GEOLOGICAL NOTES

Role Played by Strike-Slip Structures in the Development of Highly Curved Orogens: The Transcarpathian Fault System, South Carpathians

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ABSTRACT

We describe a previously unrecognized major dextral strike-slip fault system in the South Carpathians, hereafter referred to as the Transcarpathian fault system. The master fault has been active since the mid-Cretaceous and has a total offset of ~150 km, of which only <35 km are post-Oligocene. The fault acted as a subduction-transform edge propagator (STEP) fault during the mid-Cretaceous subduction of the Ceahlău-Severin ocean system and separated an area to the north where the subduction system was accretionary (the East Carpathians) from an area to the south (the western half of the South Carpathians) where the subduction system was erosive. In the South Carpathians, the oceanic basin closed during the mid-Cretaceous after commencement of higher convergence rates and subduction erosion of the trench, leading to tectonic underplating and continental collision between the Dacia and Moesian microplates. The results bolster the idea that STEP-type strike-slip faults are critical in the development of highly curved orogens and that accretionary versus erosional trench segments lead to very different structural configurations along the same subduction/collisional system.

Introduction

Significant strike-slip motion helps accommodate curvature at many highly curved modern plate boundaries, such as those surrounding the Caribbean plate, the Scotia region, the Banda arc region, and many others (Mora et al. 2006). It is also well established that strike-slip fault systems were critical in generating oroclinal bends in mountain ranges representing ancient convergent plate margins (Ratschbacher et al. 1991).

Perhaps no continental region has such a tight oroclinal bend as the Z-shaped curvature of the southeastern part of the Carpathian Mountains in Romania (fig. 1), which are the eastern continuation of the European Alps and link to the Balkans and Anatolia farther to the east (Burchfiel 1980; Mațenco et al. 2010; Cloething et al. 2011). The Z-shaped orocline is a large-scale, first-order indicator of some form of dextral shearing. There are two plausible end-member tectonic models that can explain the Carpathian orocline. In one, the tectonic escape model, dextral strike-slip fault systems within the continental lithosphere allow for large-scale translation and rotation of crustal blocks in response to the Alpine Cenozoic collision originating to the south and west of the Carpathians (Linzer et al. 1998; Fügenschuh and Schmid 2005). An alternate end-member model proposes that Mesozoic (Jurasic-Cretaceous) plate margin geometry was responsible for establishing oroclinal bends (Săndulescu 1984) well before the Cenozoic.

Small to moderate strike-slip faults (up to a few tens of kilometers of displacement) of various post-Jurassic ages have been mapped in the South and East Carpathians (e.g., Ratschbacher et al. 1993; Schmid et al. 2008). In addition, strike-slip fault motion is associated with the clockwise rotation of the Apuseni block and parts of the western South Carpathians, related to the overall escape tectonics that led to the translation of the Tisza block eastward (Balla 1987;

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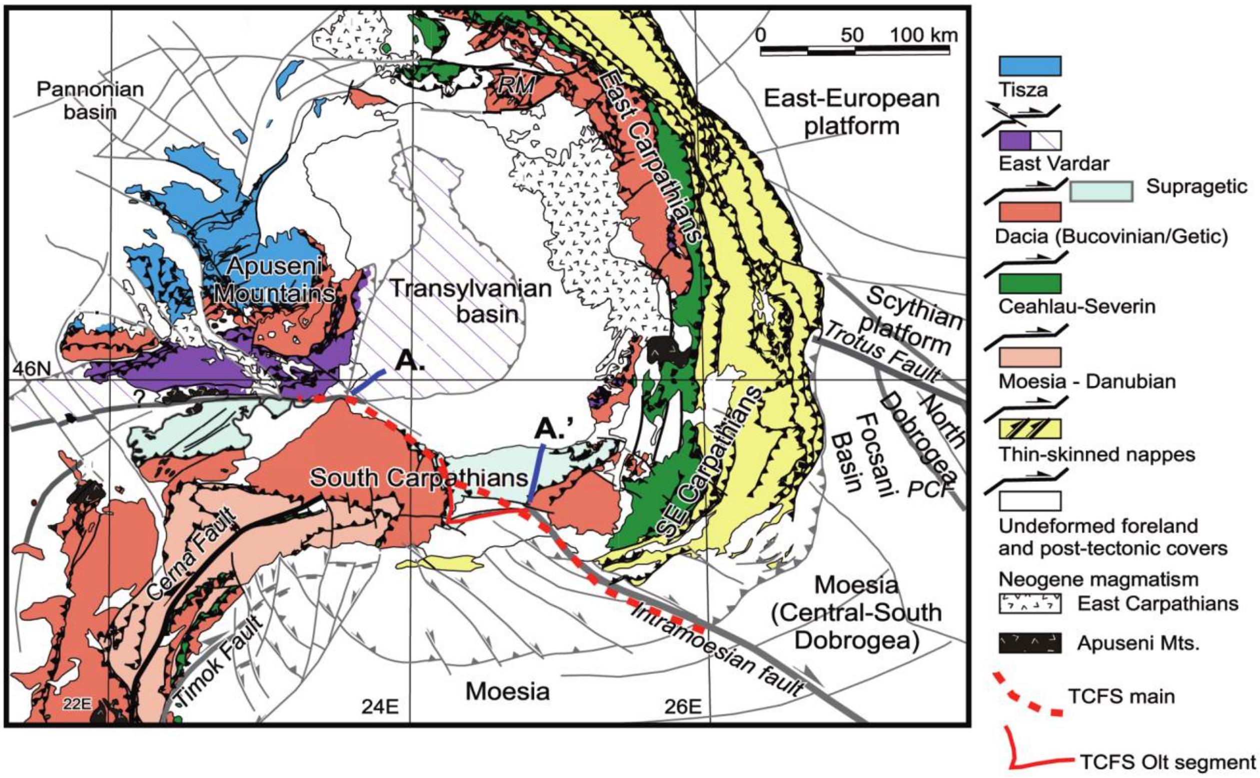

Figure 1. Modern configuration of the Carpathian orocline, with major geological and structural units and major faults. The map is compiled on the basis of the Geological Maps of Romania executed by the Geological Institute of Romania at various scales (1:1,000,000, 1:200,000, and 1:50,000; see Săndulescu 1984) and subsequent work by the Free University of Amsterdam/University of Utrech groups (Mațenco et al. 2010). The main path of the Transcarpathian fault system (TCFS) is shown with a dashed red line, whereas the Olt corridor is shown with a continuous, thinner red line. Points A and A′ are the piercing points defined by the Getic-Supragetic contact, as defined in the text. Also shown with blue rectangles are the main areas of modern seismic activity along the path of the fault. PCF = Peceneaga-Camena Fault.

Pătrașcu et al. 1994). These dextral strike-slip faults are inferred to have aided the lateral escape of the Tisza block during the Miocene and may have resulted in the formation of the East and South Carpathian orocline (Ratschbacher et al. 1993; Fügenschuh and Schmid 2005; Schmid et al. 2008), a process that certainly requires lateral faults. However, the magnitude of displacement on these strike-slip fault systems is relatively small and alone cannot justify the several hundreds of kilometers required for the oroclinal bend of the Carpathians.

Here we propose the existence of a sizable dextral strike-slip fault system that runs obliquely across the modern South Carpathians and separates an East Carpathian from a western South Carpathian Alpine plate convergence segment along the European margin of the Alpine Tethys (Handy et al. 2010). Such a fault system would fall into the category of subduction-transform edge propagator (STEP) faults (for the Carpathians, see Dupont-Nivet et al. 2005). This inferred fault system, herein referred to as the Transcarpathian fault system (TCFS), has been active since the mid-Cretaceous (and in places reactivates pre-Alpine structures), has a total dextral offset of ~150 km, and has been dismembered in places by more recent tectonism. Its documentation is mostly based on exposures in the South Carpathians, but extensions to the northwest and southeast are also plausible. Various strands of the fault are active today, such as the segment along the Olt River (Oncescu et al. 1999). The existence of a Cretaceous dextral step that separated different structural styles to its north and south helps explain the regional tectonic processes that led to differences in the geology of the South and East Carpathians and provides a simple explanation for the large oroclinal bend of the Carpathians.

This model does rule out the tectonic escape hypothesis, which undoubtedly played a significant role in the Miocene and younger tectonic evolution of the Carpathians. Instead, we suggest that Miocene escape tectonics only added to an already-significant oroclinal elbow.

Timing and Piercing Points

The location of the proposed TCFS in modern coordinates is shown in figure 1 and represents a proposed path of structural breaks that amount to major discontinuities in the regional Alpine geology. The major reasons for inferring a geologically significant fault system are (1) the abrupt truncation of the Cretaceous and younger accretionary wedge units consisting of flysch (accretionary wedge turbidites) and ocean basin remnants (Ceahlău-Severin) as well as the Miocene external units (Moldavides) south of the East Carpathians (Săndulescu 1984), with an overall drag-fold aspect of the East Carpathians approaching the TCFS; (2) the existence of 1–3-km-wide areas of steep to vertical brittle shear zones ("corridors") along the TCFS consistent with right-lateral motion (Maţenco and Schmid 1999); (3) the right-lateral offset of the Getic-Supragetic nappe units in the South Carpathians (Streckeisen 1934) along the TCFS; (4) the presence of Late Cretaceous to Cenozoic transtensional continental basins along the strike of the TCFS; and, to a lesser extent, (5) the modern activity of the fault, which is marked by numerous $3.5 < M < 4.2$ events in the historic record (Oncescu et al. 1999; Ismail-Zadeh et al. 2012; and references therein). The significance of the post-mid-Cretaceous activity on various segments of the fault is that it can provide reasoning for the discontinuous nature of this structure today given various reactivation events during the Cenozoic. However, we propose that the main period of fault development is in the mid-Cretaceous.

In our interpretation, the best piercing point for fault displacement is the thrust fault that separates the Getic and Supragetic nappes or thrust sheets (points A and A′ in fig. 1), which is displaced ~150 km. These two nappes are part of the Dacides, a sequence of thrust sheets that belong to the mobile interior of central Europe (Săndulescu 1984; Csontos and Vörös 2004; Schmid et al. 2008), and consist of basement rocks characterized by fundamental petrographic differences (Pană and Erdmer 1994), making the contact between them identifiable in the field (Iancu et al. 2005). The Getic basement was metamorphosed during the Variscan collisional orogeny (350–320 Ma; Medaris et al. 2003), whereas metamorphism in the Supragetic nappes appears to have been in part Variscan (Drăguşanu and Tanaka 1999) but also Ordovician (Profeta et al. 2013). The Getic-Supragetic discontinuity is the contact that we use for the total minimum displacement during the life of the fault. This structural boundary is at least in part Alpine in age and is sealed by small, undeformed calcalkaline dacite to rhyolite dikes of 110–105 Ma age in the Sebeş Mountains (Dobrescu et al. 2010). Tertiary strata offset along the TCFS are nonunique piercing points but allow for up to 55 km of Cenozoic displacement. Less than 35 km of post-mid-Miocene displacement is permissive on the basis of the South Carpathian foothills molasse offset (Maţenco et al. 1997).

The most critical segment of this fault is the north-south-trending path along the Olt River, one that most local geologists interpret as part of the Getic-Supragetic nappe contact (figs. 1, 2). This is an area of near-vertical structural fabrics that contain a mix of ductile and brittle deformation structures (e.g., Hann 1995; shown as a gray zone in fig. 2). Ductile deformation is Permian and Early Triassic and is referred to as the Sibişel Shear Zone (Pană and Erdmer 1994; M. N. Ducea, L. Profeta, E. Negulescu, G. Săbău, and D. Jianu, unpublished manuscript). The Sibişel Shear Zone is a mylonitic zone making up the westernmost part of the deformed area west of the Olt River, and it juxtaposes predominantly arc basement rocks deformed during the Variscan orogeny against a low-grade Ordovician island arc terrane that did not experience Variscan metamorphism, with mafic and ultramafic rocks suturing the contact in places (M. N. Ducea, L. Profeta, E. Negulescu, G. Săbău, and D. Jianu, unpublished manuscript). Garnet and monazite grew in the shear zone during the latest Permian (Negulescu et al. 2014). Overprinted on this structure, in places overlapping but mostly east of it, is a 1–2-km-thick area of intense brittle deformation that puts the entire Getic thrust sheet (or nappe) described above against a more shallowly dipping metamorphic package that is part of the Supragetic thrust sheet and makes up much of the Fagaras Mountains, east of the Olt River. The two basement domains have different rock assemblages (Pană and Erdmer 1994) and are clearly juxtaposed along a major mid-Cretaceous to Late Cretaceous brittle discontinuity (Streckeisen 1934). In detail, the fault, interpreted classically to be a thrust fault, is very steep—vertical in places—and comprises several individual faults that are more or less parallel to each other and contain blocks of both Supragetic and Getic basement, somewhat chaotically distributed and rotated (Hann 1995). The brittle fault system cuts the ductile precursor, which constrains its maximum age to the Late Permian to Early Triassic. Minor Cenomanian sediments are cut by fault strands (Hann 1995), requiring some movement along the fault to be post-Cenomanian.

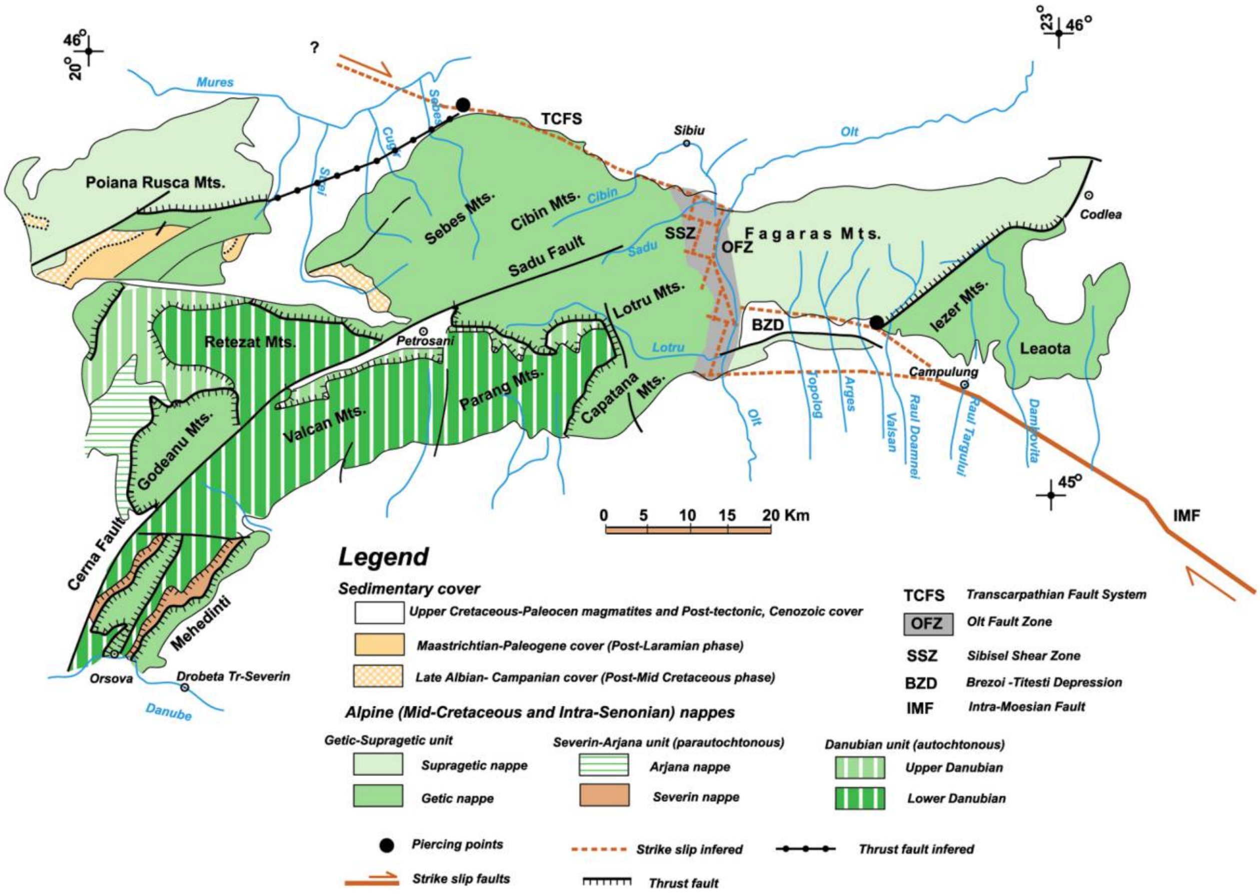

Figure 2. Simplified geological map of the central and eastern parts of the South Carpathians (originally drafted by G. Costin [unpublished] after Iancu 1986; Balintoni et al. 1989; Berza and Iancu 1994). The main basement and cover units as well as Cretaceous thrust faults are shown. The Danubian thrust sheet is divided into two separate units. The Arjana and Severin thrusts are both tectonic mélanges representing occluded remnants of the Ceahlău-Severin Ocean in the western South Carpathians. The proposed path of the Transcarpathian fault system is shown in red with the complexities described in the text around the Olt fault (proposed flower structure) and Brezoi-Titesti basin (pull-apart basin).

A Late Cretaceous to Miocene basin (Brezoi-Titesti) bounds the fault to the east. We interpret this basin to be a pull-apart basin formed in response to the development of the Olt Valley fault system as a dextral strike-slip fault. We hypothesize that the earlier path of the fault was along the Olt Shear Zone, which is now oriented north-south due to clockwise rotation of that block (figs. 1, 2). In other words, the Brezoi-Titesti basin is a basin formed along a right step along a dextral fault system. The Brezoi-Titesti basin is entirely fault bound according to some researchers (Hann 1995; Geological Institute of Romania 1968) but not others (Mațenco and Schmid 1999). Normal faulting along an east-west fault called the Lotru fault (fig. 2) has led to the duplication of some of this basin during the Miocene. Modern seismicity throughout the entire basin and its edges documents that the basin is still active today. The earthquakes are shallow (<12 km) and consistent with either a normal or a strike-slip mechanism (Romanian National Institute for Earth Physics, real-time earthquake archives, http://www1.infp.ro/realtime-archive).

The western continuation of the TCFS may be the Mureș Fault Zone (also referred to as the South Transylvanian fault), a poorly exposed but presumed-to-be-important east-west-directed strike-slip fault separating the South Carpathians from the Apuseni Mountains (Săndulescu 1984). However, documented Cenozoic rotation and translations of the Apuseni Mountains (Tisza block) around Dacia makes it difficult to speculate on the northwestern continuation of the fault, if any. The southeastern segment of the TCFS is identical with the modern Intramoesian fault (fig. 1), which has long been known in the South Carpathian foreland south of the oroclinal bend, on the basis of its seismicity (Ismail-Zadeh et al. 2012 and references therein) and offset of the youngest compressional structures in the South Carpathian foothills (Maţenco et al. 1997). No data exist on the pre-Cenozoic evolution of the Intramoesian fault, if any, but it is known that it separates western from eastern Moesian basement units that have a significantly different history: western Moesia is similar to the Danubian units exposed in the South Carpathians and contains a significant amount of late Variscan nonmetamorphosed granitoids emplaced onto a late Precambrian basement, whereas eastern Moesia is similar to the neo-Proterozoic passive margin units exposed in central Dobrogea that cover an older Proterozoic basement (Balintoni et al. 2014). Therefore, it is plausible that the proposed TCSF does have a continuation on the Moesian microplate.

Regardless of its possible extensions to the west or east, the proposed TCFS separates two segments of the Carpathians orocline (northeast and southwest of the TCFS in modern coordinates) that have different tectonic histories. This model suggests a much less curved configuration of the neo-Tethyan margin in the mid-Cretaceous (Pană et al. 2002). The TCFS was a significant structural feature in itself, but its existence as a subduction lateral ramp also simplifies the regional tectonic evolution of the oroclinal bend area and helps to decipher the regional differences between the South and East Carpathians in terms of plate kinematics.

Tectonic Evolution North of the TCFS

In the East Carpathians, north of the TCFS, westward subduction of the Ceahlău-Severin Ocean (CSO) commenced in the Jurassic (Schmid et al. 2008) and led to the accumulation of a thick Upper Jurassic and Cretaceous flysch (the Ceahlău-Severin nappes). It is unclear whether the CSO was floored by true oceanic crust or by a highly attenuated continental crust with significant basaltic input (Pană et al. 2002). Regardless, the western margin of the CSO was a subduction zone, and the turbiditic flysch deposits represent accretionary wedge materials (Lăzărescu and Dinu 1981). The subduction margin continued to be an accretionary one for much of the early Cenozoic, as evidenced by the oceanward propagation (eastward in modern coordinates) of the trench. Progressive eastward accretion of younger units toward the trench led to the development of a thin-skinned fold and thrust belt with Dacian continental basement units thrust over younger units. The existence of a wide and long-lived belt of accretionary wedge deposits in the East Carpathian thrust belt is first-order evidence that this subduction system was accretionary for much of its history. The total width of the accretionary belt is ~120 km on average.

Evidence exists that subduction continued along this segment until the Miocene (Săndulescu 1988; Ustaszewski et al. 2010), when collision with the East European Platform took place. Interestingly, arc magmatism was restricted to the syncollisional period in the East Carpathians (Seghedi et al. 1998), whereas the only potential subduction-related arc is located in the Transylvanian basin and southern Apuseni Mountains and is Upper Jurassic (Lower Cretaceous?) in age (Ionescu et al. 2009).

All Cretaceous and Paleogene nappes of the East Carpathians are truncated by the TCFS—this is a first-order structural feature in the oroclinal bend area of the southeast Carpathians. In contrast, younger molasse deposits (Miocene-Pliocene) wrap around the Carpathian bend area.

Tectonic Evolution South of the TCFS

The area south and west of the TCFS experienced a markedly different tectonic history since the mid-Cretaceous. Rapid convergence and shallow subduction of the CSO led to the closure of the oceanic realm during the mid-Cretaceous and subsequent (poorly age-constrained) collision of the Moesian continental block with Dacia (Săndulescu 1988). The thrust sheet architecture in the western part of the South Carpathians documents the closure of the CSO, now a tectonic mélange located structurally under the Getic-Supragetic basement and above the Danubian nappe, which is inferred to be part of western Moesia (Balintoni et al. 2014). In contrast to the northern segment, south of the TCFS was an erosional subduction margin whereby the flysch units and the emerging continental block of Moesia were subducted and tectonically underplated. In other words, the trench of this subduction/collision interface migrated westward, toward the interior of the upper plate. Highly attenuated equivalents of the East Carpathians flysch units are found together with mafic remnants of the CSO in a tectonic mélange together referred to as the Severin nappes, located between Dacian and Moesian basement–dominated units of the South Carpathians.

The timing of underplating of the CSO beneath Dacia is poorly constrained by age data but is loosely tied to the mid-Cretaceous (~110 Ma) on the basis of low-temperature thermochronology on prehnite-pumpellyite facies rocks of the Severin and Danubian nappes (Ciulavu et al. 2008).

We propose that the TCFS acted as a mid-Cretaceous STEP-type strike-slip fault that accommodated the

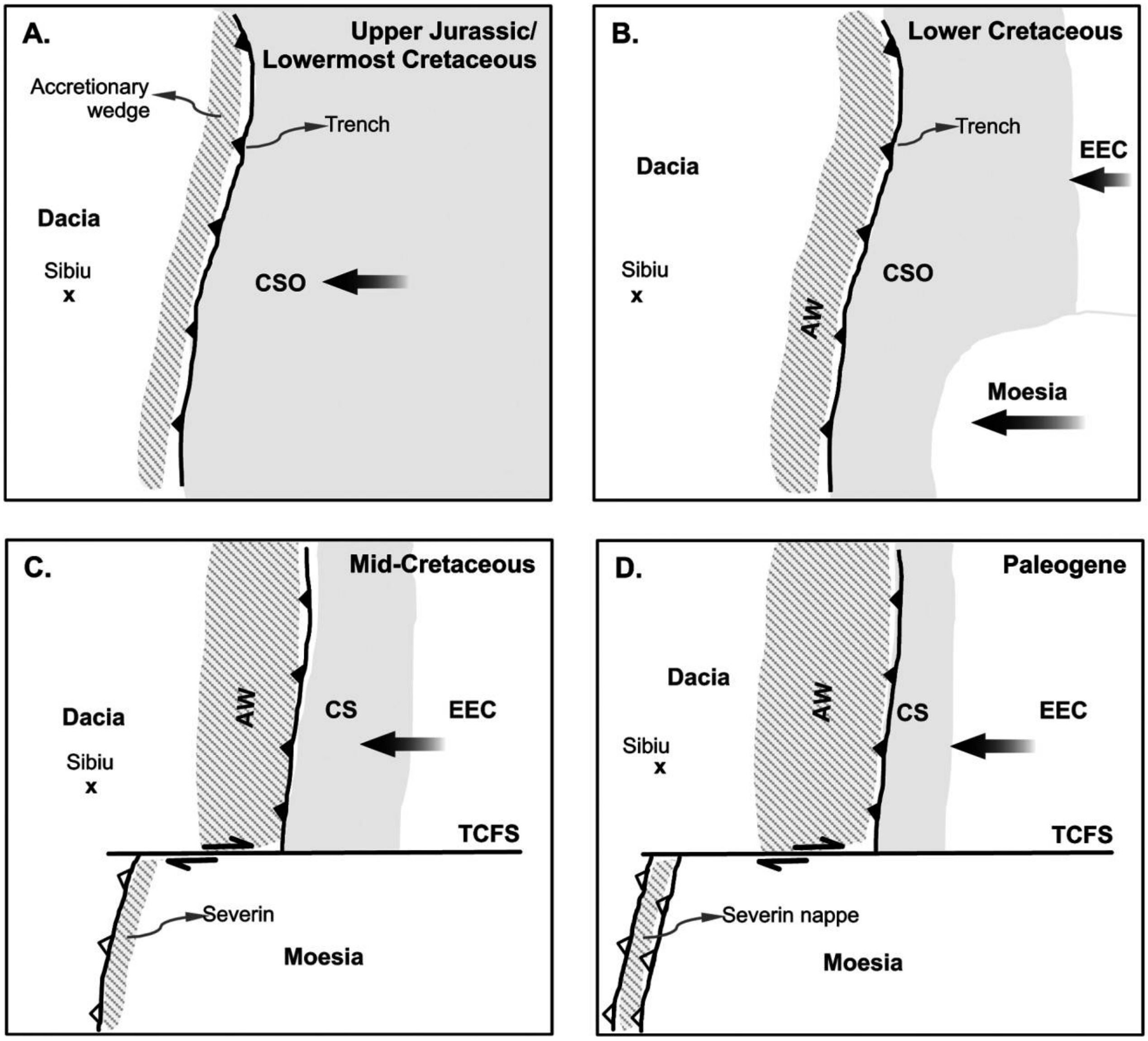

Figure 3. Cartoons depicting the proposed evolution of the Ceahlău-Severin Ocean (CSO) in the Cretaceous followed by the closure of its southern part and continuation of subduction under the northern segment, Ceahlau (CS). An arbitrary point on the upper plate (Dacia) is marked as the city of Sibiu to illustrate via the lengthening or shortening distance between the trench and that point the accreting versus eroding style of convergence in the two areas south and north of the Transcarpathian fault system (TCFS). AW = accretionary wedge (Sinaia and equivalent flysch deposits); EEC = Eastern European craton. A color version of this figure is available online.

difference between the retreating and probably faster and shallower subduction (which may have been aided by the arrival of continental Moesia) of the south along an eroding margin and the slower, probably steeper subduction to the north along an accreting margin (fig. 3).

Regional Implications

The proposed TCFS as a dextral strike-slip fault accommodating different convergent styles in the Carpathians explains some of the major differences between the southern and eastern segments of the Romanian Carpathians. The eastern segment was an accretionary convergent system through much of its Alpine subduction and collision history from the Jurassic during the subduction of the CSO to the Miocene and possibly younger, when various forms of convergence eventually led to the closure of this segment of the Tethys. The southern part, in contrast, was subject to faster convergence rates, inferred subduction erosion (trench migrating toward the upper plate interior), and tectonic underplating, leading to the consumption of the CSO and its trench-related deposits, forearc subduction, and continental collision with Moesia during the mid-Cretaceous (fig. 3).

The inferred ~150-km right-lateral displacement since the Late Cretaceous also contributes significantly to tightening the angle of oroclinal bending of the southern East Carpathians and helps reconstruct various alpine thrust sheets (although we acknowledge that subsequent rotations and translations did further shape this orogen). Right-lateral displacement on the TCFS also explains the truncation of the eastern Carpathians flysch near the oroclinal bend and the presence of a transtensional basin (Brezoi-Titesti) in the central South Carpathians (fig. 1).

The linear and narrow belt of Alpine high-angle reverse faults along the western side of the Olt River (referred to as the Olt Fault Zone by Hann 1995) is interpreted here to be a part of the TCFS and not a strand of the Supragetic thrust fault, as viewed by many (e.g., Streckeisen 1934; Săndulescu 1984; Hann 1995). It clearly reactivates an older set of ductile shear zones collectively referred to as the Sibișel Shear Zone (Pană and Erdmer 1994). The Sibișel ductile shear zone appears to have been active during the Permian and Early Triassic on the basis of geochronology, thermochronology, and the age of sedimentary units affected by strain (Negulescu et al. 2014). A 1–3-km-wide belt of brittle deformation and several distinct parallel faults along this fault zone are suggestive of a flower structure developed along this strand of the TCFS. This hypothesis requires further testing. The poor exposures make it difficult to interpret the structural architecture of this fault zone.

Our interpretation undermines the significance of the Timok and Cerna-Jiu faults (Berza and Drăgănescu 1988; Ratschbacher et al. 1993) in the central South Carpathians. These faults were active later than the main strand of the TCFS (Oligocene-Miocene), have a decreasing magnitude of displacement northward, and become insignificant in the central South Carpathians. For example, the Sadu fault, which is the northward continuation of the Cerna-Jiu fault, crosses the TCFS system south of Sibiu and has no offset on the TCFS.

The proposed TCFS system is a polygenetic and complex fault zone (Pană and Erdmer 1994). The complexity is in part due to the fact that a pre-Alpine ductile fault system (Sibișel Shear Zone; M. N. Ducea, L. Profeta, E. Negulescu, G. Săbău, and D. Jianu, unpublished manuscript) runs parallel to the TCFS along the Olt Valley; one needs to separate the original Permo-Triassic ductile deformation from the later, Alpine brittle deformation. No ductile fabrics appear to be associated with the Cretaceous and younger deformation, as medium- to low-temperature chronometers (Rb-Sr in biotite) yield Triassic or slightly older ages (Profeta et al. 2013; Negulescu et al. 2014). The mid-Cretaceous fault, in our hypothesis, acted as a STEP fault for the convergent margin involving the subduction of the CSO and was a sizable right-lateral strike-slip fault system accommodating relative motion between the South and East Carpathians. The original path of the mid-Cretaceous TCFS was rotated and gradually abandoned during the unroofing and development of the Brezoi-Titesti pull-apart basin in the Paleocene. This geometry suggests that the Olt Fault Zone transfers through the Brezoi-Titesti basin to northwest-trending faults east of the basin as a projection of the Intramoesian fault.

The complexity of the modern path of the proposed TCFS is similar to other transcurrent faults in the realm of eastern Mediterranean collision systems, in which lateral extrusion along major strike-slip faults and rotation of blocks during convergence is common. The North Anatolian fault system has a similar geometry when time integrated over the course of the late Cenozoic (Carmiati and Doglioni 2004). Older paths of the fault are abandoned after block rotation, and the fault finds a new, straighter path to continue accommodating lateral displacements. This behavior makes the identification of these faults difficult in this tectonic environment, as portions of these fault systems are progressively being rotated and abandoned, leading to a complicated collage of small blocks with a complex history of translation and rotation (Burchfiel 1980).

At large scale, a geometric analogue to the South to East Carpathian geometry proposed here is the modern Pamirs. While the Pamirs and their continuation to the east (the Himalayas) are shaped primarily by Cenozoic continental collision, they nevertheless exemplify the development of oroclinal bending generated by two segments behaving differently along the strike of the convergent margin, one retreating and one advancing relative to a fixed point on the upper plate. The Pamir area is an eroding margin, with the plate boundary having migrated northward toward the Eurasian interior (Sobel et al. 2013), whereas the Himalayan range is, for the most part, a fold and thrust belt migrating southward in an accreting style (DeCelles et al. 2001). The differences between the two types of convergence are accommodated in the Pamir mountain range by major dextral slip faults, such as the Karakorum fault. The indentor representing Moesia in the Carpathians behaved similarly to the Hindu-Kush/Karakorum indentor of the western syntaxis of the Himalayan belt, leading to a retreating segment of a margin (the

South Carpathians) juxtaposed next to an advancing (accreting) one (the East Carpathians).

Conclusions

We propose that the dextral TCFS acted as a STEP fault during subduction/collision of the CSO with Dacia in the mid-Cretaceous. The TCFS cuts across the South Carpathian mountain ranges. The fault system has a magnitude of dextral offset of ~150 km based on the truncation of Cretaceous to Miocene Alpine accretionary wedge strata of the East Carpathians and the offset of the Getic-Supragetic basement contact. The fault system is now partly rotated and dismembered by subsequent Miocene deformation. The TCFS was a major structural boundary, separating an accretionary subduction margin to the northeast from an erosive margin to the southwest in modern coordinates. In the south, subduction and closure of the CSO lead to tectonic underplating of parts of Moesia under Dacia by the mid-Cretaceous. In contrast, the block to the north of the TCFS continued to be subject to oceanic subduction until the Miocene. Various displaced strands of the TCFS were reactivated during the Cenozoic, although at reduced rates and with shifting locations to accommodate the clockwise rotation of the orogen, and some continue to be active today.

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