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Genesis of the Pieniny Klippen Belt in the Carpathians: Possible effects of a major paleotransform fault in the Neo-Tethyan domain

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ABSTRACT

The Pieniny Klippen Belt (PKB) is a narrow, discontinuous zone rich in olistostromes and olistoliths (Klippen) in the western Carpathians. This paper, based on prior works including tectonic and stratigraphic evidences, suggests that the PKB rocks were deposited from the Triassic to the Early Paleogene along the eastern footwall of a major Split–Karlovac-Initial PKB-Crustal-Zone (SKICZ) paleotransform fault zone. This transform fault was then separating the continental crust of the Austro-Alpine zone in the west and a Carpathian Embayment Ocean in the east. It was only during the Late Paleogene–Early Miocene that the PKB rocks were integrated into the accretionary prism that formed at the front of the eastward-extruded ALCAPA units. This interpretation therefore supports the existence of a major paleotransform fault zone in the Neo-Tethys during the Triassic–Early Paleogene. This paleotransform had been previously suggested to explain the observed reversal in obduction and subduction at the junction between the eastern–southern Alps and the Carpathians–Dinarides.

1. Introduction

The Pieniny Klippen Belt (PKB) in the western Carpathians (Fig. 1) is a particular, narrow, segmented isopic zone, rich in Mesozoic to Cenozoic olistostromes and olistoliths (Klippen). It has been the focus of recent studies but its paleogeographic origin is still unclear (Golonka et al., 2015; Jankowski et al., 2012; Plašienka, 2012; Ślączka et al., 2012). This contributes to make difficult the paleogeographic reconstruction of the whole Alpine Neo-Tethyan domain (Aubouin et al., 1970; Dercourt et al., 2000; Golonka, 2004; Săndulescu, 1988; Schmid et al., 2008; Stampfli and Hochard, 2009).

On the one hand, Chorowicz (1977) has suggested that a Split–Karlovac–Vienna paleotransform fault zone might have existed in the Neo-Tethys between Split and Vienna (Wien) and was forming the western end of the Carpathians (Fig. 1). On the other hand, Ratschbacher et al. (1991a, b) and Wölfler et al. (2011) have studied the Oligocene-Miocene lateral extrusion of the eastern Alps inner zones (Austro-Alpine) towards the western Carpathians. They suggested that the Austro-Alpine units prior to their extrusion were forming a compressed wedge whose eastern boundary was unconstrained.

The present paper explores the relations between the paleotransform fault zone and the genesis and paleogeographic location of the Pieniny Klippen Belt. The first section briefly reports the particularities of the Pieniny Klippen Belt. The second section discusses the process of lateral extrusion of the inner eastern Alps (Austro-Alpine) and discriminates the SK and CZ segments of the paleotransform fault zone (Fig. 1). A discussion section then examines the links between the PKB facies and the

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Fig. 1. (Color online). Geostructural frame of the Alpine belts in the Central Europe–Mediterranean region, showing the present-day location of the Split–Karlovac-Initial PKB-Crustal-Zone (SKICZ) segments of the paleotransform, drawn in blue color: SK, Split–Karlovac; PKB: Pieniny Klippen Belt; CZ: Crustal Zone. Bn: Bosnian zone; Dlm: Dalmatian zone; Hk: High Karst zone; Sr: Serbian zone. 1: front of the Alpine belts; 2: Pieniny Klippen Belt (PKB); 3: SK and CZ end segments of the SKICZ paleotransform zone (dashed line in depth, full line Krakow–Sandomierz fault at surface); 4: vergence of obducted ophiolites; 5: the Split–Karlovac–Vienna (SKW) line suggested in 1977 by Chorowicz. Fig. 2: frame of Fig. 2.

paleogeographic setting of the paleotransform fault. It is proposed that the PBK is a former central segment of the paleotransform fault.

2. Pieniny Klippen Belt

The peri-Eurasia Alpine branch in Central Europe comprises the arched western and the eastern Alps that are in line with the Carpathians and the Balkans (Fig. 1). Further south, the peri-Adria branch comprises the Apennines, the Southern Alps and the Dinarides–Hellenides. The Carpathians form around the Pannonian basin an arch that is interpreted to result from postorogenic extension in the back-arc regions of southward subduction zones (Jolivet et al., 2008). The subduction would have been that of a 'Carpathian Embayment Ocean'.

The Pieniny Klippen Belt (PKB, Fig. 1) in the northwestern Carpathians is presently a subvertical, narrow–up to 20 km-wide–600 km-long strike-slip fault zone that separates the inner and the outer nappes (Golonka et al., 2015). The PKB emerges in the west from beneath the Neogene sediments of the Vienna basin and ends to the east against the eastern along-strike continuation of the Balaton line. The 'black flysch', which crops out along the eastern continuation of the Balaton line, may belong to the PKB (Schmid et al., 2008). The Inner Northwest Carpathians, in between the Balaton line and the PKB, were compressed during the Late Paleogene–Neogene together with the inner Southeast Carpathians composed of the Tisza and Dacia units (Fig. 1). This compression pushed the outer Carpathian flysch nappes onto the Miocene deposits of the Carpathian foredeep that covers the Eurasia platform (Csontos and Vörös, 2004; Săndulescu, 1975).

The lithostratigraphic units of the PKB have been divided into several successions (Golonka and Krobicki, 2004). The matrix is shale, marls and flysch, spanning from the Triassic to the Neogene. The most typical feature of the PKB units is that they include olistostromes and olistoliths (Klippen), some of kilometer size. Deformation began during the Late Cretaceous (Nemčok and Nemčok, 1994), but mainly occurred from Eocene to Neogene times (Ratschbacher et al., 1993).

3. Lateral extrusion of Austro-Alpine units

The nappes of the inner Northwest Carpathians are similar to those of the eastern Alps inner (Austro-Alpine) zones (Săndulescu, 1988) and they together presently form the **Al**ps-**Ca**rpathians-**Pa**nnonia–or 'ALCAPA'–system (Csontos and Vörös, 2004; Fig. 1). The ALCAPA system is interpreted to result from the Oligocene to Middle Miocene lateral extrusion of fragments of Austro-Alpine units away from the zone of convergence between the Adria and Eurasia continents. This event is generally considered to be a compressional eastward tectonic escape (Wölfler et al., 2011), but it might have combined extensional collapse driven by gravity (Ratschbacher et al., 1991b). The latter authors have illustrated in map view the pre-extrusion situation during the Early Paleogene time and suggested that the Austro-Alpine continental block was separated from both the Eurasia and the Adria continents by EW-striking major contacts, whereas their eastern boundary was an unconstrained margin. The 'pre-Gosau' compression phase in the Albian to Late Cretaceous (Schuller, 2004) thickened the Austro-Alpine crust that became rheologically weak 30–50 Ma later (Oligocene). The weakened unconstrained margin subsequently collapsed toward the low domain in the east (Ratschbacher et al., 1991b).

The present Carpathian foreland was originally a passive margin bordering an oceanic lithosphere that formed the 'Carpathian Embayment–or Magura–Ocean', belonging to the Eurasian plate (Csontos and Vörös, 2004; Royden et al., 1982; Wölfler et al., 2011). Southwestward slab subduction rollback of the Carpathian Embayment oceanic lithosphere would be responsible for the current arched shape of the Carpathians (Nemčok, 1993). Subduction was active at least during the Middle Miocene, as evidenced by back-arc volcanism (Szabó et al., 1992). However, Schmid et al. (2008) compiled evidences for the Carpathian Embayment Ocean to have existed since at least the Jurassic.

Cretaceous collisions occurred on either side of the Carpathian Ocean Embayment. In the east, the Dacia and Tisza blocks were both pushed into the Carpathian Embayment during the Cenozoic (Fig. 1; Csontos and Vörös, 2004). AlCAPA is presently separated from Tisza-Dacia by the Balaton line and its mid-Hungarian eastern continuation; both are reported to have accommodated differential horizontal movements (Márton et al., 2007). During the Middle Oligocene–Neogene time, the ALCAPA and Dacia–Tisza units were docked against the Eurasia continent foreland and this induced progressive folding and thrusting of the Outer Carpathians flysch units.

4. Split–Karlovac and Vienna segments

The Split–Karlovac zone in the Dinarides (SK, Fig. 1) is a narrow NNW-trending faulted area, that modifies the otherwise regular Dinaric arrangement of the NW-trending folds and thrusts (Chorowicz, 1975). The SK faulted region comprises isopic zones that are shown in Fig. 2 and characterized in Table 1. Some units are offset and/or differ

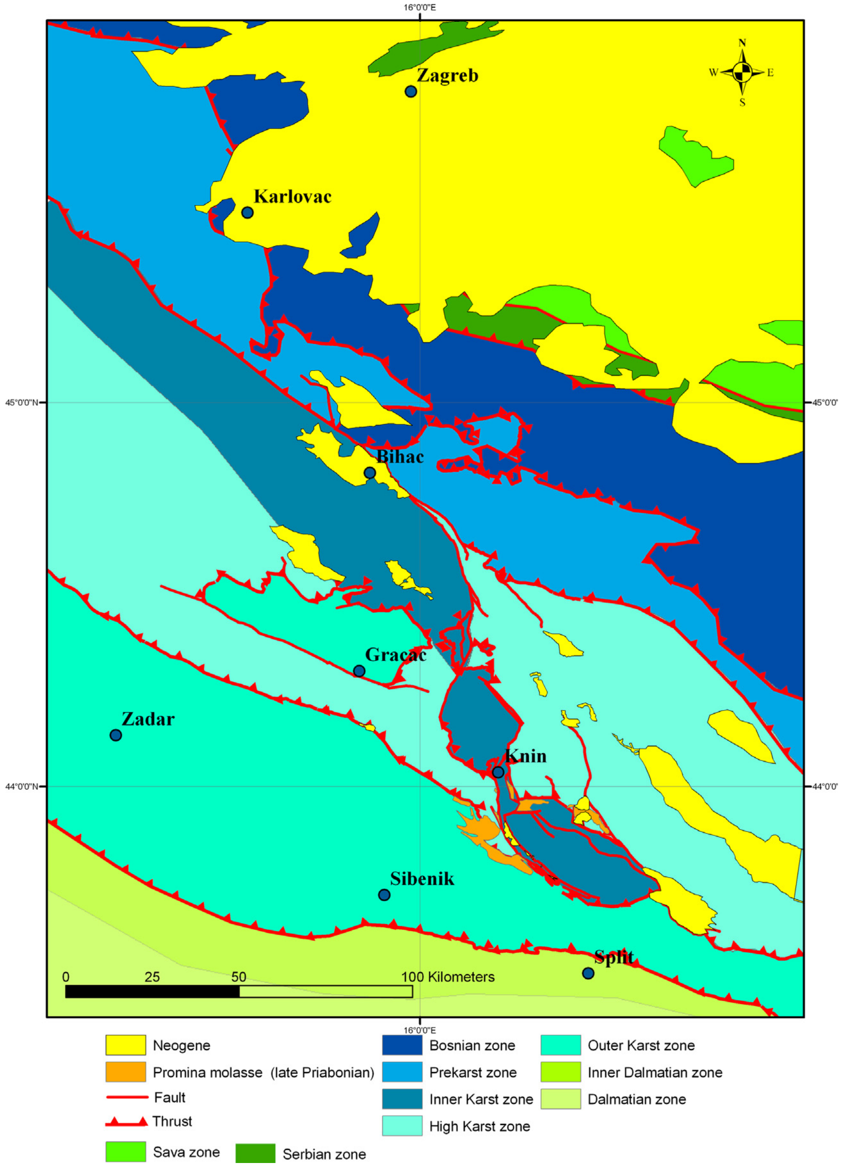

Fig. 2. (Color online). Structural map of the Dinarides between Split and Karlovac according to Chorowicz (1977), completed from Schmid et al. (2008) and Lužar-Oberiter et al. (2012). Location in Fig. 1. The isopic zones are shortly characterized in Table 1.

Table 1
Main characteristics of the isopic zones in the Split–Karlovac (SK) fault zone in the Croatia–Bosna border region of Fig. 2.

	Zones	Facies	Initiation of Flysch	Paleogeography
Inner zones	*Sava*	Continental crust + Late Cretaceous ophiolites and back-arc ocean	Late Cretaceous-Paleogene	Suture fragments of the Adria distal margin
	Serbian (Western Vardar)	Ophiolites, mélanges	Senonian	Obducted Jurassic back-arc marginal basin
	Bosnian	Dolomitic Mesozoic	1- Late Jurassic; 2- Late Cretaceous	Basin of the distal margin of Adria
	Prekarst	Slope and deep-marine Mesozoic carbonates, stratigraphic gaps	Late Cretaceous-Paleogene	Mesozoic transitional platform-slope
Outer zones	*Inner Karst*	Similar to the High Karst but pelagic Late Jurassic *Lemeš* levels		High Karst areas affected by SK paleoactivity
	High Karst	Marine Late Palaeozoic, marine Mesozoic platform carbonates	Early Eocene	Carbonate platform
	Outer Karst	Volcano-sedimentary Ladinian; marine Mesozoic platform and slope carbonates	Late Lutetian–Early Priabonian	Transitional platform slope
	Budva	Hidden by High Karst nappes but revealed by tectonic ‘slice’ of pelagic Paleocene limestone		Deep-water basin
	Inner Dalmatian	Marine carbonate rich in pelagic facies and turbidites	Early Priabonian	Transitional platform slope
	Dalmatien	Marine Mesozoic platform carbonate, bauxite, Lutetian transgression	Late Priabonian	Carbonate platform

in their lithostratigraphic successions and styles across the SK fault zone. While the outermost Dalmatian, inner Dalmatian and outer Karst zones are unmodified across the SK fault zone, except for a sigmoid change in their strike, the High Karst carbonate platform is intersected by the fault zone (Figs. 1 and 2), with an offset dating back to the Permian (Chorowicz, 1977). The High Karst zone forms a nappe sheet that rests on the outer Karst of the Gračac window. The inner Karst zone extends across the High Karst and includes Late Jurassic pelagic deposits (*Lemeš* levels). The Prekarst zone is transitional toward the northeast with the pelagic inner Bosnian zone (Blanchet et al., 1969), which is dextrally offset by about 100 km across the SK fault zone. The outer and Bosnian units of the Dinarides extend northwestward up to similar zones in the southern Alps (Cousin, 1981). Overall, the lateral offsets across the SK fault zone increase toward the inner zones whereas they die out southward in the Adria microcontinent.

The NW-striking ophiolitic nappes that extend along the Dinarides and the Hellenides form two parallel groups related to the Vardar and the Pindos domains (Smith and Spray, 1984). They both verge to the southwest (Fig. 1). The vergence is conversely to the north for the ophiolitic Penninic nappes that crop out in major windows in the eastern Alps of Austria, thus opposite to that of the Dinarides–Hellenides. This reversal in thrust vergence (Laubscher, 1971) is related to opposing subduction polarities as shown in tomographic images (Lippitsch et al., 2003). These observations suggest that a transform fault zone might have linked the eastern Alps and the Dinarides. The location of the inferred transform fault roughly coincides with that of the northward continuation of the Split–Karlovac line. The SK line has been accommodating vertical motion since at least the Permian, then was compressed in the Late Eocene, during the Alpine shortening phases (Chorowicz, 1977). Therefore, we suggest that the SK fault zone was originally forming the southern tip segment of the paleotransform fault, as such accommodating vertical motions.

Further north, the virgation of the Alpine–Carpathian front near Vienna seems to be guided by a NE-striking fault zone (Beranek and Dudek, 1972) that forms the hidden eastern boundary of the Bohemian massif. This fault zone seems to have initiated in the Permian (Suk, 1984). Zatopek (1979) and Malkovsky (1987) have evidenced a vertical step in the Moho discontinuity across the NE fault zone, which they call ‘crustal zone’ (CZ, Fig. 1). Their map of the Moho and tomographic images at 50 km depth (Ustaszewski et al., 2008; images obtained by the method of Bijwaard and Spakman, 2000) suggest that the CZ fault zone extends at depth under the Carpathian nappes, then crops out further northeast in the Carpathian foreland, where it forms the so-called Krakow–Sandomierz fault (Fig. 1; Chorowicz et al., 1999; Púchy and Varga, 1973). The overall CZ fault zone dies out further north. As the CZ fault zone locates in the prolongation of the inferred paleotransform fault, we suggest that it represents the continuation of that transform fault within the Eurasia continent. Similar to the SK segment further south in the Adria continent, the CZ fault zone would have been the northern tip segment of the paleotransform, and as such would have originally accommodated mainly vertical motions.

5. Discussion

5.1. Time and space distribution of PKB facies

The PKB olistostrome and olistolith deposits were formed either because an orogenic front was advancing towards the foreland (Golonka et al., 2015) or because an accretionary prism was forming above a subduction (Birkenmajer, 1986). They might also have formed during rifting and be subsequently integrated into a subduction-related accretionary prism (Cieszkowski et al., 2009).

The analysis of the distribution of the PKB facies through time and space allows distinguishing: a) clast samples, representative of the history of the uplifted areas; b) matrix and flysch deposits, characterizing lower sedimentary basins. To examine whether the PKB facies are related to the time evolution of the transform fault zone, they must be analyzed over different time periods, mainly the Triassic–Jurassic–Early Cretaceous, then the Late Cretaceous–Early Paleogene, and finally the Late Paleogene–Early Neogene. In doing so, the PKB deposits should be moved back to their original inferred position along a ~NS-trending transform fault.

1. From the Triassic to the Early Cretaceous times, the diversified olistostromes and olistoliths are consistent with the PKB being at the eastern foot of pronounced fault escarpments. Clasts are found for instance in the 'black flysch' of Early Jurassic age (Birkenmajer et al., 2008). Conglomerate yields small clasts of metamorphic, magmatic and sedimentary rocks from the Eurasian continent, whose basement was affected by the Variscan orogeny and was partly covered by a Mesozoic carbonate platform. By contrast, west of the suggested transform fault, stratigraphy indicates that a shallow marine pelagic environment first developed during the Middle Triassic to Early Dogger (Mišík, 1993); then a deeper basin developed during the Middle to Late Jurassic–Early Cretaceous. During the Late Jurassic-Early Cretaceous, Penninic obductions and the 'pre-Gosau' compression in the Austro-Alpine domain altogether created new reliefs west of the transform fault. In contrast, east of the transform fault, the Carpathian Embayment Ocean remained a deep basin.
2. During the Late Cretaceous–Early Paleogene, the eastern boundary of the newly formed Austro-Alpine and West-Carpathian belt remained an unconstrained margin (Ratschbacher et al., 1991b). Clasts in the PKB reveal that Austro-Alpine facies were uplifted west of the transform fault; and that finally a carbonate platform was created during the Maastrichtian–Paleocene. In Poland and Slovakia, the facies of the Late Cretaceous–Early Paleogene flysch of the PKB and the Magura nappe (Cieszkowski et al., 2009) show that the PKB was lying along the deep Carpathian Embayment (Golonka and Krobicki, 2004). In western Ukraine (Ślączka et al., 2006), the Late Cretaceous–Early Paleogene matrix shows facies attesting to a deep-marine origin east of the transform, whereas clasts reveal:
   - Lower Jurassic (Hettangian?) clastics;
   - Middle Jurassic crinoidal limestone;
   - Bajocian to Tithonian red nodular limestones of Ammonitico Rosso-type with thin radiolarite intercalations;
   - Berriasian Calpionella-bearing limestones;
   - Berriasian basaltic pillow lavas.

   The latter magmatism is of midocean-ridge basalt (MORB) type, which suggests the existence of an oceanic crust (Golonka and Bocharova, 2000). There are also evidences of subduction-related calc-alkaline volcanics in the area during the Berriasian (Krobicki et al., 2003). Occurrence of Jurassic ophiolites west of the transform was also suggested from heavy mineral analyses (Aubrecht et al., 2009).
3. During the Late Paleogene–Early Neogene time, olistostromes are more likely due to brittle faulting on faults that destructed the pre-existing fold-and-thrust structures (Ratschbacher et al., 1993). The PKB was integrated into an accretionary prism at the front of the eastward-extruded Austro-Alpine and West-Carpathian units that now form the ALCAPA.

5.2. Paleogeographic location of the paleotransform zone segments

The paleogeography of the transform zone can be best understood at the Oxfordian (155 Ma) because that period predated the first Late Jurassic–Early Cretaceous obductions in the concerned area (Fig. 3). A paleogeographic reconstruction must however be regarded as purely speculative (Schmid et al., 2008). The proposal here is that the SK segment in Adria and the CZ segment in Eurasia were both trending ~NNE–SSW relative to Eurasia during the Oxfordian (Fig. 3). The two segments were almost aligned. Moving the PKB back to its original position 'I' ('**I**' for **I**nitial position, in dotted blue in Fig. 3) between the SK and the CZ segments makes the 'I' segment becoming almost north–south. The SK, 'I' and CZ segments were thus altogether forming a single north–south fault zone, dubbed here the SKICZ transform fault zone. At the Oxfordian time, the original PKB ('I') central segment of the transform fault was possibly linking several oceans (to the west, the Penninic Ocean and the inferred Insubric Ocean; to the east, the Carpathian Embayment and the Vardar oceans) and was likely accommodating a transcurrent motion between accretion or/and subduction zones. This central 'I' transcurrent segment possibly also included during the Oxfordian elongate fault compartments along the boundary of the Austro-Alpine/western Carpathians continental fragments and the Carpathian Embayment Ocean (Fig. 3), for example the Czorsztyn Submarine Ridge (Mišík, 1993). The two SK and CZ segments were forming the tips of the whole transform fault zone and, as such, they were sustaining vertical movements. The SKICZ paleotransform fault zone was active from the Permian to at least the Late Jurassic–Early Cretaceous. During that entire period, it kept a ~north–south overall trend. It was partly the eastern unconstrained boundary of the Austro-Alpine belt during the Late Cretaceous–Early Paleogene. It is only later that the transform fault was divided into three main sections that were rotated up to their present attitude.

Presently, the SK and CZ segments almost meet northwest of Zagreb and strike at right angle to each other (Fig. 1). Paleomagnetic data (Muttoni et al., 2001) show that Adria and Africa have rotated counterclockwise from Permian to Late Cretaceous by almost 90° relative to

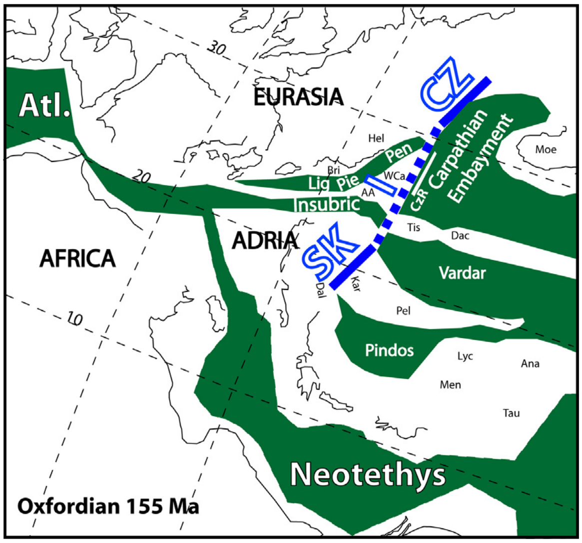

Fig. 3. (Color online). Location of the SKICZ paleotransform during the Oxfordian (155 Ma). The purpose of this map is purely paleogeographic; it does not explicitly concern the plate geodynamics, and the map does not show the zones of accretion, subduction, obduction, back-arc basins and other transforms but the SKICZ. Drawings are superimposed over extracts of Figures from Stampfli et al. (2001), Stampfli and Hochard (2009) and Bonev and Stampfli (2011) that provide the main geometry of the European, African and Adria continents and the paleolocation of mega-units. Dark green: oceanic lithosphere; white surfaces: continental lithosphere; blue lines, the SKICZ paleotransform comprising: dashed line labelled as 'I' in the text, transcurrent movements; full lines, SK and CZ, with vertical movements. The Insubric line is sometimes considered to represent a former major suture between the Eurasia and Adria continents (Dewey and Bird, 1970). AA: Austro-Alpine; Ana: Anatolia; Bri: Briançonnais; CzR: Czorsztyn ridge; Dac: Dacia; Dal: Dalmatia; Hel: helvetic; Kar: High Karst; Li: Liguria; Lyc: Lycia; Men: Menderes; Moe: Moesia; Pel: Pelagonian; Pen: Pennic; Pie: Piemont; Tau: Taurus; Tis: Tisza; WCa: West-Carpathians.

Eurasia. Since then, the Africa/Eurasia convergence has been ~north–south (Platt et al., 1989). These rotations and northward convergence have modified the original trends of the SK and CZ segments, up to their present attitude.

Some authors have already suggested the existence of paleotransform fault zones in the Neo-Tethys (Aubouin et Dercourt, 1975; Chorowicz et Geyssant, 1976; Chorowicz et al., 1980; Debelmas and Săndulescu, 1987; Lyberis et al., 1982; Robertson and Shallo, 2000; Royden et al., 1982; Smith and Spray, 1984; Trümpy, 1988). In particular, Stampfli et al. (2001) have drawn a transform zone fairly similar to the SKICZ between the Vardar Ocean opening in the north and the Paleo-Tethys subduction in the south, active during the Late Permian–Anisian. The transform would have then extended at the western border of the Vardar Ocean during Carnian, Sinemurian, and Oxfordian times. Csontos and Vörös (2004) have suggested a transform line between the Pindos and the Vardar oceans in the Late Permian, Carnian, Sinemurian and Oxfordian times. Debelmas and Săndulescu (1987) have associated the PKB with a Penninic transform fault zone that would have been EW-trending with respect to Eurasia and active in the Early Cretaceous. Ustaszewski et al. (2008) have proposed that a transform fault is needed to explain the observed reversal in obduction and subduction polarities between the eastern Alps and the Dinarides, and this transform could be the Balaton line and its eastern continuation. This latter transform zone is nearby the SKICZ transform that we suggest here. Although the interpretation of Ustaszewski et al. (2008) is reasonable, the SKICZ transform that we propose better reconstructs the original position of the PKB deposits.

6. Conclusions

The Pieniny Klippen Belt (PKB) in the Carpathians was originally a segment of a large transform fault in the Neo-Tethys, the SKICZ paleotransform. The transform fault was active from the Permian to the Early Paleogene. During this time interval, clasts depositing in the PKB originated from the west, from zones of uplifts west of the SKICZ central 'I' segment, essentially from the Austro-Alpine continental lithosphere. It is only afterward, during the Late Paleogene–Early Neogene that these clasts were included into the accretionary prism that formed along the free border of the Austro-Alpine units as the latter were laterally extruding eastward.

The paleotransform acted as a transcurrent transform fault zone linking opposite subduction and obduction polarities (Alpine polarity vs. Dinaridic polarity). In the Late Jurassic, the paleotransform formed the western boundary of the Carpathian Embayment and of the Vardar oceans, against the free border of the future ALCAPA units. The SK and CZ fault zones in Adria and Eurasia continents, respectively, were the fault sections developed at the tips of the paleotransform. As such, they mainly accommodated vertical motions. The SKICZ paleotransform was a major tectonic structure in the western Neo-Tethys, whose existence and functioning are consistent with several of the models and paleogeographic maps that have been proposed to explain the formation of the Alpine belts.

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