (Fig. 1). Previously, Golonka

et al. (2018b) reprocessed and interpreted the older seismic lines 24-5-87K and 24A-5-87K, that illustrate the plates suture of the Central Carpathian Plate–European Plate collision zone along the major Carpathian transect Kraków–Zakopane (Figs. 2 and 3; see also Sikora et al. 1980; Golonka et al. 2005). Here, we present the newest deep seismic reflection survey available in the central part of the Polish Carpathians (Fig. 3). This survey was carried out in the framework of the IS-EPOS: Digital Research Space of Induced Seismicity for EPOS Purposes project (Lasocki and Orlecka-Sikora 2016).

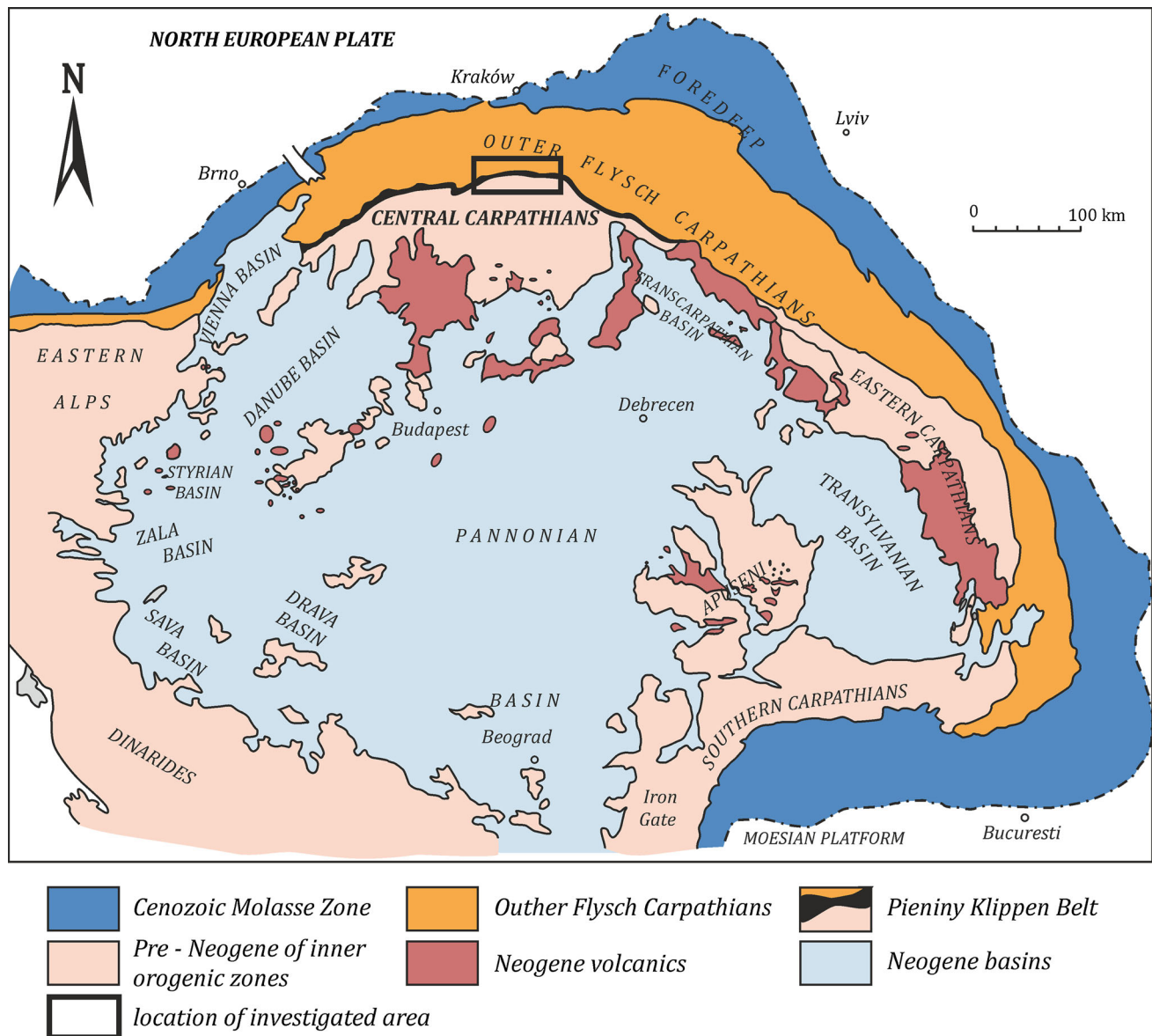
The PKB suture zone and its relationship with the other main domains in the area was the subject of conflicting interpretations based on surface geology, geophysical investigations and deep drillings. Picha (1996) and Picha et al. (2006) postulated that the Central Carpathian plate was thrust over the North European Plate in the western

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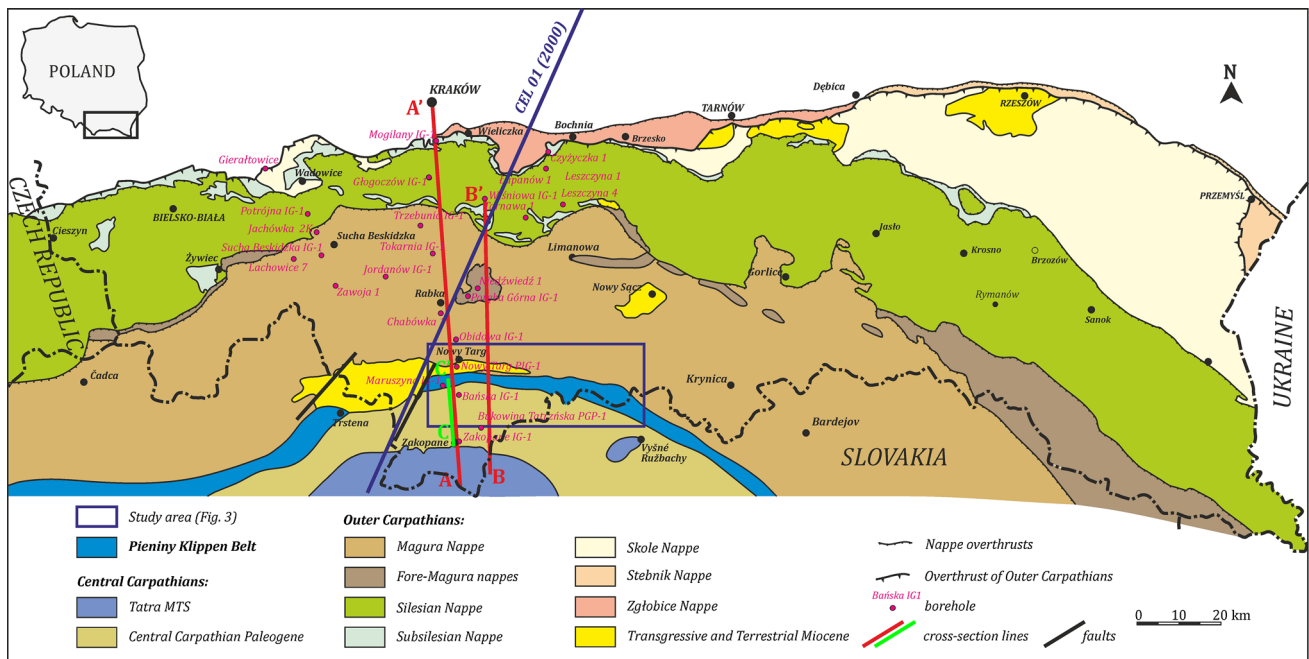
**Fig. 1** Geological map of Carpathians and adjacent areas with location of investigated area. Modified from Kováč et al. 1998; Golonka et al. 2018b

part of the Carpathians. A similar conceptual idea was presented by Roca et al. (1995), Zattin et al. (2011), Juriewicz (2005), Castelluccio et al. (2015, 2016) following Lefeld and Jankowski (1985). On the other hand, Froitzheim et al. (2008) and Plašienka (2018) depicted a steep to subvertical contact between the North European and Central Carpathians deriving from the Adriatic plate. Several deep boreholes in the study area (see Figs. 2 and 3) did not reach the crystalline basement of the Central Carpathian or European plate.

The Deep Seismic sounding CELEBRATION 2000 revealed the deep structure of Central Europe (Grad et al. 2006; Sroda et al. 2006; Janik et al. 2009, 2011; Hrubcová and Šroda 2015). The CEL01 line located west of the

investigated area (Fig. 2) shows the existence of feature interpreted by the authors (Janik et al. 2011) as a shear zone related to collision and possibly ongoing convergence between major lithospheric plates. The Moho depth rises southward from the Outer Carpathians (European Plate) towards the Central Carpathians and the Pannonian Basin (Fig. 4). Detailed geological maps depict the PKB as bordering the sedimentary cover of the Central Carpathian Plate, represented by the Central Carpathian Paleogene in the south, and the Outer Carpathians Magura Flysch in the north (Watycka 1964a, b; Kulka et al. 1985; Nemčok 1990; Gross et al. 1993; Janočko et al. 2000; Golonka et al. 2018a, b). Geomorphological studies revealed active vertical movements, which led to the uplift of the Pieniny





**Fig. 2** Map of the northern part of the Outer Western Carpathians in Poland with locations of the study area (Fig. 3) and of the cross-sections A–A' (Fig. 19), B–B' (Fig. 20), C–C' (Fig. 4) and

Celebration CEL01 deep seismic profile (Fig. 20) (see Sroda et al. 2006). Compiled and modified from various sources (Lexa et al. 2000; Ślaczka et al. 2006; Golonka et al. 2018b)

Klippen Belt (PKB) causing incision of the antecedent Dunajec River into a gorge (Golonka and Krobicki 2007). Vertical movements were also postulated by Castelluccio et al. (2015, 2016).

## 2 General outline of the geology

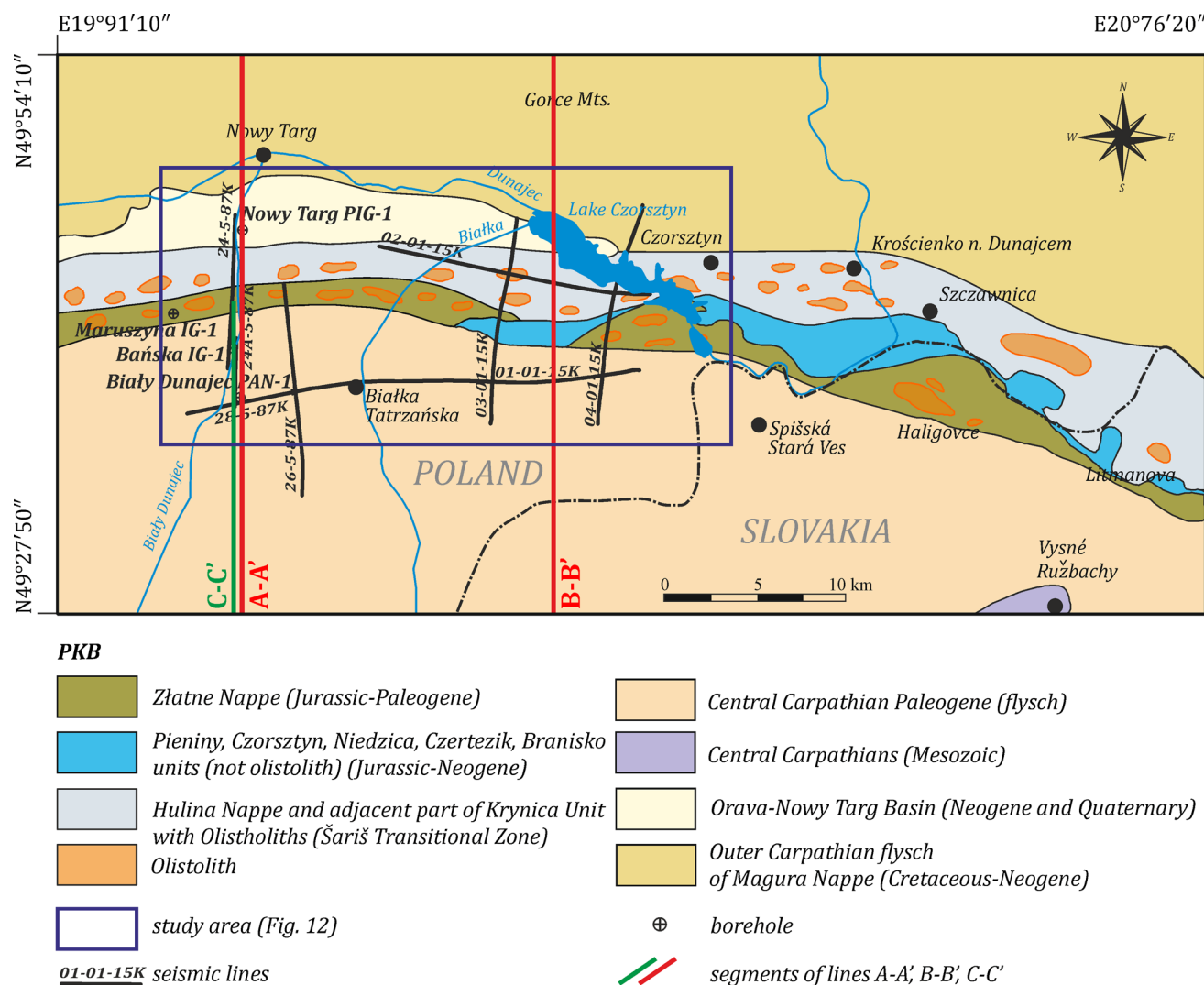
The Central Carpathians, Pieniny Klippen Belt (PKB) and Outer Carpathians units are the main domains marking the boundary between Central Carpathian units derived from the Adria Plate and the European Plate in Poland (Fig. 1) (Golonka et al. 2018b). The European Plate is a continental plate amalgamated in the Precambrian and Paleozoic. Its basement consists of Proterozoic, Vendian (Cadomian) and Lower Paleozoic (Caledonian) fragments, deformed and metamorphosed. The sedimentary cover includes Paleozoic, Mesozoic and autochthonous Miocene sequences (Golonka et al. 2011).

The Central Carpathians, PKB and Outer Carpathians are parts of the Carpathian orogen, which forms an extensive mountain arc, stretching for a distance of more than 1300 km from Austria to Romania (Fig. 1). The Central Carpathians are also part of the ALCAPA mega-unit (Csontos et al. 1992). They include a pre-Alpine Protocarpinian basement and a complex Alpine nappe pile primarily formed during the Late Cretaceous (e.g. Plašienka 2018). The term Protocarpinian refers to the igneous and metamorphic Precambrian–Paleozoic rocks occurring

in the Central Carpathians, exposed or forming the basement below younger Mesozoic and Cenozoic rocks. The Precambrian–Paleozoic and Mesozoic rocks are exposed in the Tatra Mountains, in the southernmost part of Poland, south of Zakopane (Fig. 2). North of the Tatra Mountains, in Poland, they are covered by the Paleogene rocks known as the Central Carpathian Paleogene (CCP) and recognized only from boreholes and geophysical data (Fig. 5; Golonka et al. 2005, 2018b).

The pre-Alpine Tatric basement consists of Paleozoic polygenetic granitoids intruded during the Variscan orogeny and pre-Variscan to Variscan metamorphics. The metamorphic envelope is composed of two units: the Upper Structural Unit and the underlying Lower Structural Unit, divided by a zone of ductile thrusting, recognized in the Tatra Mts. (i.e. Kahan 1969; Putiš 1992, 1994; Burda and Gawęda 2009). Rocks of the Upper Structural Unit are generally migmatized. Both metapelitic gneisses and amphibolites occur there (Burda and Gawęda 1999; Gawęda et al. 2000).

The crystalline basement cropping out in the Tatra Mts. is covered by Mesozoic rocks. The rocks that are in stratigraphic contact with the basement are called High Tatric “autochthonous succession” (e.g. Łuczyński and Jezierska 2018). They are thrust by an only a few km thick pile of cover napped also belonging to the High Tatric Nappe system and traditionally and confusingly called “Subtratic” although in a higher tectonic position (e.g. Kotański 1959, 1973; Lefeld 1985, 1999; Wiczorek 2000; Golonka et al. 2005), following Uhlig’s (1897, 1908)



**Fig. 3** Sketch map of the central part of the Pieniny Klippen Belt in Poland with the locations of the seismic profiles presented and segments of cross-sections A–A' (Fig. 18), B–B' (Fig. 19), C–C' (Fig. 4). Modified from Golonka et al. (2018b)

subdivision into “Hochtatrische and Subbtatrische Zone”. The Subtatric slices in Poland correspond to the Krížna and Choč (or Hronic) cover nappes defined in Slovakia (e.g. Mahel 1974) forming units of the Central Carpathian nappe stack tectonically overlying the High Tatric nappe). The term High Tatric is still being used by Alpine and Carpathian geologist (e.g. Dumont et al. 1996; Madzin and Sýkora 2014; Jurewicz 2018). We decided to follow Jurewicz's (2018) example and use the term High Tatric (Tatricum) and the terms Krížna and Choč (both parts of the Fatricum) in the present paper.

The High Tatric (Tatricum), Krížna and Choč (Fatricum) units include Permian, Triassic, Jurassic and Cretaceous cover rocks, mainly clastics and carbonates. Most cover rocks belonging to the High Tatric succession form the direct sedimentary cover of the Tatric crystalline basement. However, some sedimentary slices belonging to

the High Tatric nappe system are thrust over basement and cover of the main body of the High Tatric rocks, forming High Tatric nappe. The next higher Krížna nappe is thrust over the High Tatric nappe while the Choč nappe is thrust over the Krížna nappe.

The Mesozoic sedimentary rocks, mainly carbonates, were drilled by several boreholes located between the Tatra Mts. and PKB that reached the Mesozoic sedimentary rocks. These rocks were assigned to structural units named after the names of the boreholes (see Fig. 5). These are the Biały Dunajec and Bańska units, which were distinguished in the deep wells Bańska IG-1, Bańska PGP-1, Biały Dunajec PGP-2 and Biały Dunajec PAN-1 (Wieczorek and Barbacki 1997; Chowaniec and Kępińska 2003; Chowaniec 2009; Golonka et al. 2018b). Middle Eocene conglomerates and limestones, followed by up to 3000 m thick CCP rocks (mostly Podhale flysch), cover the Mesozoic units.

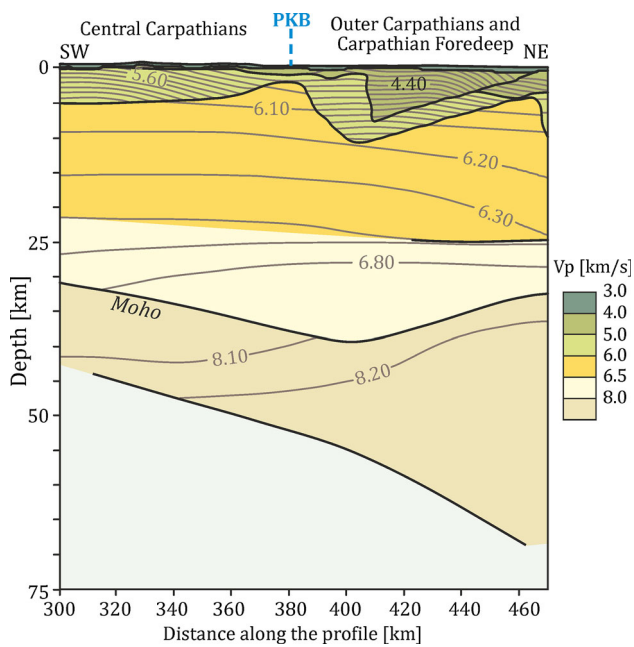


Fig. 4 Fragment of Celebration CEL01 deep seismic profile taken from Sroda et al. (2006). See Fig. 2 for profile location

The lithostratigraphic section of these deposits has been recognized by numerous natural exposures (Gołab 1959; Watycha 1959, 1968, 1975, 1976a, b, 1977) and by several deep boreholes (Fig. 3) (Wieczorek and Barbacki 1997; Chowaniec and Kępińska 2003; Chowaniec 2009). The largest thickness of the CCP, ca. 3000 m, was recorded in borehole Chochółów PIG-1 (Chowaniec et al. 2001; Golonka et al. 2005). The flysch rocks are strongly deformed along their boundary with the PKB, cropping out in an about 2 km wide zone. Castelluccio et al. (2016) observed a normal fault at the southern border of the PKB with the CCP. Ludwiniak (2018) documented faults parallel to the PKB that he relates to dextral strike-slip motion. NE–SW and W–E trending dextral-reverse oblique slip faults are also present (Mastella 1975; Mastella et al. 2012; Ludwiniak 2010, 2018). The W–E fault zone related to the sinistral strike slip at the northern boundary of the CCP also separates the underlying Central Carpathian units from the PKB (Birkenmajer 1960; Mastella 1975; Sperner et al. 2002; Schmid et al. 2008; Mastella et al. 2012). Ludwiniak (2018) argued that late-stage brittle structures in the Central Carpathians and PKB contact zone indicate dextral transpression along of this contact. Ludwiniak et al. (2019)

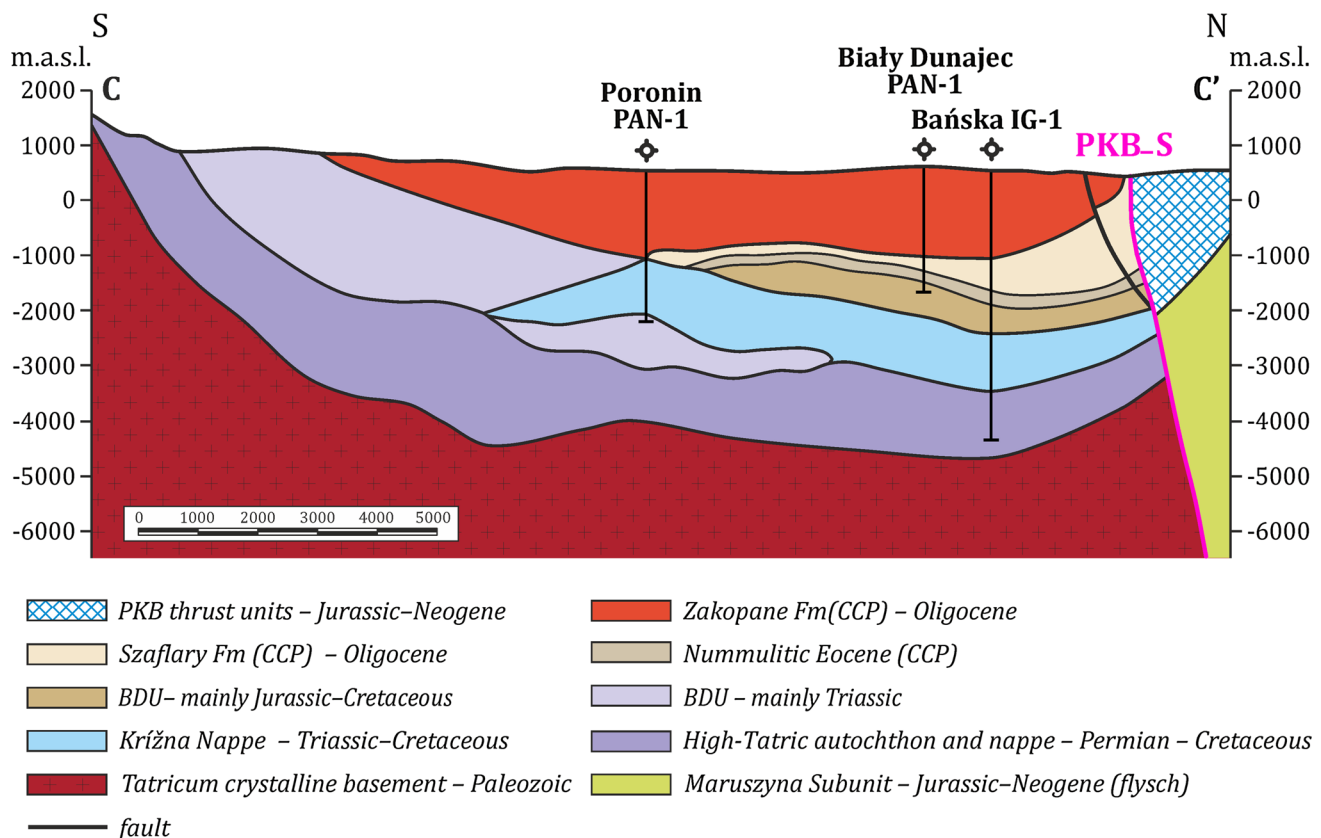


Fig. 5 Cross-section through the Podhale Trough between the Central Carpathian Tatra Mountains and the Pieniny Klippen Belt (southern part of Zakopane–Kraków line, Fig. 2), based on Wieczorek and Barbacki (1997), Krobicki and Golonka (2008), Golonka et al. (2018b)

		ZŁATNE	PIENINY BRANISKO CZERTEZIK NIEDZICA	CZORSZTYN	ZAWIASY	HULINA	KRYNICA
NEOGENE	Miocene	Kremna Fm					Kremna Fm / Stare Bystre Fm
	Oligocene						Malcov Fm / Magura Fm
PALEOGENE	Eocene	Złatne Fm					Zarzeczce Fm
	Paleocene	Żilina Fm / Proč Fm				?	Jarmuta Fm / Szczawnica Fm
			?	?	?	Jarmuta Fm	
CRETACEOUS	Maastrichtian						
	Campanian	Jaworki Fm	Sromowce Fm	Jaworki Fm	Jaworki Fm	Malinowa Sh Fm	Malinowa Sh Fm
	Santonian						
	Coniacian		Jaworki Fm			Hulina Fm	
	Turonian			Pomedznik Fm / Chmielowa Fm	Kapuśnica Fm	Sprzyczne Fm; Sztolnia Fm; Kapuśnica Fm	
	Cenomanian	Trawne Fm	Kapuśnica Fm				
	Albian						
	Aptian						
	Barremian	Pieniny Lms Fm	Pieniny Lms Fm	Spisz Fm / Łysa Fm	Pieniny Lms Fm	Pieniny Lms Fm	?
	Hauterivian			Dursztyn Lms Fm			
JURASSIC	Berriasian						
	Tithonian						
	Kimmeridgian	Czajakowa Radiolarite Fm			Czajakowa Radiolarite Fm		
	Oxfordian			Czorsztyn Lms Fm			
	Callovian	Sokolica Radiolarite Fm			Sokolica Radiolarite Fm		
	Bathonian						
	Bajocian	Podzamcze Lms Fm		Krupianka Lms Fm	Podzamcze Lms Fm		
	Aalenian			Smolegowa Lms Fm / Skrzypny Sh Fm			

**Fig. 6** Stratigraphic table for the sedimentary successions in the Pieniny Klippen Belt (southernmost units to the left) and the adjacent part of the Outer Carpathian Magura Nappe (right) called Krynica Subunit in Poland and bordering part of Slovakia. Table compiled after Andrusov (1965), Sikora (1971), Birkenmajer (1977), Golonka

and Sikora (1981), Potfaj (1997), Golonka et al. (2006b, 2015, 2018a), Wierzbowski et al. (2006), Golonka and Waškowska (2014), Oszczypko and Oszczypko-Clowes (2010), Oszczypko et al. (2015)

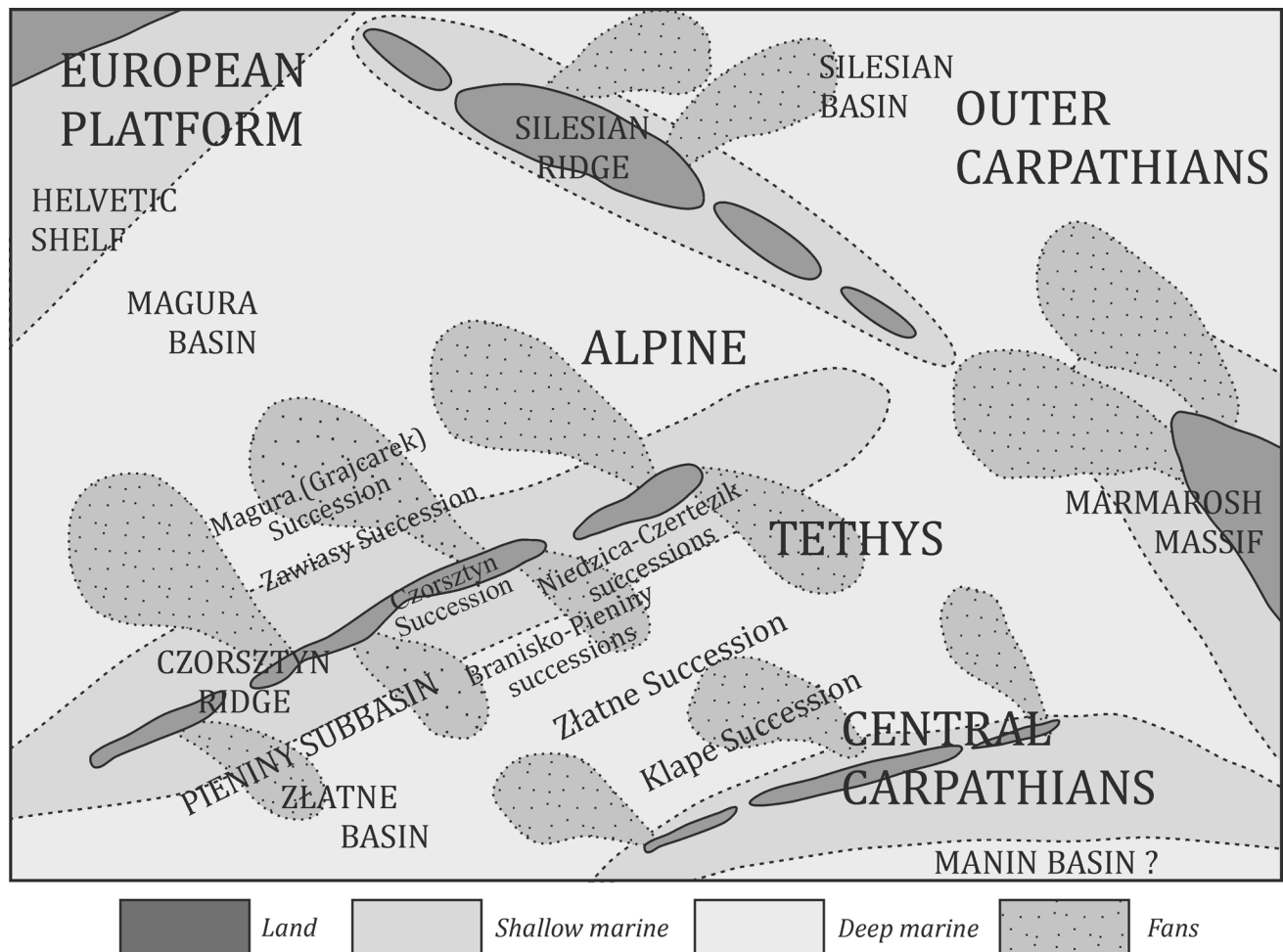
noted evidence of large-scale Miocene to Quaternary sinistral wrenching in this area.

In summary, the PKB marks the boundary between Central Carpathians and European plate not only at the surface but also at depth (Książkiewicz 1977; Birkenmajer 1986; Kovač et al. 1993; Roca et al. 1995; Nemčok et al. 1998; Plašienka 2012, 2018; Oszczypko et al. 2015; Golonka et al. 2018b; Ludwiniak 2018). The name Pieniny Klippen Belt first used by Neumayr (1871) was derived from the Pieniny Mountains (mountain range in Poland and adjacent Slovakia) and from the term “Klippen”, denoting erosion-resistant blocks surrounded by and rising above less competent rocks, mainly turbiditic sandstones and mudstones (flysch), shales and marls. These blocks or

“Klippen” are composed of different successions of mainly deep and shallow-water limestones, covering a time span from the Early Jurassic to the Early Cretaceous (Andrusov 1938; Birkenmajer 1977, 1986, 1988; Mišík 1994). The map pattern of the PKB in the investigated area (Watycha 1964a, b, 1975; Kulka et al. 1985) generally reveals the presence of blocks of Jurassic and Lower Cretaceous carbonate rocks. Several formations were assigned to these different successions that define paleogeographical domains (Fig. 6) (Birkenmajer 1977).

During the Jurassic and Cretaceous, the sedimentary rocks of the PKB were deposited in a SW–NE oriented paleogeographic realm that is part of the Alpine Tethys and divided into deeper basins to both sides of a submarine





**Fig. 7** Palaeoenvironment and paleo lithofacies and main paleogeographical elements of the Alpine Tethys and adjacent areas during the Albian (from Golonka et al. 2017, modified). Plate reconstruction at 112 Ma

high named Czorsztyn Ridge and Czorsztyn sequence of Fig. 6 (Fig. 7) (Birkenmajer 1977, 1986; Golonka and Krobicki 2004; Schmid et al. 2008; Golonka et al. 2015, 2018a). The submarine Czorsztyn Ridge and its slopes were characterized by a pelagic type of sedimentation from the Bathonian onwards (Birkenmajer 1977, 1986). The Jurassic–Lower Cretaceous rocks deposited on the southeastern slopes of the Czorsztyn Ridge represent the Czorsztyn, Niedzica, Czertezik, Branisko and Pieniny klippen successions (*sensu* Birkenmajer 1977, 1986, with modification by Wierzbowski et al. 2006; Golonka et al. 2018a; see Fig. 6). Very deep-water pelagic limestones and radiolarites were followed by Albian–Lower Miocene clastics within the basins surrounding the Czorsztyn Ridge (Sikora 1962, 1974; Birkenmajer 1977; Golonka and Krobicki 2004; Oszczytko et al. 2015). Golonka and Krobicki (2004) proposed the name Złatne Basin for the southeasternmost basin preserved within the Alpine Tethys (future PKB) following Sikora (1971, 1974), who characterized the Złatne Succession as being

composed of a thin Jurassic–Lower Cretaceous sequence, covered by Albian–Lower Miocene flysch (see also Golonka and Sikora 1981; Oszczytko et al. 2005; Golonka et al. 2018a). The Magura Basin represented the north-western part of the Alpine Tethys (future PKB) (Fig. 7).

The deposits of the marginal part of the Magura Basin incorporated into the Pieniny Klippen Belt structure are known as Hulina, Grajcarek or Šariš Unit, depending on the authors (see Sikora 1962; Golonka and Sikora 1981; Birkenmajer 1986, 1988; Golonka and Krobicki 2004; Pieńkowski et al. 2008; Plašienka 2012; Oszczytko et al. 2015; Birkenmajer and Gedl 2017; Golonka et al. 2018a). We prefer the name Hulina (Fig. 6) following Sikora (1962, 1971, 1974), who first described this succession from Hulina Mountain in Szczawnica emphasizing the nature of the of Upper Cretaceous–Cenozoic flysch succession, while Birkenmajer (Birkenmajer 1977, 1986, 1988; Birkenmajer and Gedl 2017) mainly highlighted the Jurassic–Lower Cretaceous pelagic rocks, using the name Grajcarek name for this unit. Plašienka (2012) defined his Šariš

Unit as lateral eastward continuation of the Hulina formation. Later, Jurewicz (2018) used the name Šariš Transitional Zone postulating a *mélange* character for this unit. The Albian–Upper Cretaceous sediments of the Hulina sequence, as well all other sequences shown in Fig. 6, are represented by flysch deposits and/or pelagic marls. Flysch sedimentation continued through the Paleogene and even reached Early Miocene times (Fig. 6). The flysch sequences contain numerous exotic elements in the form of large exotic blocks that constitute olistoliths. The exotics from the Złatne Basin mainly reveal Central Carpathian material, while the exotics from the Hulina and Krynica (Magura) sequences contain a lot of material derived from the Czorsztyn, Niedzica, Czertezik, Branisko and Pieniny successions (Sikora 1971, 1974; Birkenmajer 1986, 1988; Pieńkowski et al. 2008; Plašienka 2012; Oszczytko et al. 2015; Golonka et al. 2015, 2017, 2018a, b). These blocks composed of several successions of limestones and cherts are distributed as blocks-in-matrix within flysch of the Złatne and Hulina sequences. Castelluccio et al. (2015, 2016) depicted the stratigraphy of PKB in terms of a Jurassic–Lower Cretaceous ridge (Czorsztyn) succession followed by Upper Cretaceous Eocene “wildflysch”.

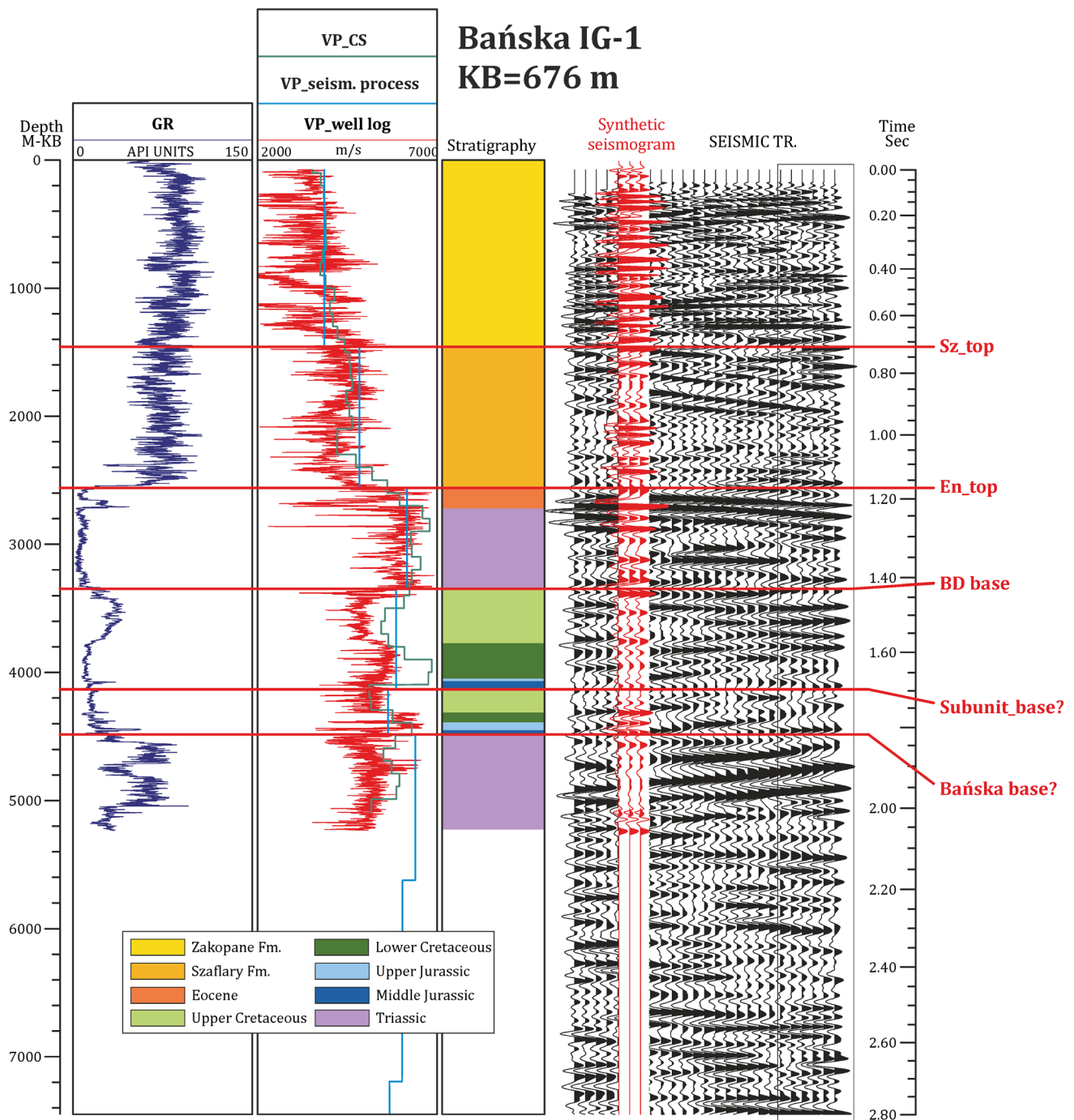
The PKB displays a particular tectonic character first noted by Uhlig (1897, 1903), visible in the maps of this region, as well as in regional cross-sections (e.g. Watycha 1964a, 1964b, 1975; Sikora et al. 1980; Birkenmajer 1983, 1986; Kulka et al. 1985; Jurewicz 1994, 1997; Froitzheim et al. 2008; Chrutek et al. 2004; Mastella et al. 2012; Ludwiniak 2010; Castelluccio et al. 2015, 2016; Golonka et al. 2018b). The Polish segment of the PKB shows both strike-slip and thrust components (e.g., Książkiewicz 1977; Birkenmajer 1986; Ratschbacher et al. 1993; Nemčok and Nemčok 1994; Jurewicz 1994, 1997). Birkenmajer (1986, 1988) distinguished several tectonic units that correlate with Czorsztyn, Niedzica, Czertezik, Branisko, Pieniny and Hulina successions. The entire tectonic sequence of units of the PKB is visible only in the Pieniny Mts. located in Poland and adjacent Slovakia, i.e. between Spišská Stará Ves and Krościenko (Fig. 3). In other places the Jurassic–Lower Cretaceous rocks of these successions are only found in olistoliths or small tectonic slivers embedded within Lower Jurassic and Late Cretaceous–Paleogene flysch sequences. Uhlig (1907) distinguished two nappes, a lower Sub-Pieniny Nappe, and an upper Pieniny Nappe. Książkiewicz (1977) followed Uhlig and distinguished upper (Branisko and Pieniny successions) and lower (Czorsztyn, Czertezik and Niedzica successions) nappes. According to Sikora (1971, 1974), the Czorsztyn (Sub-Pieniny) Nappe is thrust over the Hulina Nappe, while the Złatne Nappe is thrust over the Pieniny Nappe. Plašienka (2012) depicted the Sub-Pieniny thrust over the Šariš Unit (equivalent of Hulina Nappe). The

thrust of the Złatne Nappe over the Hulina Nappe is visible in the Zakopane–Kraków cross-section along the Biały Dunajec River (Golonka et al. 2018b).

Roca et al. (1995), Zattin et al. (2011) and Castelluccio et al. (2015, 2016) treated the PKB as a single entity in their balanced cross-sections. Jurewicz (2018) depicted the PKB as thrust over what she refers to as Šariš Transitional Zone exhibiting a gradual transition between PKB and Magura Unit. The margins of the PKB are generally represented by subvertical faults and shear zones (e.g. Birkenmajer 1983; Ludwiniak 2018). The shortening of the original sedimentary basins took place during foreland thrusting followed by strike-slip shearing.

Typically, a subvertical strike-slip fault zone separates the PKB from the present-day Outer Carpathians (e.g. Watycha 1964a, b, 1975; Sikora et al. 1980; Kulka et al. 1985). Several Outer Carpathian nappes and thrust-sheets are thrust 70 km (distance between the Carpathian front in the vicinity of Kraków and the PKB in the vicinity of Nowy Targ) onto the North European Plate in a section between Nowy Targ and Kraków (Książkiewicz 1977; Sikora et al. 1980). These Outer Carpathian nappes are built by Upper Jurassic–Lower Miocene, up to six kilometers thick, continuous flysch sequences, mainly deep-water turbidites. Magura, Fore-Magura (Grybów and Dukla), Silesian, Sub-silesian and Skole (Skiba) nappe were distinguished within the Outer Carpathians (Fig. 2) (e.g. Książkiewicz 1977; Żytko et al. 1989; Żytko 2001a; Ślaczka et al. 2006). The rocks of the Magura nappe, the southernmost unit of the Outer Carpathians, were deposited within the Magura Basin. Some of the deposits of the Magura basin became incorporated into the Pieniny Klippen Belt tectonic structure, while the remaining parts presently form the Magura Nappe. According to Kaczmarek et al. (2016), marine Miocene deposits occur in the zone next to the PKB in the vicinity of Nowy Targ (see also Cieszkowski 1992).

The Central Carpathians, PKB and Outer Carpathian nappes are cut by several local and regional major young faults of different origins (e.g. Mastella et al. 1988; Kovač and Hók 1993; Ratschbacher et al. 1993; Nemčok and Nemčok 1994; Sperner 1996; Plašienka et al. 1997; Soták and Janočko 2001; Sperner et al. 2002; Marko 2003; Marko et al. 2017; Golonka et al. 2005; Jurewicz 2018). The Carpathian rivers often follow S–N faults. The major dextral strike-slip S–N Dunajec fault cuts PKB and Outer Carpathians (Jurewicz 2018). The faults along Biały Dunajec and Bialka river cut CCP and PKB (Mastella et al. 1988). The E–W subvertical faults separate the PKB from CCP and Outer Carpathians (e.g. Watycha 1964a, b, 1975; Sikora et al. 1980; Birkenmajer 1983; Ludwiniak 2018). Faulting and uplifting played a tremendous role during the Neogene tectonic evolution of the PKB in Poland (Roca



**Fig. 8** Synthetic seismogram of borehole Bańska IG-1. GR gamma ray, VP\_CS interval velocities from check shot, VP\_well log interval velocities acoustic log, VP\_seism. Process interval velocities from stacking process (calibration of time to depth conversion velocity

model). Markers: *Sz\_top* top of Szaflary Formation, *En\_top* top of Eocene nummulitic limestone, *BD base* base of Biały Dunajec Unit, *Bańska base* base of Bańska Unit

et al. 1995; Zattin et al. 2011), Castelluccio et al. (2015, 2016). A subhorizontal Late Badenian to Quaternary sequence, which partially covers the Magura Nappe (including deformed Lower Miocene rocks) above an unconformity in the western part of the investigated area (Figs. 2, 3) belongs to the Orava-Nowy Targ Neogene

Basin, which contains over 900 m of gravel, sand-silt and clay deposits in the Polish and adjacent parts of western Slovakia. 920 m of Miocene and Pliocene deposits were encountered in the borehole in the vicinity of Czarny Dunajec (Watycha 1977). The Orava-Nowy Targ Neogene Basin stretches parallel to the PKB and is bordered by sets



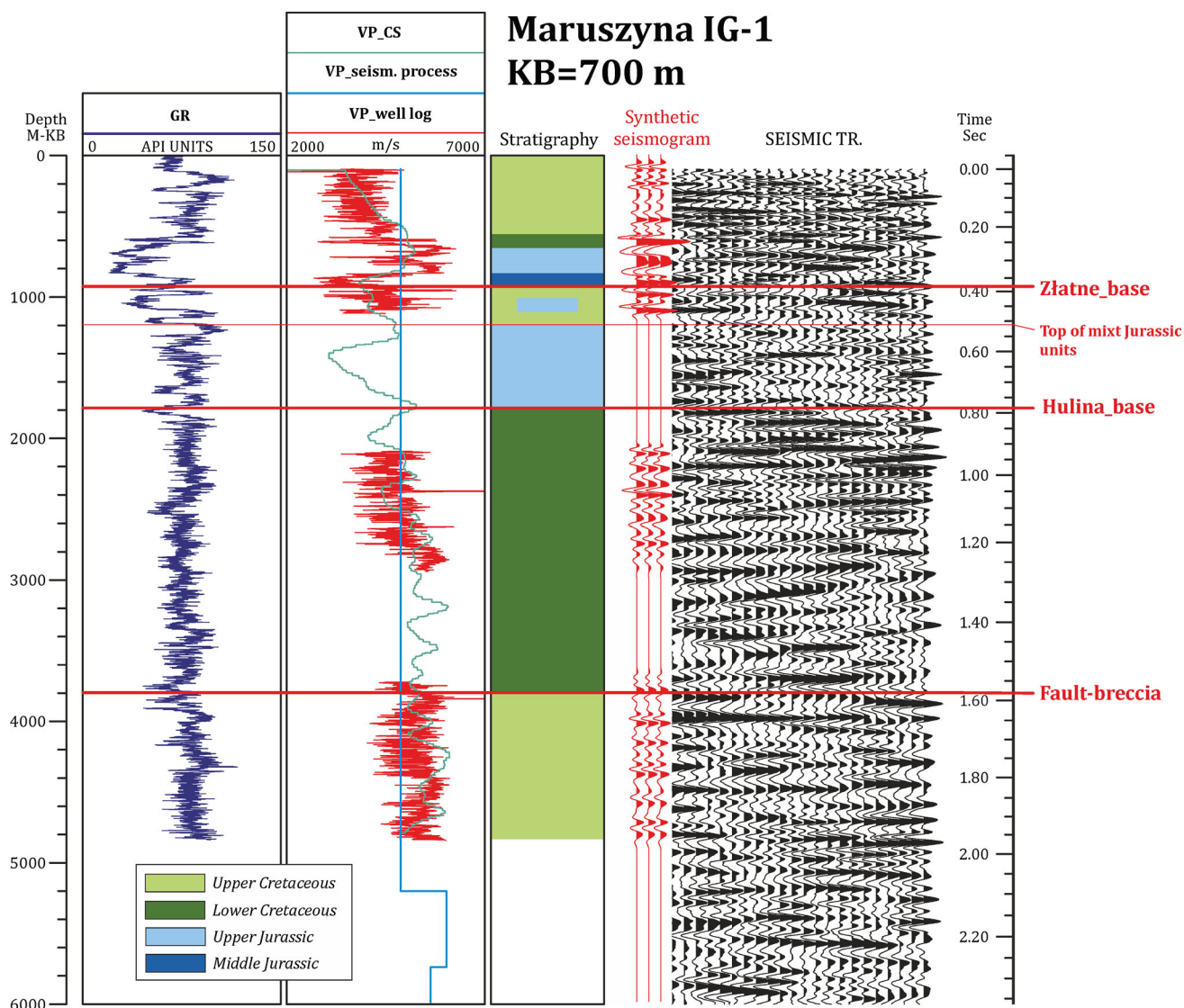
of normal faults (Pomianowski 2003; Golonka et al. 2005; Struska 2009 and references therein). A large-scale, NE–SW directed, sinistral strike-slip fault of Miocene age also played an important role in the development of Orava-Nowy Targ basin (Fig. 2; near the western end of this basin) (see Struska 2009; Ludwiniak et al. 2019). The PKB unit is submerged entirely below this young basin between Stare Bystre in Poland and Trstená in Slovakia (Chowanec and Cieszkowski 2009). Fresh-water sedimentation started in the Late Badenian (Serravallian) in the Orava-Nowy Targ Basin (Oszast and Stuchlik 1977; Golonka et al. 2005; Łoziński et al. 2017; Wysocka et al. 2018). The youngest sediments are represented by the recent pebbles of the Dunajec River and its subsidiaries. The Nowy Targ PIG-1 borehole revealed 59.5 m of the Quaternary gravels and sands (Paul and Poprawa 1992).

**Fig. 10** Seismic depth section—composite line 24-5-87K and 24A-5-87K. **a** Raw data with selected reflections highlighted and with marked PKB border faults. **b** Interpreted. *ZF* Zakopane Formation, *SF* Szaflary Formation, *BU* Bańska Unit, *BDU* Biały Dunajec Unit, *HTN* High Tatric Nappe, *HTa* High Tatric “autochthonous”, *Hrz* high reflections zone, *PKB\_N* north PKB fault, *PKB\_S* south PKB fault. Black lines—other faults. Modified from Golonka et al. (2018b)

## 3 Methods

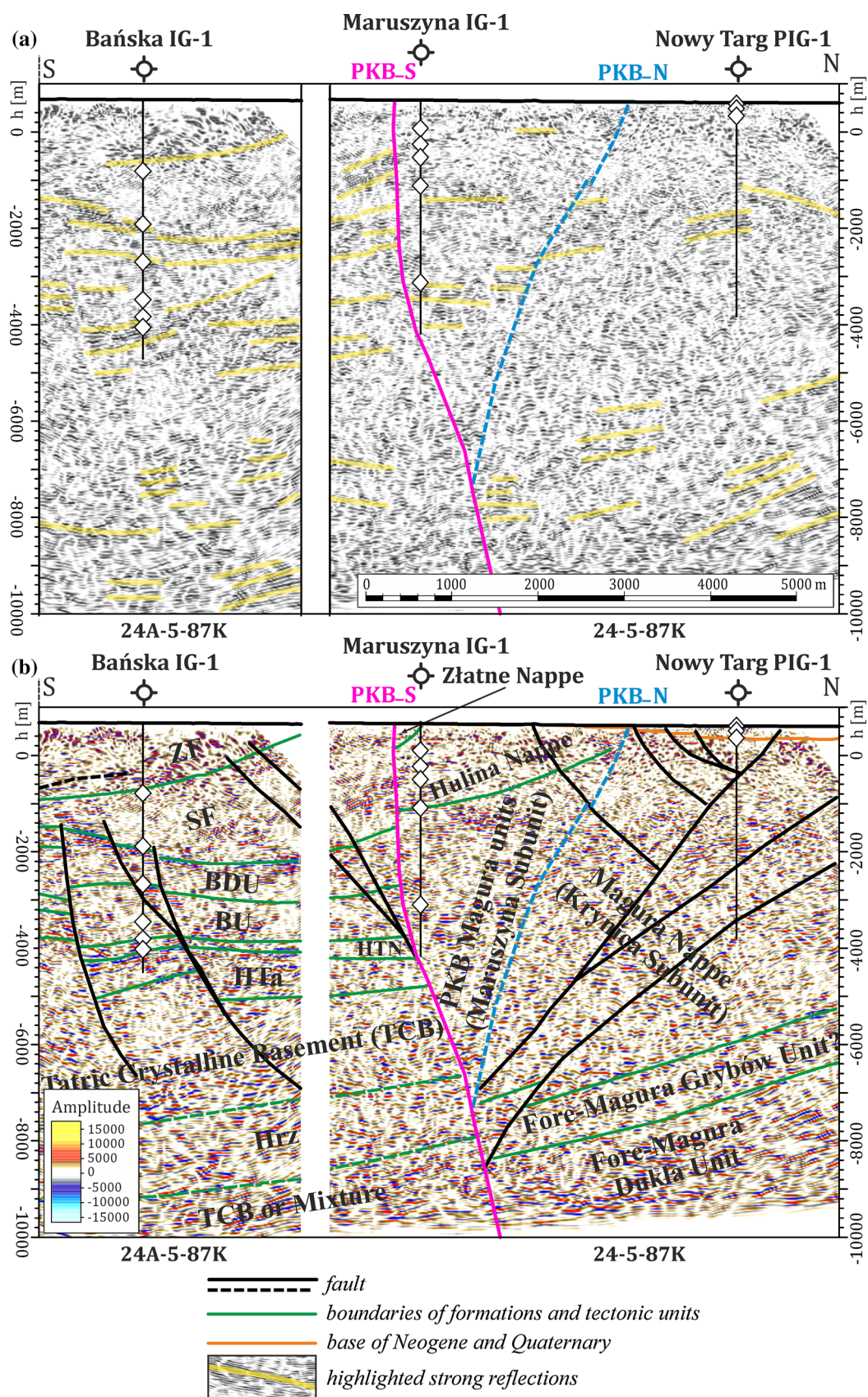
### 3.1 Seismic surveys

Input data for this study come from the 2D seismic survey “Czorsztyn” (lines 01-01-15K, 02-01-15K, 03-01-15K and 04-01-15K), which was acquired in 2015 by Geofizyka Kraków SA for the Institute of Geophysics, Polish

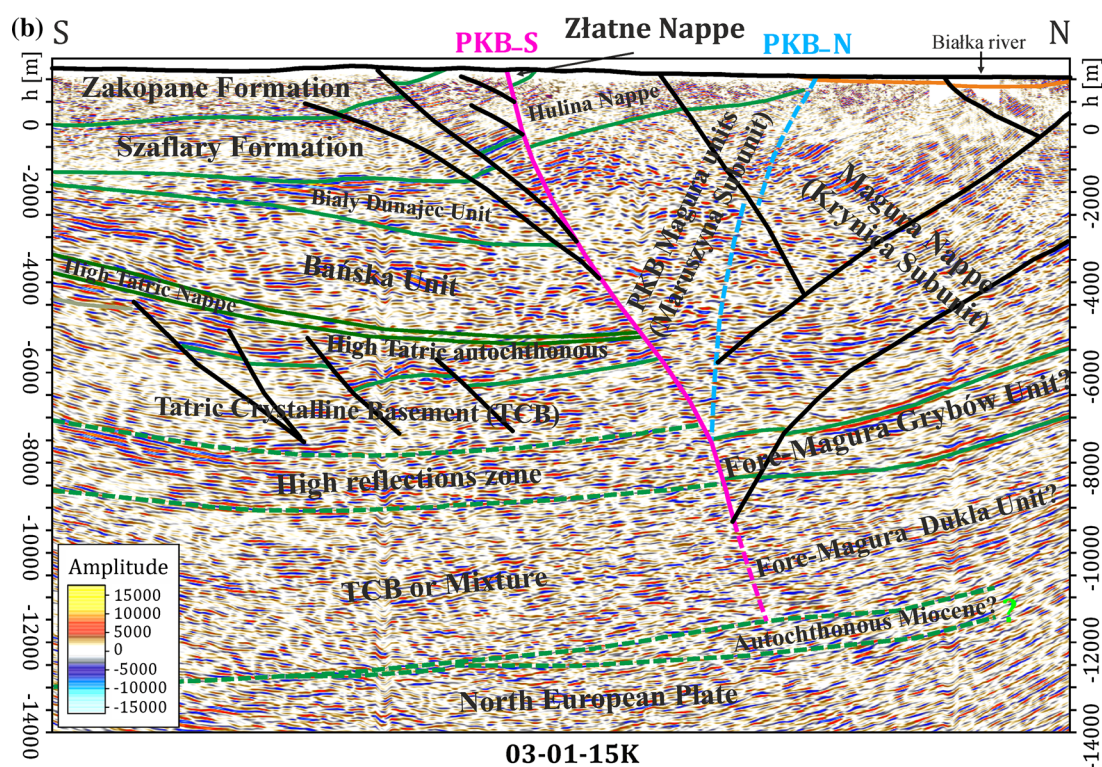
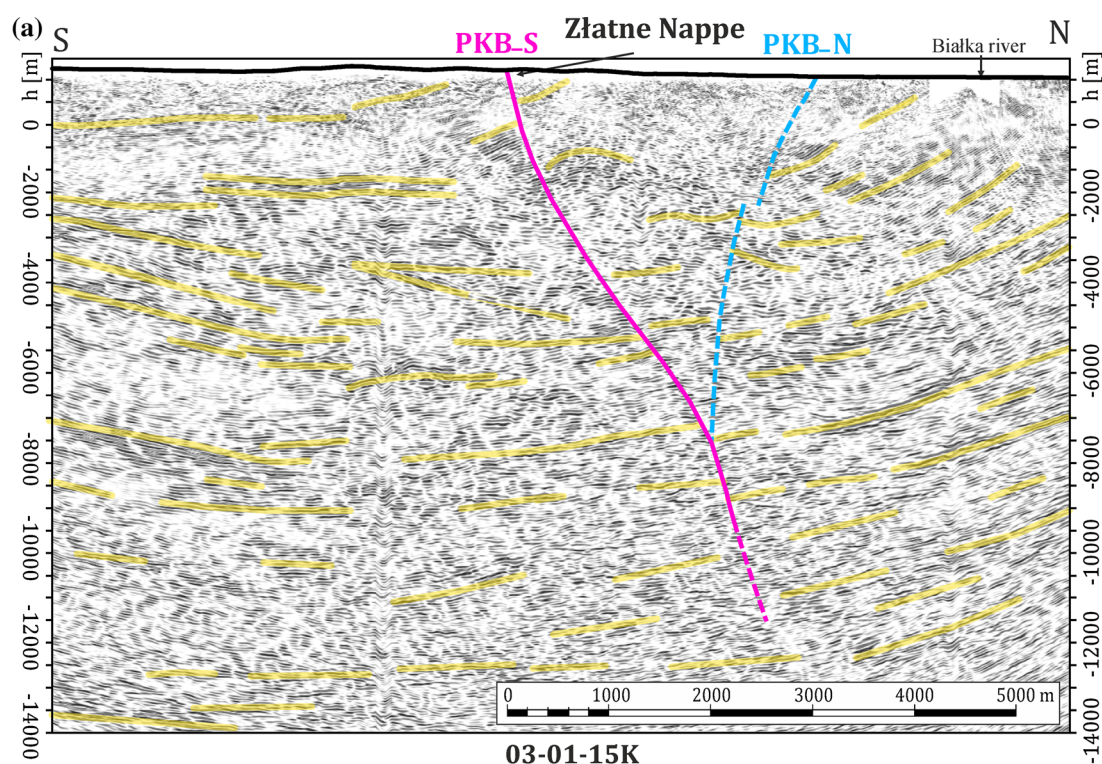


**Fig. 9** Synthetic seismogram of borehole Maruszyňa IG-1. *GR* gamma ray, *VP\_CS* interval velocities from check shot, *VP\_well log* interval velocities acoustic log, *VP\_seism. process* interval velocities from stacking process (calibration of time to depth conversion velocity model)









- fault
- base of Neogene and Quaternary
- formation and tectonic units boundaries
- highlighted strong reflections



◀**Fig. 11** Seismic depth section of line 03-01-15K (see Fig. 3 for its location west of line B–B' presented in Fig. 20). **a** Section with raw data and selected reflections highlighted and with marked PKB border faults. **b** Interpreted section. *PKB\_N* northern PKB border fault, *PKB\_S* southern PKB border fault

Academy of Sciences (IG PAS) in the framework of the IS-EPOS: Digital Research Space of Induced Seismicity for EPOS Purposes project (Lasocki et al. 2016; Lasocki and Orlecka-Sikora 2016), as well as four archival profiles (24-5-87K, 24A-5-87K, 26-5-87K and 28-5-87K) acquired in 1987 by the same company. The location of the seismic profiles is shown in Fig. 3. Shot station spacing was 50 m, and receiver station spacing was 25 m, giving 12.5 m between the CMPs (Common Mid Points-related to Common Depth, reflecting Points). Maximum offset ranges were up to 16.560 m, and the average fold was 125. A seismic sweep signal was generated by vibroseis, with the length of 16 s and bandwidth 6–80 Hz. The data have a record length of 8 s (two-way time) and a sampling rate of 2 ms. Four archival seismic lines were acquired in the same way. The differences were only in record length (4 s two-way time), maximum offset (up to 1935 m), and average fold of 32. For actual and archival profiles, the seismic processing steps included geometrical spreading compensation, coherent noise and anomalous amplitude attenuation, time-variant surface-consistent predictive deconvolution, surface-consistent amplitude compensation, high resolution multiple removal, DMO (deep move-out—partial time migration), NMO (normal move-out) velocity estimation, post-stack time migration and FX deconvolution (procedure removing the random noise). The data were processed with relative amplitude preservation. The main goal of the seismic surveys was to recognize the velocity field and the deep structure. Often, a part of the records related to the shallow subsurface zone was muted in processing of seismic data. Therefore, the seismic image lacks a part corresponding to a depth interval of 0–200 m below datum (650 m a.s.l.). Despite complex topography and geological structure, the acquired seismic data provide sufficient quality.

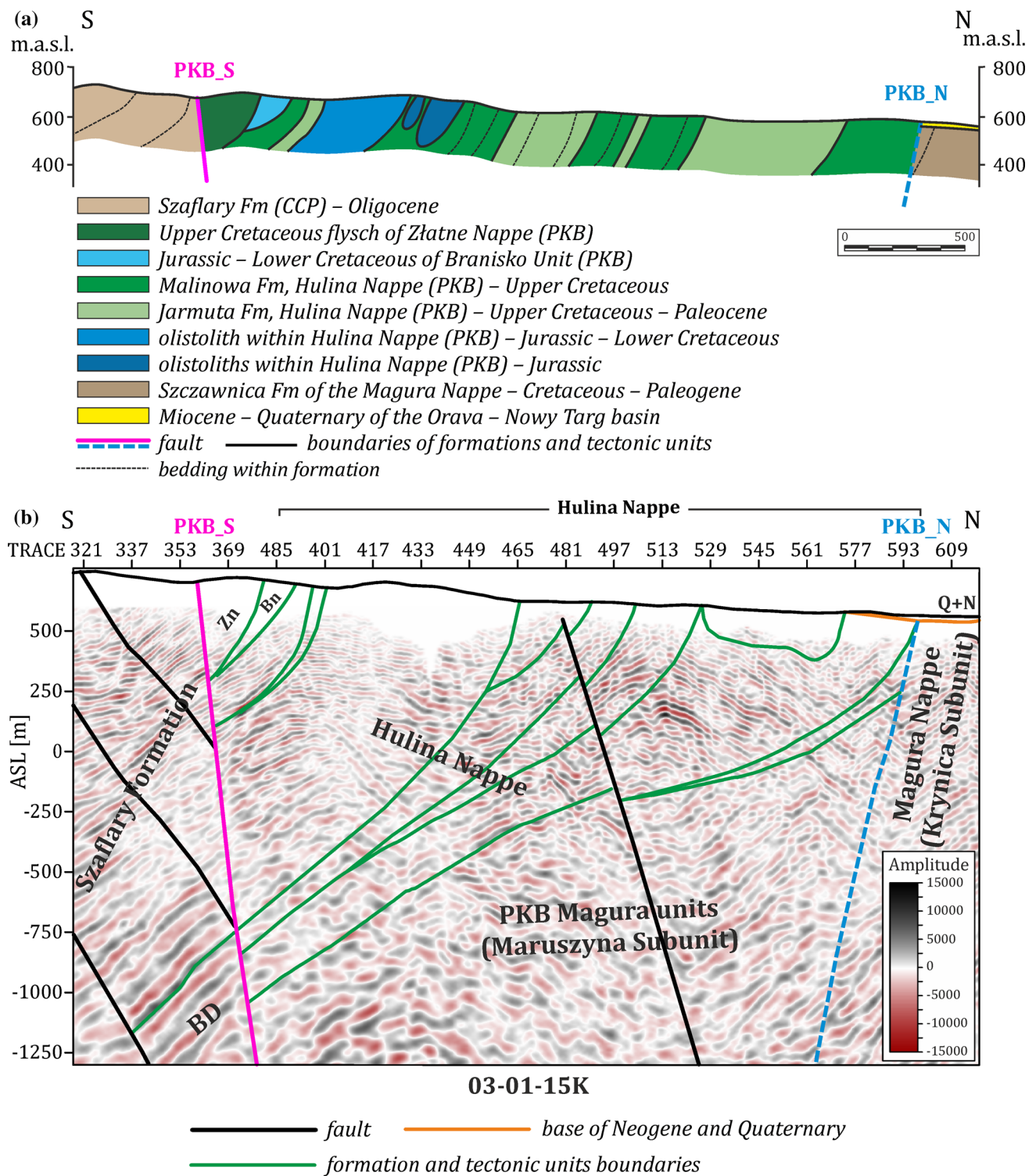
### 3.2 Seismic well tie

Geological interpretation of seismic profiles requires borehole data tied through the synthetic seismograms to the acquired and migrated seismic data. This procedure allows for correlation of geological boundaries identified in a borehole with specific seismic reflections on the seismic section. The Bańska IG-1 borehole (Fig. 8), located on the south side of the Pieniny Klippen Belt (PKB), penetrates the CCP. It was used to correlate seismic horizons on lines 24A-87K, 26-5-87K, 28-5-87K, 01-01-15K, 03-01-15K

and 04-01-15K (Fig. 3). The Maruszyna IG-1 borehole (Fig. 9) (Birkenmajer and Gedl 2012; Golonka 2012), which penetrates the PKB, was used for correlation of seismic horizons on lines 24-5-87K, 02-01-15K, 03-01-15K and 04-01-15K. The seismic depth sections are depicted in Figs. 10, 11, 12, 13, 14, 15, 16 and 17. The Maruszyna IG-1 borehole was projected on line 24-5-87K (Fig. 10). The geological profile and calculated synthetic seismogram (Fig. 9) allowed the authors to identify, in particular, the base of the Złatne Nappe and the base of the Hulina Nappe on seismic profiles. The Nowy Targ PIG-1 borehole is the only borehole located on the northern side of the PKB (Outer Carpathians) and provided the only geological profile (Paul and Poprawa 1992), which was used to correlate seismic horizons on profile 24-5-87K (Fig. 10).

### 3.3 Seismic interpretation

The seismic time sections were converted to depth with the application of a smoothed velocity field. Stacking velocities were converted to interval velocities and next to average velocities, which was finally calibrated by wells (Figs. 8, 9) and smoothed. In the seismic image, we observe strong reflections and non-reflective zones (e.g. profiles 03-01-15K of Fig. 11 and profile 01-01-15K of Fig. 17 discussed later). Intervals with strong reflections are associated with sedimentary rocks containing very high velocity beds (e.g. carbonate rocks inside of the Bańska and Biały Dunajec units (Figs. 8, 11) or sequences of high and low impedance (e.g. Oligocene shale and sandstone sequences forming the top of the Grybów and Dukla units (Fig. 11). Non-reflective zones can be interpreted as crystalline rocks (e.g. Tatric Crystalline Basement (TCB) in Fig. 17) or heterolithic flysch (e.g. lower part of the Szafary Formation in Figs. 13 and 15). Sometimes, the seismic image also shows discontinuities of reflections. There are many areas of rapid dip changes and faults (e.g. Figs. 11, 13). The composite line 24-5-87K and 24A-5-87K, as well as seismic profiles 03-01-15K and 04-01-15K, which cross all geological domains from South to North, are shown as raw data (Figs. 10a, 11a, 13a) and as interpreted versions (Figs. 10b, 11b, 13b). The profile 02-01-15K (Fig. 15) and the composite line 28-5-87K and 01-01-15K (Fig. 17) are located in parallel to the PKB. The seismic interpretation in this area (Figs. 12, 14, 16) is also based on variability of the recorded wave field in connection with the surface geological map. Mapping was conducted along the seismic profiles and across major tectonic zones. The observations in outcrops allowed us to correlate seismic intervals with geological formations, within the limits caused by the aforementioned gap in seismic imaging between surface and 200 m depth. For example, Fig. 12a presents a



**Fig. 12** Shallow parts of seismic depth section of line 03-01-15K (see Fig. 3 for its location west of line B–B' presented in Fig. 20). **a** Simplified shallow geological cross-sections along seismic profile 03-01-15K. **b** Interpreted shallow parts of seismic profile 03-01-15K.

Abbreviations in seismic profile 03-01-15K are: *Zn* Złatne Nappe, *Bn* Branisko Unit, *BD* Biały Dunajec Unit (Fatric), *Q+N* Quaternary and Neogene, *PKB\_N* northern PKB boundary fault, *PKB\_S* southern PKB boundary fault

simplified shallow geological cross-sections alongside the seismic profile 03-01-15K (Fig. 12b). The southern part of this section shows a sharp contrast between the CCP

(Szaflary Formation, oldest CCP flysch deposits) and Cretaceous flysch of the Złatne Nappe. The tectonic contact crops out quite well (Ludwiniak 2018). The Central



part allows for observing the contact between carbonate olistoliths and the surrounding flysch matrix (in outcrops), as well as tectonic boundaries between nappes. The boundaries repeating sequences of Upper Cretaceous red and variegated shales of the Malinowa Formation and Upper Cretaceous–Paleocene sandstones, conglomerates and shales (flysch) of the Jarmuta Formation were used for correlation of scale boundaries within Hulina Nappe (see also Figs. 14, 16). The interpretation of seismic sections in some parts can be debatable because of missing deep boreholes, which are essential for good geological interpretation of seismic reflections. Sometimes seismic data quality is insufficient and the tectonics of the PKB and Magura units are very complex.

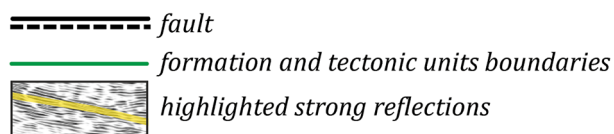
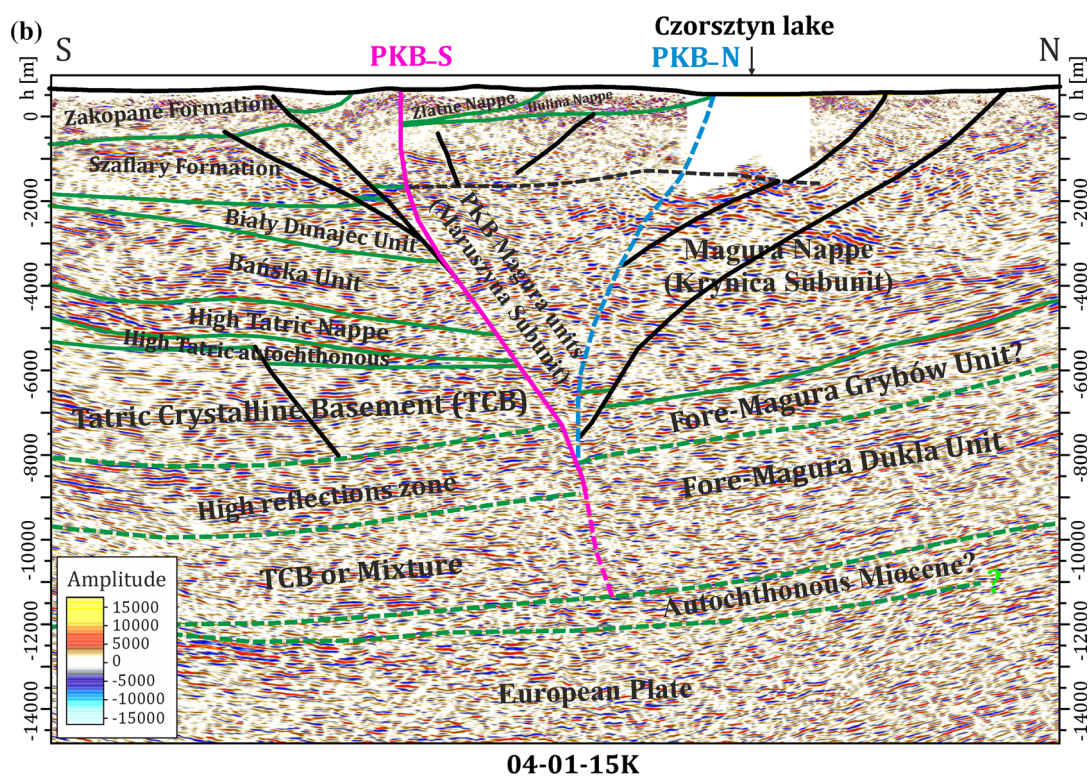
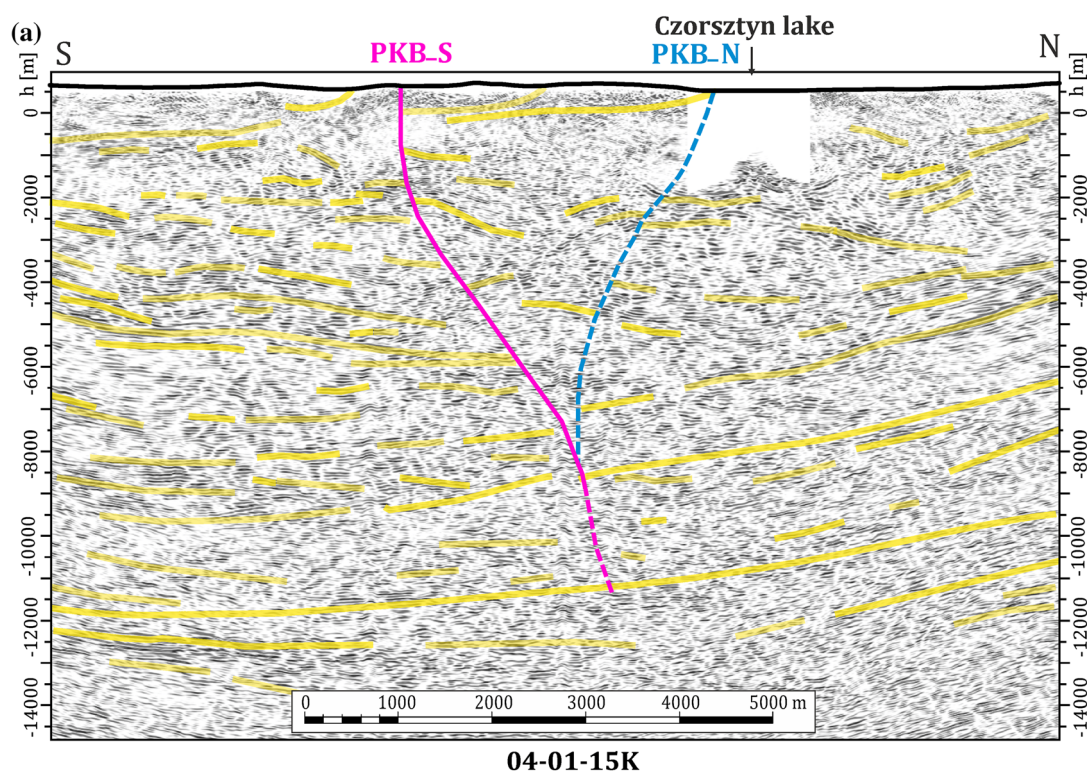
## 4 Results

The seismic profiles based on old and recently acquired seismic data depict the structure and mutual relationship between the main analyzed domains—the Central Carpathians, PKB and Outer Carpathians. The orientation of seismic boundaries, south of the PKB (CCP) was estimated based on lithostratigraphic data from the deep borehole Bańska IG-1 (Fig. 8). The CCP structure is shown on seismic sections 24A-5-87K (Fig. 10), 03-01-15K (Figs. 11, 12) and 04-01-15K (Figs. 13, 14). The bottom surface of the CCP rocks is expressed as high-amplitude horizon in the seismic sections 24A-5-87K (Fig. 10), 03-01-15K (Fig. 11), 04-01-15K (Fig. 13) and composite lines 28-5-87K and 01-01-15K (Fig. 17). The Szaflary Formation represents the oldest CCP flysch deposits, which are heavily deformed and often vertical in the border zone near the PKB (Mastella 1975; Golonka et al. 2018b; Ludwiniak 2018). The Szaflary formation is covered by younger shaly flysch strata of the Zakopane Formation. They dip gently towards the center of the Podhale Basin. The CCP is cut by several north-dipping faults (Figs. 10, 11, 13, 17). The large listric, transverse, faults are (see also e.g. Mastella et al. 1996, 2012; Ludwiniak et al. 2012) displace formations between tens and more than 200 meters.

The tectonic units below the Central Carpathian Paleogene visible in Fig. 17 are correlated with the Tatra Mts., depicted in the diagrammatic cross section (Fig. 5). Tatric (“autochthonous” and High Tatric nappe system) and Fatric (Križna and Choč) units include Triassic, Jurassic and Cretaceous sedimentary rocks, clastics and carbonates. The Križna and Choč nappes south of the PKB are represented by the Biały Dunajec Unit (BDU), mainly composed of Jurassic–Cretaceous rocks, and the Triassic of the Bańska Unit (Figs. 8, 10, 11, 13, 17) (Golonka et al. 2018b). These Fatric cover nappes are underlain by the

High Tatric sedimentary successions and Tatric crystalline basement (Figs. 5, 10, 11, 13, 17). The reflection pattern within the both High Tatric units stems from the bedding of the sediments that is parallel to the top of the crystalline basement succession. The reflections are parallel to the base of this unit, sometimes chaotic or dipping southwards displaying a tectonic boundary between two High Tatric subunits. A detached sedimentary slice of the High Tatric nappes system is thrust over the sedimentary cover (“autochthonous High Tatric succession”) of the crystalline Tatric basement. A high-reflection zone is visible between two non-reflective zone rocks of the Tatric crystalline basement (Figs. 5, 10, 11, 13, 17), allowing one to divide this basement into two units. Two alternative interpretations are possible: (1) correlation of these two units with the aforementioned Upper Structural Unit and Lower Structural Unit within the Tatric basement, or, (2) correlation of the upper unit with the Tatric basement and the lower unit with a mixture of Paleozoic–Neogene rocks of the European Plate, allochthonous Outer Carpathian units and Pieniny Klippen Belt rocks.

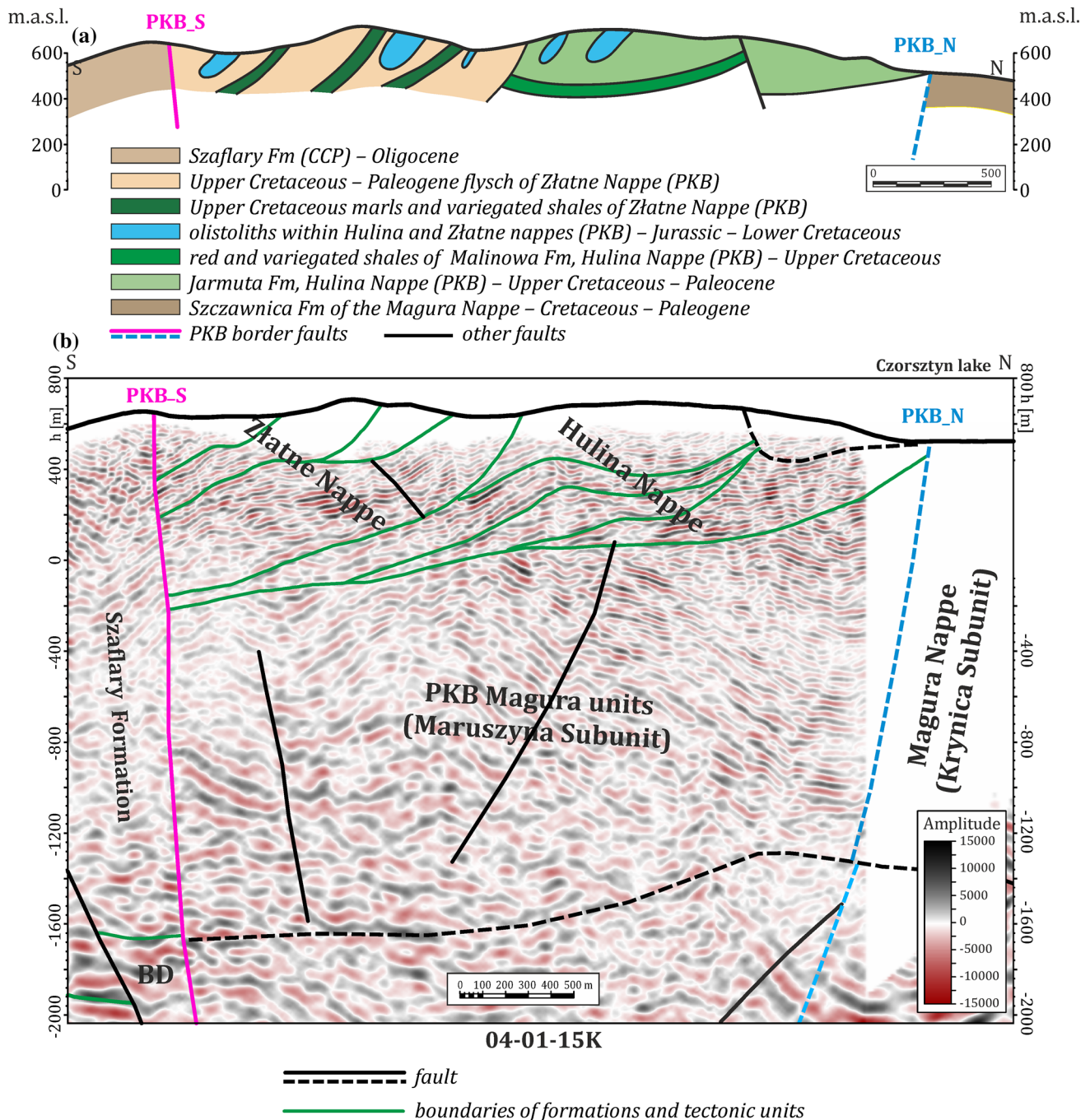
The Pieniny Klippen Belt is limited by two fault zones: the northern PKB\_N and the southern PKB\_S faults (Figs. 10, 11 and 13). These are sub-parallel in the map view (Fig. 18). PKB\_N dips steeply south, while PKB\_S dips steeply north. The two merge into a single vertical fault, which goes down all the way to the top of the descending European Plate. The PKB forms, in general, a strongly tectonized, subvertical structure that is about 3 km wide. It includes Jurassic, Cretaceous, Paleogene and Neogene sedimentary sequences. Several north-vergent thrust-sheets or nappes are visible in the analyzed profiles: 24-5-87 (Fig. 10), 03-01-15K (Figs. 11, 12), 04-01-15K (Figs. 13, 14) and 02-01-15K (Fig. 15). The chaotic structural arrangement within these thrust-sheets suggests the existence of olistoliths surrounded by flysch deposits (see Golonka et al. 2015, 2017) and red marls. The seismic data only allow distinguishing boundaries between structural units. Two larger units or nappes, containing several thrust-sheets each, were distinguished in the analyzed profiles: the northern Hulina Nappe and the southern Złatne Nappe (Golonka et al. 2018b). The northern Hulina Nappe contains up to seven thrust-sheets. These thrust-sheets were observed in the surface geology as repeated sequences of upper Cenomanian–Coniacian variegated shales of the Malinowa Formation and Maastrichtian–Paleocene sandstones of the Jarmuta Formation. The southern Złatne Nappe contains up to five thrust-sheets in the eastern part of the analyzed region. Four thrust-sheets were distinguished in the analyzed seismic profiles, and the fifth is visible at outcrop (Fig. 18). These thrust-sheets were recognized as repeated sequences of the Cretaceous (Sromowce Formation) and Paleocene–Oligocene flysch





◀ **Fig. 13** Seismic depth section line 04-01-15K (see Fig. 3 for its location east of line B–B' presented in Fig. 20). **a** raw data with selected reflections highlighted and with marked PKB border faults. **b** interpreted. *PKB\_N* north PKB border fault, *PKB\_S* south PKB border fault

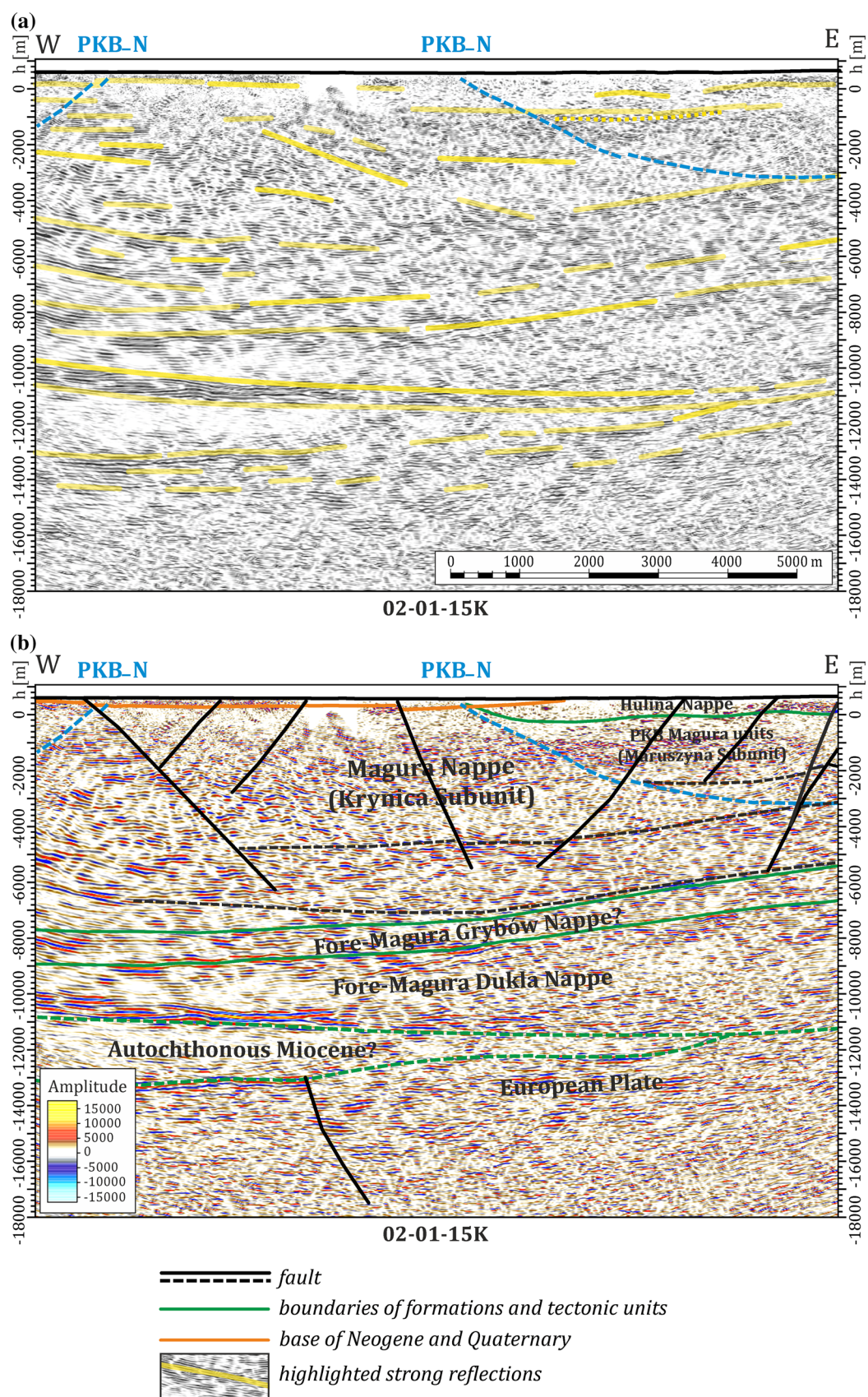
sequences, with thick-bedded coarse-grained sandstones and conglomerates. The Złatne Nappe is quite narrow in the western part of the analyzed region. These Hulina and Złatne nappes unconformably cover the lower unit. The reflection pattern within this unit resembles the pattern



**Fig. 14** Shallow parts of seismic depth section line 04-01-15K (see Fig. 3 for its location east of line B–B' presented in Fig. 20). **a** Simplified shallow geological cross-sections along seismic profile

04-01-15K (see Fig. 3 for its location east of line B–B' presented in Fig. 20). **b** Shallow part of the seismic profile 04-01-15K. *PKB\_N* north PKB border fault, *PKB\_S* south PKB border fault

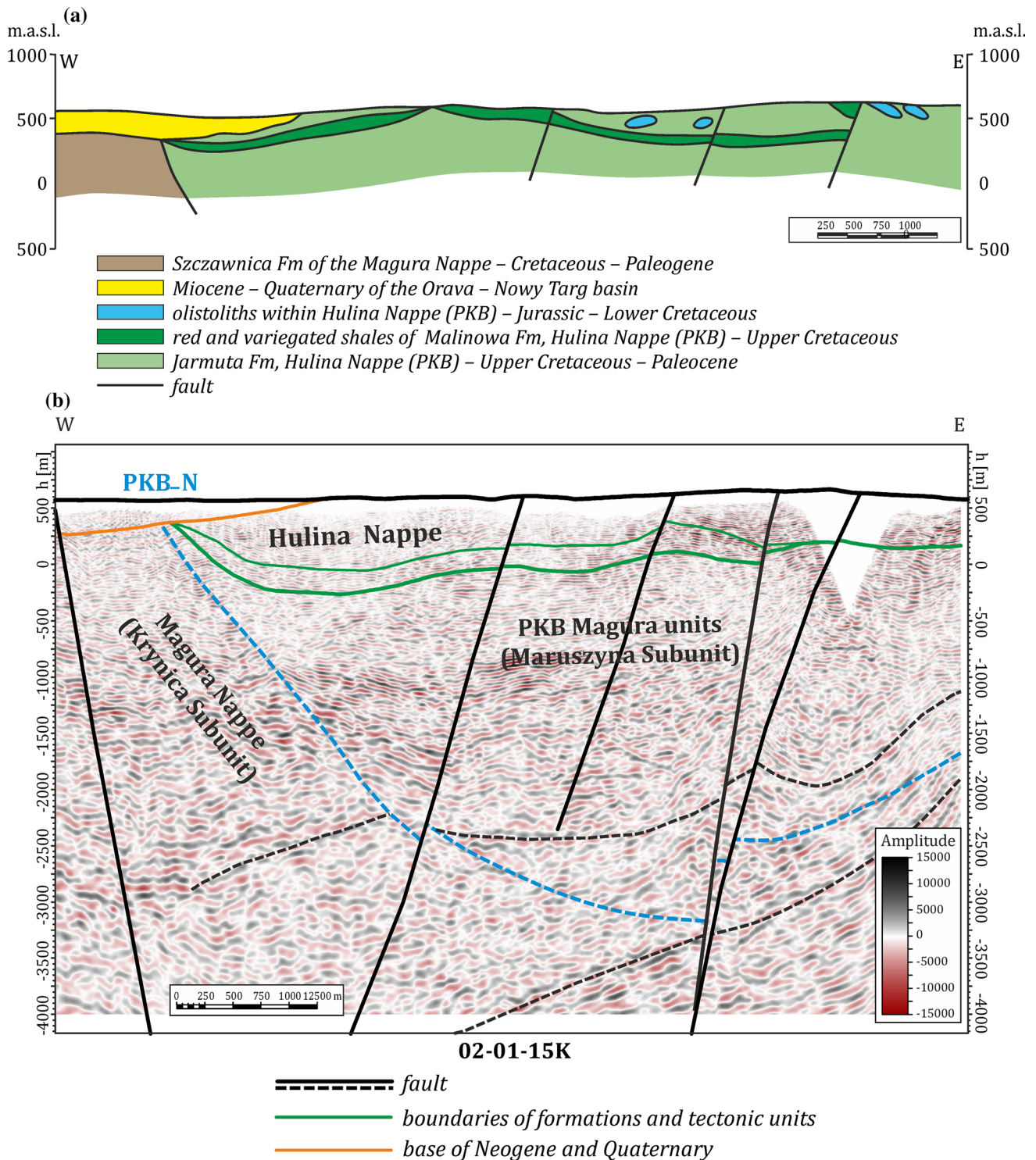






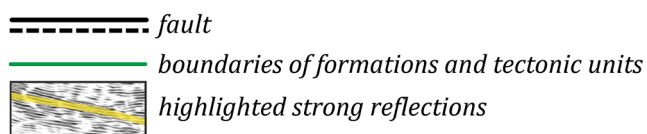
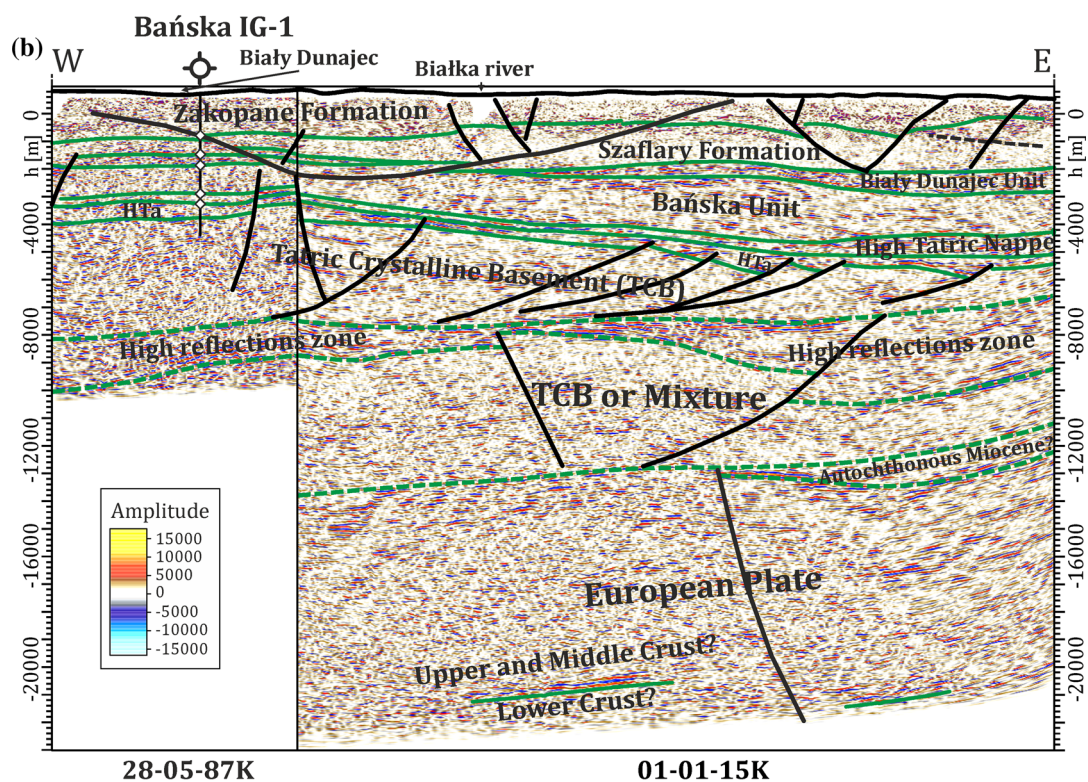
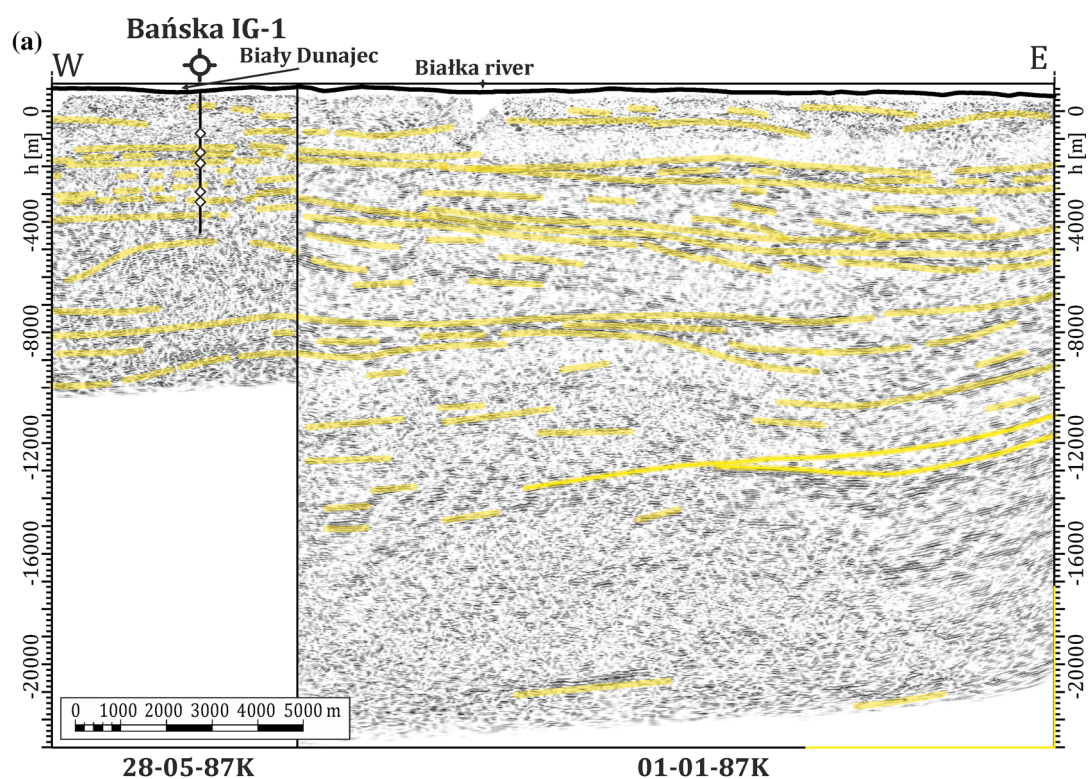
◀ **Fig. 15** Seismic depth section line 02-01-15K running E–W (see Fig. 3 for its location within the PKB). **a** Raw data with selected reflections highlighted and with marked PKB border faults. **b** Interpreted section. *PKB\_N* northern PKB border fault

within the Krynica Subunit of the Magura Nappe (Figs. 10, 11, 13, 15). We named it Maruszyna Unit. The Upper Cretaceous flysch rocks, belonging to the Maruszyna Unit were encountered in the Maruszyna IG-1 borehole below



**Fig. 16** Shallow parts of seismic section line 02-01-15K running E–W (see Fig. 3 for its location within the PKB). **a** Simplified geological cross-sections along seismic profile 02-01-15K. **b** Shallow part of the seismic profile 02-01-15K. *PKB\_N* northern PKB border fault



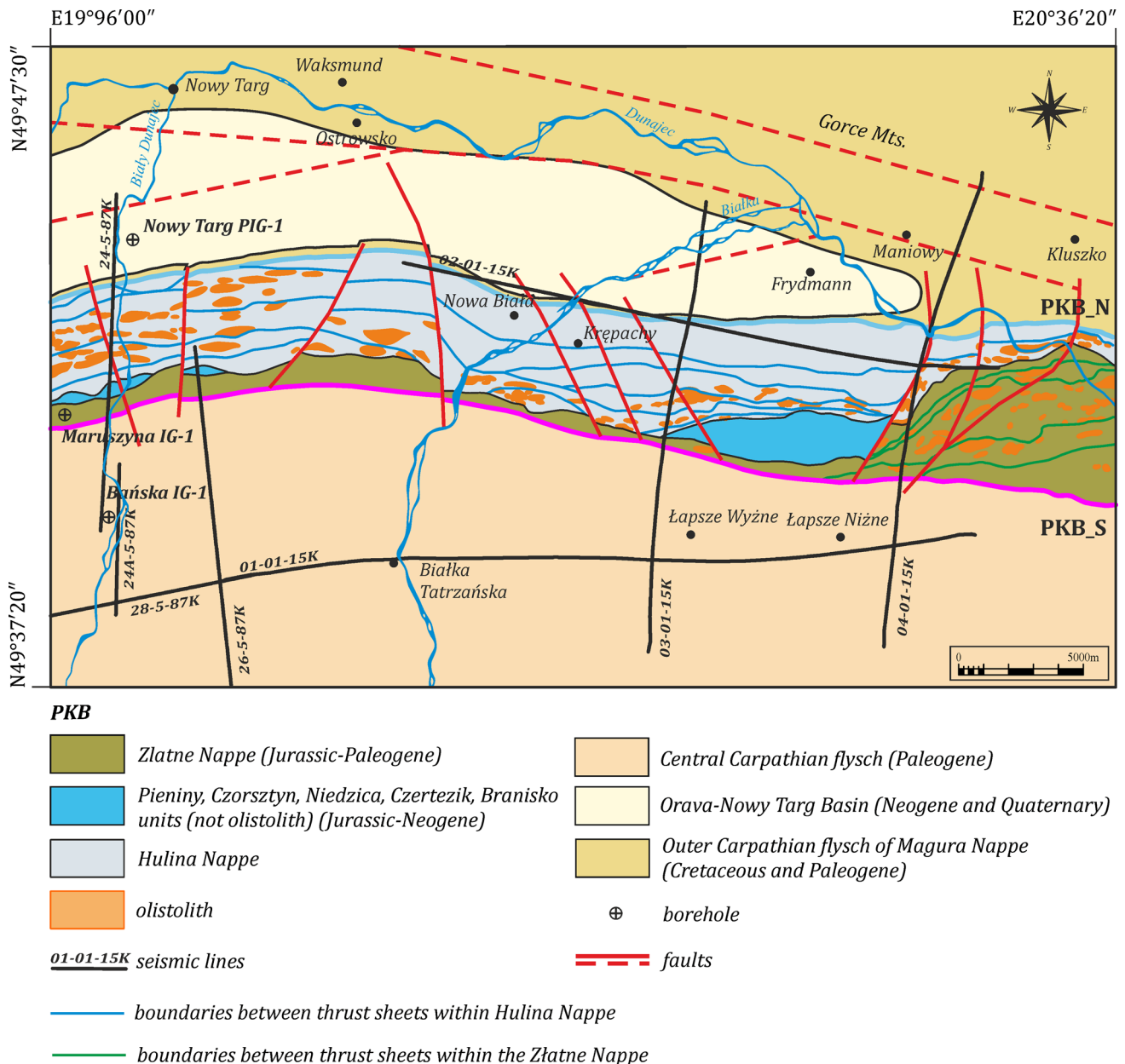




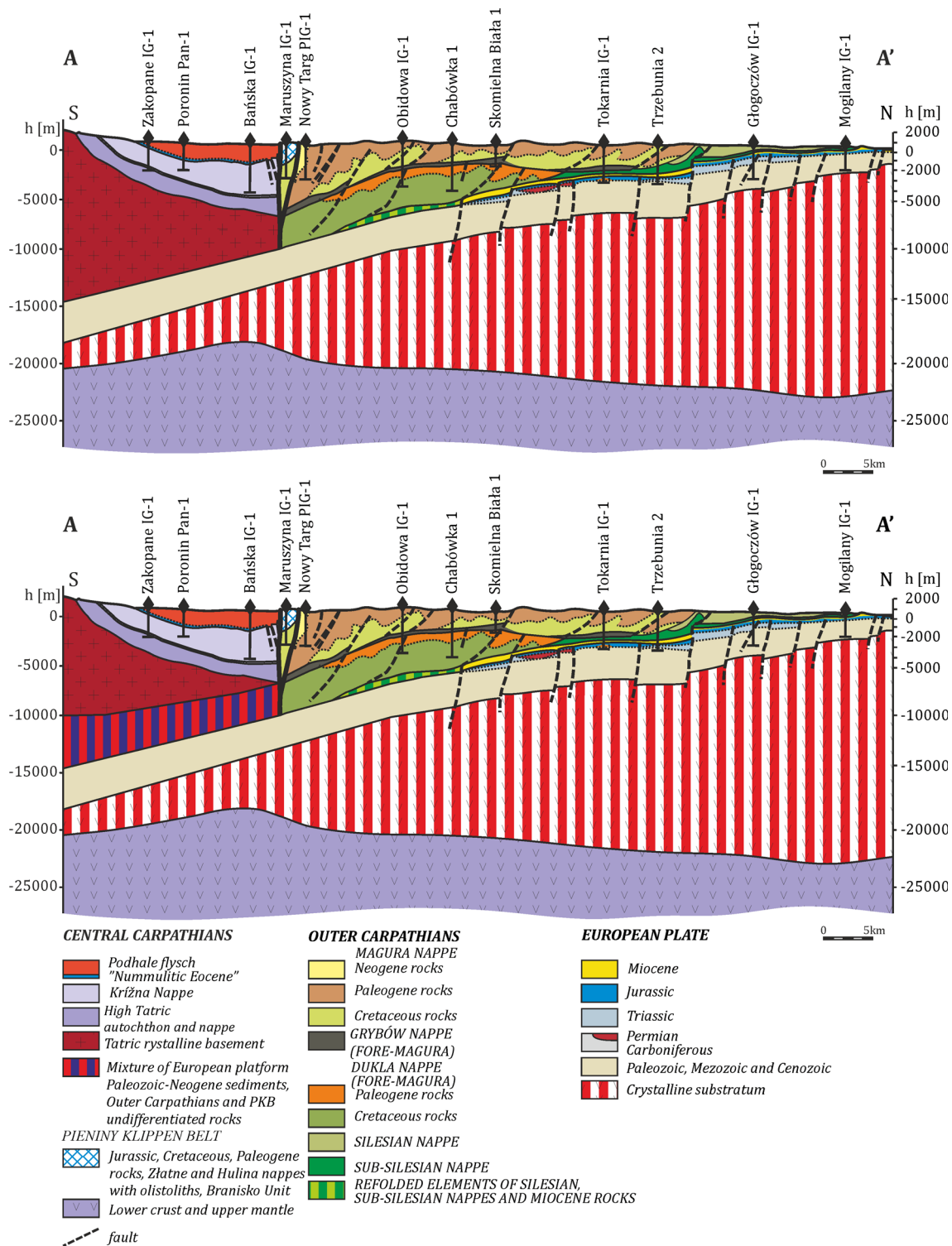
◀ **Fig. 17** Seismic depth section of composite lines 28-5-87K and 01-01-15K (see Fig. 3 for its location south of the PKB). **a** Raw data with selected reflections highlighted. **b** Interpreted section

the base of Hulina Nappe (Figs. 9, 10) (Golanka et al. 2018b). The lithology of these rocks is similar to the lithology of the Magura Flysch known from the outcrops. Similar rocks were also recognized in the borehole in Szczawnica (outside study area) below the Hulina Nappe (Birkenmajer et al. 1979).

The tectonic boundaries illustrating the structure north of the PKB (Outer Carpathians) were estimated based on the seismic sections 02-01-15K (Figs. 15, 16), 04-01-15K (Fig. 13), 03-01-15K (Fig. 11), 24-5-87K (Fig. 10) and on results of the Nowy Targ PIG-1 borehole (Paul and Poprawa 1992). Unconformable Quaternary and Neogene deposits are exposed in basins close to the northern boundary of the PKB. They were mapped, while gravity and electric surveys (Pomianowski 2003) were used to estimate their thickness, which does not exceed 100 m in the investigated area.



**Fig. 18** Map of the tectonic units of the Pieniny Klippen Belt and the Orava-Nowy Targ Basin in the investigated area (see Fig. 3 for location of investigated area)



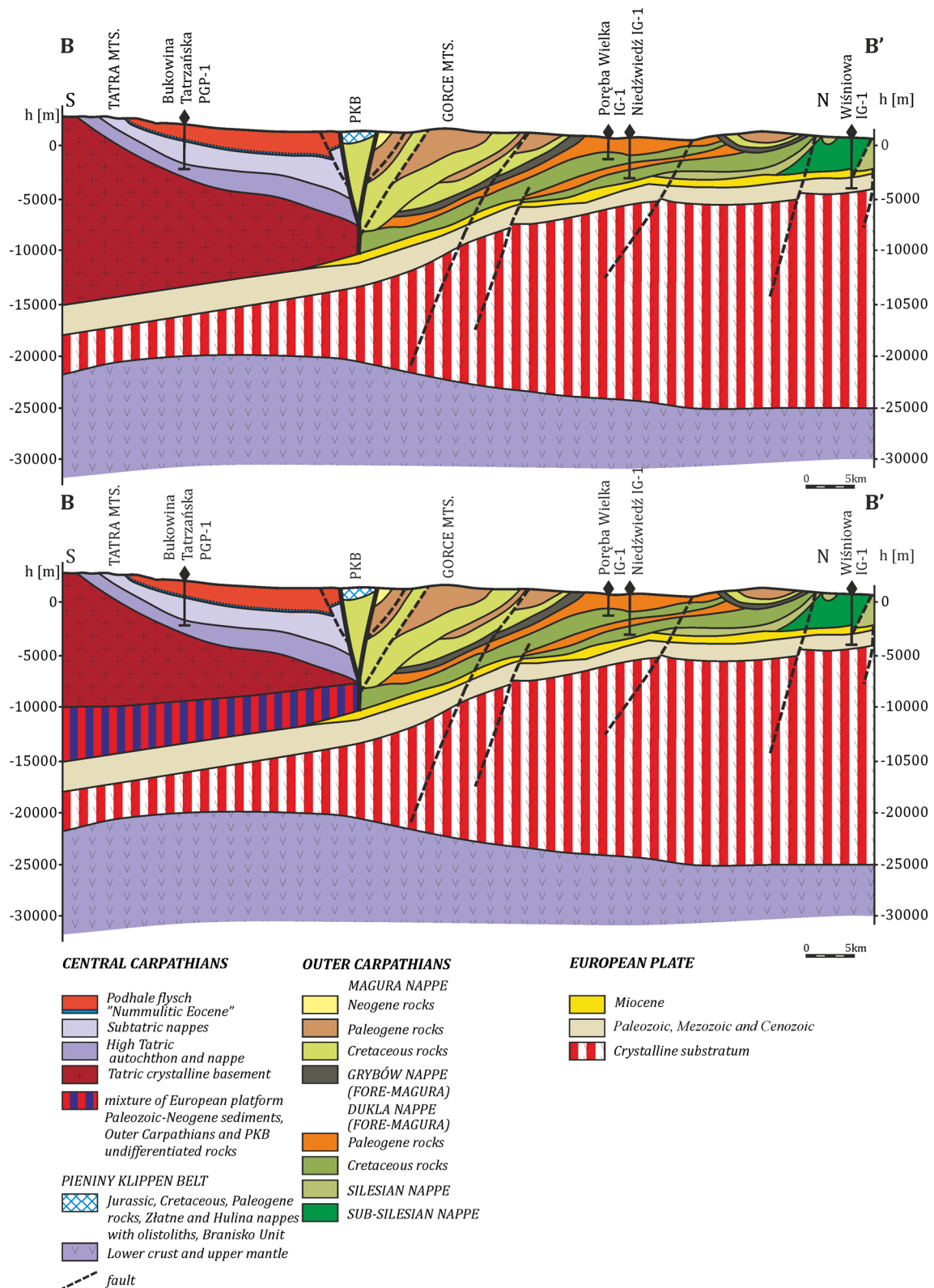
**Fig. 19** Cross-section A–A' through the Western Carpathians, between the Central Carpathian Tatra Mountains and the Carpathian Foredeep (Zakopane–Kraków line), based on Cieszkowski in Golonka et al. (2005), Chowaniec and Cieszkowski (2009), Golonka et al.

(2018b) including results of the interpretation of seismic profiles. Upper and lower version display alternative possible interpretations. For the location of the trace of the cross-section see Figs. 2 and 3

The allochthonous Outer Carpathians nappes are thrust over each other and onto the European Plate, which is dipping gently southwards. Several boreholes allow for

distinguishing a pile of nappes (thrust-sheets) verging northwards (Figs. 19, 20).





**Fig. 20** Cross-section B-B' through the Western Carpathians between the Central Carpathian Tatra Mountains and the Wiśniowa area (based on Burtan et al. 1974; Watycha 1975; Oszczypko 2004; Szczęch et al. 2016 and results of seismic profiles interpretation).

Upper and lower parts display alternative interpretations. Upper and lower version display alternative possible interpretations. For the location of the trace of the cross-section see Figs. 2 and 3

The Magura flysch complex belonging to the Krynica Subunit of the Magura Nappe reaches 4000–5000 m in thickness. It is cut by several faults striking W–E. These faults are well visible, especially in the area adjacent to the PKB. They do not reach the European basement, but probably cut the basal horizons of the Magura nappe. They are similar to the northern PKB\_N fault and could be part of the PKB flower structure. The Magura Nappe rocks in the vicinity of the PKB crop out in the eastern part of the investigated area. In the western part of this area, the Magura nappe is partially covered by the Neogene and Quaternary complex (Figs. 3, 12, 18). The Upper Cretaceous, Paleogene and Lower Miocene deposits (Ślaczka et al. 2006 and references therein; Cieszkowski 1992; Kaczmarek et al. 2016), dip southwards, detached from their substratum. A part of the Magura flysch deposits was incorporated into the PKB tectonic structure during the Miocene, and is separated from the Krynica Subunit by the PKB\_N fault. It is located now below Hulina and Złatne nappes and distinguished as the Maruszyna Subunit (Figs. 10, 11, 12, 13, 14, 15, 16).

The deposits visible in the seismic profiles tectonically beneath the Magura Nappe were identified as the Fore-Magura group of nappes, represented by the Grybów and Dukla nappes (Figs. 10, 11, 13, 15). This Fore-Magura group of nappes is exposed in the Mszana Dolna area (e.g. Mastella 1988), north of the Gorce Mts. and encountered in the Obidowa IG-1, Chabówka 1, and Niedźwiedź IG-1-boreholes (e.g. Mastella 1988; Sikora et al. 1980; Cieszkowski 1985, 2001; Oszczytko 2004; Golonka et al. 2005). We extrapolated these outcrop and borehole results into our investigated area. The lower part of the Outer Carpathian nappes gently dip southwards, parallel to the sedimentary cover of the European Plate (Figs. 11, 13, 15). The European Plate reaches the area south of the PKB flower structure (Figs. 19, 20).

A transitional zone is visible in the seismic profiles 01-01-15K, 03-01-15K and 04-01-15K (Figs. 11, 13, 17) below the Tatric Crystalline Basement (TCB), at a depth of 8–12 km. The upper part of this zone at a depth of 8–9 km (high reflection zone) has a continuous layered structure while the lower part is discontinuous, and the reflections are chaotic (depth of 9–12 km). This zone possibly represents a mixture, which can include autochthonous Paleozoic–Neogene rocks, as well as allochthonous Outer Carpathian and Pieniny Klippen Belt rocks. A group of the almost horizontal seismic horizons is observed below at depth interval 12–14 km and is interpreted as the sedimentary cover of the North European Plate. This sedimentary cover perhaps includes autochthonous Paleozoic, Mesozoic and Neogene rocks. The mostly non-reflective complex visible in profile 01-01-15K (Fig. 17) is characteristic for non-sedimentary rocks and represents the

crystalline rocks of the North European Plate. The reflectors visible in this profile at a depth below 20 km (Fig. 17) show a possible boundary between crustal elements within the European Plate. This boundary is related to the abrupt change in seismic velocity (Fig. 4). The nature of this boundary is uncertain. It is possibly related to the thrust between two crustal units.

## 5 Discussion

The studied profiles cover the depth interval of around 23 km. The reflections visible at a depth of 20 km in the Central Carpathian study area (Fig. 17) possibly show the boundary between different crustal elements within the European Plate. These elements were identified as Pieniny Lower Crust and Pieniny Upper and Middle Crust in deep seismic profiles CELEBRATION 2000 (CEL012, CEL04 and CEL01) in SE Poland in the PKB zone (Janik et al. 2009, 2011). Schmid et al. (2008, 2019) depicted a similar boundary at the same depth between Tatricum and an underlying unit they attribute to the Briançonnais. The lower boundary of thinned continental crust, a possible Moho, could also theoretically be considered as a candidate. We decided to follow the interpretation of Janik et al. (2009), showing that the depth of these reflections is far too shallow to represent the Moho of the European Plate. However, we did not apply names such as Pieniny Lower Crust and Pieniny Upper and Middle Crust, because this boundary is visible only in the E–W running seismic profile 01-01-15K (Fig. 17), located south of the PKB (Fig. 3). Similar reflectors to those visible in the Central Carpathians have not been recorded north of the PKB. Hence, the lower boundary of the thinned continental European crust is probably located below 23 km in the area of the profile of Fig. 17. The seismic profiles from refraction and the wide-angle reflection of the Celebration experiment show a similar boundary in the Western and Eastern Carpathians (Grad et al. 2006; Środa et al. 2006; Janik et al. 2009, 2011; Starostenko et al. 2013; Hrubcová and Środa 2015). Figure 4 displays a segment of the Celebration CEL01 deep seismic profile located close to our research area (Fig. 2). The abrupt change of seismic velocity, related to the boundary between crustal elements is visible at a depth of 22–25 km. The nature of this boundary is uncertain and, as mentioned earlier, might also possibly be related to a thrust between older, i.e. Cadomian (see Gawęda et al. 2019), and younger, i.e. Variscan crustal units. As seen in Fig. 4 the Moho of the European Plate beneath the Outer Carpathians north of the PKB rises southward towards the Pannonian Basin. This is perhaps due to the extension in the Pannonian basin and the southern Carpathians (Schmid et al. 2019). The mantle rising towards the Pannonian Basin is



manifested by high heat flow (Boldizsár 1967), as well as by Miocene and Quaternary volcanism in Slovakia and Hungary (Fig. 1) (Seghedi et al. 2004; Wilson and Downes 2006). The northern boundary of this volcanism is located within the PKB (Birkenmajer and Pécskay 1999; Golonka et al. 2005; Jurewicz and Nejbert 2005; Anczkiewicz and Anczkiewicz 2016; Jurewicz 2018).

The seismic profiles (Figs. 10, 11, 13, 17), together with borehole data, show that the CCP rocks cover the Tatric and Fatric units south of the PKB. These units include the Krížna and Choč nappes (Fatricum), the detached High Tatric sedimentary slices, the Paleozoic Tatric crystalline basement and its stratigraphically overlying High Tatric “autochthonous” sedimentary cover (e.g. Kotański 1959, 1973; Lefeld 1985, 1999; Wieczorek 2000; Golonka et al. 2005 and references therein). A zone of high reflectivity was distinguished within the Tatric basement (Figs. 11, 13, 17). Two alternative interpretations are possible. The first interpretation correlates the high reflectivity zone with a zone of ductile thrusting between the upper and lower structural units known from the Tatra Mts. (Burda and Gawęda 1997, 1999; Gawęda et al. 1998, 2001; Golonka et al. 2005). The second alternative interprets that the unit below the high reflectivity represents a mixture of Paleozoic to Neogene rocks, allochthonous Outer Carpathian units and Pieniny Klippen Belt rocks. The Tatric crystalline rocks thrust the sedimentary rocks of the European Plate (Figs. 11, 13, 17). The European Plate is suspected below these sedimentary rocks. These sedimentary rocks possibly represent a mixture of platform Paleozoic to Neogene sediments, as well as Outer Carpathian and PKB rocks (see e.g. Jurewicz 2005, 2018).

The present day structure of the PKB and the strong shortening of the former sedimentary basins evolved during a complex history of this domain. The older sediments were deposited in a several hundred kilometers wide paleogeographic realm of Alpine Tethys in Jurassic to Early Cretaceous times (Fig. 7) (see e.g. Schmid et al. 2008 and references therein). The younger sediments were accumulated in Late Cretaceous to Neogene times in a synorogenic setting during the closure of the Alpine Tethys. An accretionary prism formed in front of the moving plate (Golonka et al. 2006a). During the Late Cretaceous–Paleocene, the accretionary prism was overriding the Czorsztyn Ridge, causing partial destruction of this ridge. The ridge supplied huge amounts of coarse-clastic material, including olistoliths located within the flysch deposits of the Hulina Nappe (Golonka et al. 2015, 2017; Jurewicz 2018). This sediment accumulation led to further development of the accretionary prism and formation of flysch nappes. Imbricated thrusting led to the formation of a nappe stack consisting of the Złatne, Hulina, Magura and Outer Carpathian nappes. The Central

Carpathian Plate, including the Outer Carpathian flysch units, was subsequently thrust onto the European Plate. According to Plašienka (2018), complex translational and rotational movements of ALCAPA dominated the Miocene evolution of the Western Carpathians (see also Csontos and Vörös 2004; Márton et al. 1999, 2004, 2013). The strike-slip process along the boundary between the Central Carpathians and the European Plate led to the deformation of previously created nappes within the Pieniny Klippen Belt. The latter is preserved within a 3–5 km wide flower structure limited by fault zones that include faults that cut the Central Carpathian Paleogene rocks as well as the Krynica subunit of the Magura Nappe.

The fault marking the southern limit of the PKB is especially well visible in the seismic sections (Figs. 10, 11, 12, 13, 14, 15, 16). This PKB flower structure developed in Neogene times. It displays mixed transpressional and transtensional features. Similar phenomena were observed in the eastern part of the PKB in Slovakia, where, according to Hruščeký et al. (2006), the boundary zone was reactivated several times in Paleogene to Neogene times as transpressional and/or transtensional (see also Ratschbacher et al. 1993; Nemčok and Nemčok 1994). According to Marko (2003) and Marko et al. (2017), a WSW–ENE oriented dextral strike-slip fault zone exists within the PKB in Poland and the adjacent part of western Slovakia, however the sinistral strike slip at the northern ALCAPA boundary is dominant (Birkenmajer 1960; Sperner et al. 2002; Schmid et al. 2008; Ustaszewski et al. 2008; Mastella et al. 2012). Castelluccio et al. (2015, 2016) argued that Neogene vertical movements, uplift and related faulting also played an important role during the formation of PKB structure.

At least some of the transverse faults, as well as faults perpendicular to the strike of the PKB were still active during the Quaternary time (Zuchiewicz et al. 2002). Białoń et al. (2015) studied the earthquakes likely to be triggered by the filling of the Czorsztyn artificial lake located in the northeastern part of the study area (Fig. 4). The earthquake occurrences signify the presence of remnant tectonic loading. The earthquakes exhibit strike-slip mechanisms with nodal planes oriented NS and EW, which could be linked to the mentioned transpression. The recent uplift rates in the area are up to + 0.5 mm per year (Vanko 1988; Vass 1998) while the horizontal movement attain up to 5 mm per year (Łój et al. 2007).

Transtension prevailed during the formation of the Neogene Orava–Nowy Targ Basin, which postdates the Serravallian formation of the Outer Carpathian fold-and-thrust belt. According to Ludwiniak et al. (2019), this basin developed under the influence of transtension between two large NE–SW-directed sinistral fault zones.

The Złatne Nappe, the southernmost thrust-sheet within the PKB (Golonka et al. 2018b), contains mainly Upper Cretaceous to Paleogene flysch. It is visible in the studied profiles as a narrow sliver in the western part of the study area (Figs. 3, 10, 11, 12, 13, 14). It is wider in the eastern part, where the type locality of the Złatne Succession was defined by Sikora (1971, 1974; see also Golonka and Sikora 1981 and references therein). The Złatne Nappe is thrust over the Hulina Nappe. Both units are thrust over lower units, distinguished as the Maruszyna Subunit, which possibly belongs to the Magura Nappe. A similar thrust of the Hulina Nappe over the Magura Nappe was also recognized in the borehole in Szczawnica (Birkenmajer et al. 1979). The Magura Nappe also emerges as tectonic windows from the olistostrome type *mélange* of the Hulina Nappe in the Małe Pieniny Mountains (Golonka and Rączkowski 1984a, b; Jurewicz 1994, 1997; Oszczytko and Oszczytko-Clowes 2014). These observations support our interpretation that the Hulina Nappe was thrust over rocks that possibly belong to the Magura Nappe (Krynica Subunit).

The Krynica Subunit crops out along the PKB\_N fault. This unit was also encountered in the deep drillings in Nowy Targ PIG-1 and Obidowa IG-1. The youngest, Miocene marine rocks belonging to the Waksmund, Stare Bystre, Kopaczyska and Pasięka formations are exposed between Stare Bystre and Waksmund (Cieszkowski and Olszewska 1986; Cieszkowski 1992). The Upper Cretaceous to Paleocene rocks of the Szczawnica Formation form the southern marginal part of the Krynica Unit in the slopes of the Pieniny Mountains and in the Krościenko-Szczawnica area (Kulka et al. 1985; Chrustek et al. 2004; Golonka and Waśkowska 2014). We extrapolated the Upper Cretaceous to Paleogene and Lower Miocene rocks under the Złatne-Hulina thrust.

The Fore-Magura group of nappes was encountered in the Obidowa IG-1 and Chabówka 1 wells. The Grybów and Dukla nappes were distinguished in these wells (Ślęczka et al. 2006). The strata of these units gently dip towards the south, usually without any intense tectonic deformations, except in the higher part. The position of the lower unit within the Outer Carpathian structure is a matter of controversy (Sikora et al. 1980; Cieszkowski et al. 1981a, b; Cieszkowski 1985, 2001; Żytko and Malata 2001; Żytko 2001). It is meant to belong either to the Dukla (our preference) or to the Skole nappes. The Dukla Nappe forms the lowermost Outer Carpathian Nappe or is underlain by the Silesian Nappe (Figs. 19, 20). The deep seismic reflection profile 2T, which is located in Slovakia south-west of the research area, demonstrates two groups of south-dipping reflections located north of the Pieniny Klippen Belt (Tomek 1993; Bielik et al. 2004). The upper

one belongs to the boundary between the Magura Nappe and the lower to the accretionary wedge complex (Dukla-Silesian-Subsilesian group of units).

## 6 Conclusions

The 40 km long Polish part of the Pieniny Klippen Belt (PKB) belongs to a complex geological structure that is some 600 km long, 1–20 km wide and stretching from Vienna in Austria to northern Romania. The PKB marks the boundary between the Central Carpathian Plate and the European Plate.

Seismic lines show the CCP rocks covering the Paleozoic Tatric Basement, stratigraphically overlain by its sedimentary cover, which is in turn overlain by detached High Tatric sedimentary successions and finally still higher slices of the Krížna and Choč nappes, all located south of the PKB. The crystalline Central Carpathian rocks are thrust over sedimentary rocks possibly belonging to the European Plate cover and representing a mixture of Paleozoic to Neogene platform sediments, as well as rocks from the Outer Carpathian units and PKB rocks. The basement of the European Plate is visible below these sedimentary rocks. The reflections at a depth below 20 km show a hypothetical boundary between crustal elements within this plate.

The PKB forming the main part of the 3–5 km wide flower structure is limited by fault zones, including faults cutting across the Central Carpathian Paleogene rocks and the Magura Nappe. Especially the fault marking the southern limit of the PKB is well visible in the seismic sections. The Albion to Lower Miocene flysch sequences, constituting much of the volume of the PKB, form north-vergent thrust-sheets. The PKB originated during the development of the accretionary prism in front of the moving Central Carpathian Plate during the Albion to Early Neogene. This was followed by vertical axis rotations and strike-slip processes, taking place along the interface between the Central Carpathians and the European plate.

The Central Carpathian units as derivatives of the Adriatic plate are thrust over the European Plate. The Outer Carpathians represent an allochthonous thrust complex above the European Plate. They form several north-verging imbricated nappes (thrust-sheets) thrust onto the North European Plate. This European plate gently dips southwards below the suture zone between the Central Carpathians and the Europe-derived allochthons located along the PKB. The latter is cut by several deep-reaching faults.

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