Crustal constraints on the origin of mantle seismicity in the Vrancea Zone, Romania: The case for active continental lithospheric delamination

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Abstract

The Vrancea zone of Romania constitutes one of the most active seismic zones in Europe, where intermediate-depth (70–200 km) earthquakes of magnitude in excess of \( M_w = 7.0 \) occur with relative frequency in a geographically restricted area within the 110° bend region of the southeastern Carpathian orogen. Geologically, the Vrancea zone is characterized by (a) a laterally restricted, steeply NW-dipping seismogenic volume (30 × 70 × 200 km), situated beneath (b) thickened continental crust within the highly arcuate bend region of the Carpathian orocline, and (c) misalignment of hypocenters with the position of known or inferred suture zones in the Carpathian orogenic system. Geologic data from petroleum exploration in the Eastern Carpathians, published palinspastic reconstructions, and reprocessing of industry seismic data from the Carpathian foreland indicate that (1) crust of continental affinity extends significantly westward beneath the external thrust nappes (Sub-Carpathian, Marginal Folds, and Tarcau) of the Eastern Carpathians, (2) Cretaceous to Miocene strata of continental affinity can be reconstructed westward to a position now occupied by the Transylvanian basin, and (3) geologic structure in the Carpathian foreland (including the Moho) is sub-horizontal directly to the east and above the Vrancea seismogenic zone. Taken together, these geologic relationships imply that the Vrancea zone occupies a region overlain by continental crust and upper mantle, and does not appear to originate from a subducted oceanic slab along the length of the Carpathian orogen. Accordingly, the Vrancea zone appears to potentially be an important place to establish evidence for active lithospheric delamination.

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1. Introduction

Ever since the recognition of deep focus earthquakes (Wadati, 1928), the cause of mantle seismicity has been a long-standing problem in the Earth sciences. While early workers observed that earthquake focal depths generally increase with distance from the trench, forming dipping seismogenic planes in the mantle (Wadati, 1928, 1935; Benioff, 1949), it was many years before such seismicity was correlated with the subduction of plates of oceanic lithosphere. Development of plate-tectonic theory in the late 1960s subsequently provided
a fundamental new framework in which to explain the origin and geodynamic significance of earthquakes occurring at depths of 70–700 km, along so-called Wadati–Benioff zones (Isacks et al., 1968). We now commonly understand such intermediate-to deep-focus seismicity as brittle deformation of descending, rigid oceanic slabs at subduction zones.

In the past two decades, delamination of thickened continental lithosphere has gained favor as an important geodynamic process in orogenic settings (e.g., Nelson, 1991), and has been proposed as an alternative mechanism for generation of mantle seismicity (e.g., Seber et al., 1996). Such an interpretation seems plausible where earthquake foci do not align along a dipping Wadati–Benioff plane, but cluster in a more concentrated volume. ‘Delamination’ was first introduced in the late 1970s within a theoretical context (Bird, 1978, 1979), and was originally conceived as detachment of thickened lithospheric mantle from overlying crust during continental collision (Bird, 1978). Subsequently, the concept has come to encompass a much broader range of processes, including removal of material from the base of the lithosphere due to gravitational instability (Bird, 1979), detachment of oceanic slabs (Sacks and Secor, 1990), or foundering of mafic lower crust and upper mantle driven by phase changes (Kay and Kay, 1993; Nelson, 1991).

Regardless of the specific mechanism, the removal of continental lithosphere into the underlying mantle has been routinely invoked to explain the geologic evolution of orogenic systems (e.g., Furlong and Fountain, 1986; Dewey, 1988; Austrheim, 1991; Baird et al., 1996). If such a process has operated regularly in the development of mountain belts, it has far-reaching implications for the evolution of continental lithosphere (e.g., Nelson, 1991), the dynamics of the crust/mantle (Moho) and lithosphere/asthenosphere boundaries, and perhaps most significantly, the long-term geochemical budget of both crust and mantle. The tectonic and geodynamic consequences of lithospheric delamination are generally agreed to include (1) post-orogenic extensional collapse, (2) regional uplift, (3) deep-seated alkaline magmatism, (4) elevated heat flow, and (5) subcrustal seismicity. Accordingly, the Vrancea zone of Romania constitutes one of the most active seismic zones in Europe, where mantle (70–200 km) earthquakes of magnitude in excess of $M_w = 7.0$ occur with relative frequency in a geographically restricted area (Fig. 1). For centuries, these seismic events have resulted in a high toll of human casualties and property damage, and make Bucharest today one of the largest population centers in Europe at significant seismic risk. Geologically, the Vrancea zone is characterized by (a) a laterally restricted, steeply NW-dipping seismogenic volume ($30 \times 70 \times 200$ km; Wenzel et al., 1998), situated beneath (b) thickened continental crust within the highly arcuate bend region of the Carpathian orocline (Radulescu, 1981), (c) misalignment of hypocenters with either documented or inferred suture zones in the Carpathian orogenic system (Linzer, 1996), and (d) pronounced and localized Late Miocene/Pliocene subsidence in the Focsani basin of the foreland (Artyushkov et al., 1996; Matenco et al., 2003), an area that also exhibits (e) active surface deformation and crustal seismicity. These geologic relationships are for the most part specific to the bend region, and as such, do not appear to support the premise of a subducted oceanic slab along the length of the Carpathian orogen. Accordingly, the Vrancea zone may be the unique place to establish evidence for active lithospheric delamination.

Despite these considerations, and several recent seismological investigations focused on the mantle source region of the Vrancea zone (Fan et al., 1998; Wenzel et al., 1998; Wortel and Spakman, 2000; Hauser et al., 2001), the weight of scientific opinion remains overwhelmingly in favor of a subducted slab origin for Vrancea seismicity. Both active- and passive-source studies in Romania in the last decade have resulted in a substantially improved understanding of the velocity structure of the crust and upper mantle. Similarly, the spatial relationship of Vrancea mantle seismicity to active surface deformation in the foreland suggests that these regions are mechanically coupled through the crust and upper mantle, which would be a fundamental constraint on the competing geodynamic models.

Here we present interpretations of existing data from petroleum exploration and reprocessing of deep seismic reflection data that document the continuity of continental crust beneath the external nappes of the Eastern Carpathians, and accordingly, above the Vrancea seismic zone. These surface and subsurface data appear to preclude the possibility that a slab, either still attached or now detached, was subducted either in place within the Carpathian foreland (e.g., Wortel and Spakman, 2000) or beneath the Eastern Carpathians (e.g., Wenzel et al., 1998), or beneath the Eastern Carpathians.
et al., 1998; Girbacea and Frisch, 1998; Gvirtzman, 2002). Accordingly, the NW-dipping seismogenic body of the Vrancea zone may more likely have originated as delaminating continental lithosphere (Diaconescu et al., 2000, 2001; Knapp et al., 2001), or through some as yet unidentified geodynamic process for generating spatially restricted intermediate-depth seismicity in the absence of subducted oceanic lithosphere.

2. Geologic background

Formation of the Carpathian orogen (Figs. 1 and 2) can be broadly understood in the framework of Mesozoic and Cenozoic closure of the Tethys ocean during continental collision of the Eurasian and African plates. Two main periods of compressional deformation are recognized in the Eastern Carpathians, one during Late Cretaceous time that was responsible for emplacement of large crystalline thrust sheets (Getic, Supragetic, and Bucovinian nappes) now exposed in the westernmost Eastern Carpathians, and a second phase during Early and Middle Miocene time that involved imbrication of a Cretaceous through Miocene stratigraphic sequence in the external nappes (Sandulescu, 1988; Fig. 2). This sedimentary section is tectonically detached from the basement upon which it was deposited, and records Miocene-age thin-skinned shortening of as much as 180 km (Roure et al., 1993; Ellouz et al., 1994). Neogene strata within the external nappes show a clear stratigraphic affinity with the East European and Moesian continental basement on which they now rest tectonically (e.g., Sandulescu, 1980). Final nappe emplacement in the Eastern Carpathians was mid-Miocene (11–9 Ma) in age, and was followed by continued compression and backthrusting in Pliocene time (Stefanescu, 1986; Sandulescu, 1988; Horvath and Cloetingh, 1996; Matenco, 1997; Matenco and Bertotti, 2000; Ciulavu et al., 2000).

Tectonic elements of the Carpathian system that are critical to the evaluation of competing geodynamic models for the origin of Vrancea seismicity are highlighted in Fig. 2 and include (1) the Cretaceous (Transylvanian) suture zone of the hinterland, (2) the crustal structure of the Transylvanian basin, (3) an enigmatic Neogene volcanic arc developed behind and on top of the fold and thrust belt, (4) foreland subsidence in the Focsani basin, (5) basement structure in the foreland as it pertains to active deformation there, and (6) Quaternary basins which are forming within the bend region of the Carpathian fold belt and hinterland.
Fig. 2. Geologic map of Romania (modified after Sandulescu et al., 1978), emphasizing (1) position of mid-Cretaceous suture zone (Transylvanides) in the Transylvanian basin, (2) late Tertiary volcanic arc (red) and (3) thrust nappes of Eastern Carpathians developed in Cretaceous to Miocene strata (green, orange, and yellow units) deposited on the East European/Moesian continental plates. Thrust deformation in the Eastern Carpathians was primarily Early to Middle Miocene in age. Locations of geologic sections in Figs. 3 (Section 1) and 4 (Section 2) indicated by heavy black lines. Sections A and B are deep seismic reflection profiles projected into the cross-section X–X′ (light grey) in Fig. 5.
Burchfiel (1976) and Sandulescu (1988) first suggested that a marginal ocean basin once occupied the area of the present-day Carpathian/Pannonian system. Evidence for closure of an ocean basin during Cretaceous time is preserved in ophiolites (Transylvanides) between the Southern Carpathians and northern Apuseni Mountains (Sandulescu, 1988; Royden and Baldi, 1988; Fig. 2). Using gravity and magnetic data, this ophiolitic complex was traced toward the NE beneath the Transylvanian basin and was interpreted to be the root zone of a Transylvanian nappe (Fig. 2; Sandulescu, 1980).

The case for closure of an ocean-floored basin in Miocene time is far less compelling. Scattered occurrences of Mesozoic mafic rocks occur along the inner (western) margin of the Eastern Carpathians, structurally above the crystalline basement rocks of the Getic and Supragetic nappes of the Eastern Carpathians (Fig. 2). Many studies have interpreted these mafic rocks as evidence for subduction of oceanic lithosphere during Miocene formation of the Eastern Carpathians (Balla, 1987; Sandulescu, 1988; Csontos et al., 1992; Csontos, 1995; Ratschbacher et al., 1993; Linzer, 1996). In turn, it is this putative Miocene slab that many workers now interpret as the source for Vrancea seismicity (e.g., Linzer, 1996; Wortel and Spakman, 2000). It remains unclear whether these rocks of oceanic affinity are rooted in the crust, or whether the eastern Transylvanian basin is underlain, at least in part, by continental crust of East Europe and Moesia.

Probably one of the strongest arguments for subduction of an oceanic slab beneath the Eastern Carpathians is the presence of a linear arc of Neogene volcanism within the hinterland (Fig. 2). This volcanic chain, comprised of both calc-alkaline and alkaline magmas, was active from Middle Miocene to Quaternary time (13.4–0.2 Ma), and migrated successively from north to south (Mason et al., 1998). Although major- and trace-element geochemistry of the calc-alkaline lavas suggest they are subduction-related (e.g., Pecskay et al., 1995; Mason et al., 1998), (1) this magmatic activity largely post-dated the final stages of deformation in the Eastern Carpathians, and (2) the volcanic chain actually crosscuts the surface trace of the putative Miocene subduction zone from which it was presumably derived (Fig. 2). Salters et al. (1988) offered an alternative suggestion that both calc-alkaline and alkaline lavas of the Carpathian hinterland could be derived from a single mantle source, and reflect differing degrees of crustal contamination.

Several hypothetical models for the geodynamic setting of the Vrancea zone have been posed, revolving primarily around variations on subduction of oceanic lithosphere. Numerous authors (e.g., Balla, 1987; Csontos et al., 1992) have suggested that oceanic lithosphere attached to the East European craton (Fig. 1) was subducted west- and southwestward along the entire Carpathian arc during Miocene time, and now coincides with the Vrancea zone. In this model, the subducting slab presumably began to progressively tear once thick continental crust entered the subduction zone at ~70 km depth (e.g., Wortel and Spakman, 2000). Alternatively, some authors (Linzer, 1996; Girbacea and Frisch, 1998; Mason et al., 1998) have proposed that the subducting basin was attached to the Moesian platform (Fig. 1), and was subducted northwestward beneath the Carpathian orogen. Subsequent large scale roll-back from NW to SE over a distance of ~130 km resulted in positioning of this detached slab with the Vrancea zone. Such a model is in agreement with (1) migration and diminution of Neogene calc-alkaline magmatism in the Eastern Carpathians from northwest to southeast along the arc (Mason et al., 1998), and (2) the NW-dipping geometry of the Vrancea seismic body (Girbacea and Frisch, 1998).

3. Discussion

Existing geological and geophysical data from the Eastern Carpathians and the adjacent foreland place critical constraints on the geodynamic setting of the Vrancea zone. Both surface and subsurface data along the length of the Eastern Carpathians argue that continental crust of the East European and/or Moesian platforms can be traced, as a minimum, beneath the external nappes, and above the locus of Vrancea seismicity. On this basis, any model explaining the origin of Vrancea seismicity must account for the existence of this seismogenic zone beneath continental lithosphere.

Shown in Fig. 3 is a geologic section through the frontal nappes of the Eastern Carpathians based on petroleum industry data (Dicea, 1996). Deep wells from this transect in the Moldova River valley (see Fig. 2 for location) penetrate deformed strata associated with the Tarcau, Marginal Folds, and Sub-Carpathian nappes, before sampling Cenozoic (Sarmatian and Badenian) and Mesozoic formations of the autochthonous cover of the East European platform. While the westernmost well on this section is situated more than 10 km west from the exposed thrust front of the Eastern Carpathians, the Mesozoic and underlying Paleozoic platform strata at depth appear to project considerably further to the west. Based on such data, it follows that the autochthonous continental basement on which these
strata were deposited extends a considerable distance westward beneath the external nappes of the Carpathians. Minimum figures reported by Dicea (1996) are 20 km in the Moldova Valley, and 30 km in the Bistrita and Trotus valleys further to the south. Unfortunately, such seismic and well data sampling the rocks beneath the external nappes near the Vrancea zone are not currently available. Given the highly cylindrical structure of the Eastern Carpathians, however, projection of this crustal configuration southward along orogenic strike seems reasonable. While this projection is admittedly more than 200 km removed from the Vrancea zone, the surface geology exposed within the nappes of the Eastern Carpathians is remarkably laterally consistent, and implies a continuity of geologic structure since Mesozoic time. Similarly, the stratigraphy of the Cretaceous to Miocene stratigraphic section exposed in the Eastern Carpathians is quite continuous along strike (Contescu, 1974). Faults such as the Trotus fault have been interpreted as major crustal boundaries within the Carpathian foreland (Matenco, 1997; Tarapoanca et al., 2003), but such structures are not manifest in either the stratigraphy or structure of the external Carpathian nappes (Fig. 2), implying that the basement upon which these strata were deposited and subsequently emplaced behaved uniformly along strike. As shown in Fig. 3, projection of Dicea’s (1996) section, controlled by well penetrations of the autochthonous basement of the East European platform, implies continental crust lies both updip of and above the steeply northwest dipping Vrancea zone.

In the central portion of the Eastern Carpathians, Burchfiel (1976) produced a palinspastic reconstruction of deformation, extending from the autochthonous platform in the east to the crystalline thrust nappes (Bucovinian) exposed in the hinterland (Fig. 4). While no one thrust nappe contains the entire Cretaceous to Tertiary sequence, a contiguous stratigraphic section from Late Cretaceous through Pliocene age can be reconstructed across the successive nappes of the Eastern Carpathians. Of critical importance are the observations that (1) this stratigraphic section can be tied to Neogene strata that were clearly deposited on the autochthonous continental platform, and (2) such stratigraphic continuity across the Eastern Carpathians appears to preclude a significant intervening basin floored by oceanic crust during Neogene time. Published seismic reflection sections at this same latitude (Dicea, 1995) image the platform stratigraphy extending a minimum of 10 km (and presumably much further) westward beneath the frontal edge of the Sub-Carpathian nappe. Furthermore, Burchfiel’s (1976) section results in an estimate of ~125 km of shortening...
Fig. 4. Palinspastic reconstruction (below) through central portion of the Eastern Carpathians (modified after Burchfiel, 1976), based on W–E structural cross-section (above). Reconstruction is pinned at eastern end, within the autochthonous crust of the East European craton. A contiguous Cretaceous to Pliocene stratigraphic section can be traced from the autochthon to the western end of the section (crystalline Bucovinian nappes) without interruption. See Fig. 2(Section 2) for location.
within the central Eastern Carpathians, implying that at the latitude of this section, crust of continental affinity extends a similar distance westward beneath the Eastern Carpathian nappes. While the rocks of the Ceahlau nappe may be an exception, it is certainly plausible on the basis of this analysis that East European and/or Moesian continental crust projects tens of kilometers west of the current known extent, and did so prior to shortening in Miocene time.

As with the exposed stratigraphy and shallow geologic structure of the Eastern Carpathians, the crustal-scale structure of the Carpathian foreland provides additional constraints on the origin of Vrancea seismicity. Deep seismic reflection data from the Carpathian foreland (Ramnicu Sarat profile) and the Transylvanian hinterland (Targu Mures I profile) are combined in a lithosphere-scale cross section across the Vrancea zone (Fig. 5; see Fig. 2 for location). While some dipping structure is evident at the basement-cover contact within the deep Focsani basin, crustal fabrics and structure at the Moho are comparatively sub-horizontal, and inconsistent with a significant bending of the crust into the Vrancea seismic zone. Indeed, strata presumably deposited on continental crust (based on palinspastic reconstruction of the fold and thrust belt) occupy the high topography of the Eastern Carpathian directly above the Vrancea zone. While it may yet be permissible that the continental crust imaged by these deep seismic data in the foreland rolls over essentially vertically into the adjacent Vrancea zone (Fig. 5), such a geometry does not appear consistent with geologic data presented here.

Based on these geological and geophysical observations, three contrasting models have been or can be posed for the geodynamic setting of the Vrancea region (Fig. 6): (A) oceanic slab break-off and retreat, (B) oceanic slab subduction within the foreland, and progressive lateral tearing of the slab, or (C) lithospheric delamination due to continental underthrusting and orogenic thickening. Each of these envisions a relatively cold and dense body of lithospheric material that is presently situated in the upper mantle beneath the bend region generating seismicity in the Vrancea region. The first two models require subduction of oceanic lithosphere to explain Vrancea seismicity, and can be distinguished on the basis of where the proposed subduction occurred within the orogen, and how the subducted slab evolved (break-off and trenchward re-

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**Fig. 5.** WNW–ESE transect (~320 km) along cross-section X–X’ showing interpreted crustal structure above Vrancea zone (hypocenters in black dots). Topography across the profile (above) shown in m, and depth below sea level (below) shown in km. Insets show industry (Targu Mures I) and reprocessed (Ramnicu Sarat) versions of deep profiles (A and B in Fig. 2; sections plotted ~1:1 at 6 km/s). Moho beneath Carpathians determined from refraction and gravity modeling (Radulescu, 1981).
Fig. 6. 3-D perspective lithosphere-scale block models (view towards NNW), illustrating contrasting scenarios for geodynamic setting of the Vrancea zone. (A) Oceanic slab subduction and break-off. (B) Oceanic slab subduction and progressive lateral tear within the Carpathian foreland. (C) Continental lithospheric delamination. Green = Moesian/East European crust; yellow = Transylvanian crust; pink = continental mantle lithosphere; purple = oceanic lithosphere; grey = asthenosphere. Vrancea zone is located in lower front corner of models. See text for discussion.
treat vs. migration of a lateral tear along the orogen). The third model could be generated through closure of an intracontinental basin and lithospheric thickening, and does not require the former presence of an ocean-floored basin, or the subduction of oceanic lithosphere.

Each of these models has implications for the associated crustal structure, and is readily testable through integration of surface and subsurface observations. In particular, if an ocean-floored basin was consumed during the formation of the Eastern Carpathians, evidence for the former boundary between two distinct continental plates should be recorded in both the surface geology (suture zone) and the underlying crustal structure. The predicted position of such a boundary differs by more than 150 km in the two subduction models (Figs. 5 and 6A and B). To date, no conclusive evidence has been documented for such a crustal (and lithospheric) boundary in either position. Furthermore, the tectonic affinity of Neogene strata exposed in the Eastern Carpathians should be diagnostic. Models A (slab break-off) and C (continental delamination) clearly imply an East European/Moesian crustal affinity for these Neogene age strata, whereas model B (slab tear model) requires that these strata were separated from the East European/Moesian margin by an intervening ocean-floored basin.

Although widely accepted in the scientific literature, the subduction model for the Vrancea zone presents several clear weaknesses. The Vrancea zone, if now represented by a remnant slab, does not coincide updip with the surface expression of a suture zone. Similarly, Neogene volcanism west of the Eastern Carpathians occurs in such close proximity (<50 km) to the zone of modern seismicity (Fig. 2) that any subducting slab would not likely be at depths to dewater and induce melting of the overlying mantle. Vrancea zone earthquakes are located beneath the external fold and thrust belt and the adjacent Focsani depression. Furthermore, eruption of Quaternary alkaline basalts in eastern Transylvania appears to be unrelated to subduction volcanism. Mason et al. (1998) appealed to late-stage slab break-off and asthenospheric upwelling to generate these basalts. Perhaps most importantly, if such a detached slab is present, it did not sink vertically through the mantle, but moved by ~130 km horizontally to the southeast relative to the suture zone identified in Transylvania. Moreover, development of extensional sedimentary basins of Miocene–Quaternary age in the vicinity of the Vrancea zone, as well as extensive development of uplifted fluvial terraces in the foreland, would appear to be at odds with subduction geodynamics.

While continental delamination was proposed as a mechanism to produce mantle seismicity in the Alboran Sea (Seber et al., 1996; Mezcua and Rueda, 1997), Vrancea zone seismicity has not been widely viewed in this light. Some workers (Csontos, 1995; Girbacea and Frisch, 1998; Gvirtzman, 2002) have appealed to foundering of lithospheric mantle as the final stages of slab subduction beneath the Eastern Carpathians, but these models still require the consumption of oceanic lithosphere in Miocene time. A number of observations appear consistent with active delamination of continental mantle lithosphere in the southeastern Carpathians including: (1) the narrow, cylindrical shape of the seismogenic zone, and implicitly, the lack of a well-defined Benioff plane, (2) the miscorrelation of hypocenters (spatially) and volcanism (both spatially and temporally) with the expected position of a “normal” descending slab (Girbacea and Frisch, 1998), (3) the eruption of Quaternary alkali basalts in the vicinity of the Vrancea zone, (4) the presence of an aseismic gap between 40 and 70 km depth, with low P-wave velocity (Fuchs et al., 1979; Oncescu, 1984; Lorenz et al., 1997; Fan et al., 1998), and high attenuation (Q; Mocanu et al., 1999), (5) a weak zone beneath the crust based on lithosphere strength modeling (Lankreijer et al., 1997), (6) the late Miocene to Pleistocene subsidence of the Carpathian foreland basin in the absence of major surface loads (Artyushkov et al., 1996), (7) the development of Quaternary extensional basins in the vicinity of the Vrancea zone (Ciulavu et al., 2000), and (8) active deformation in the Carpathian foreland, concentric about the locus of Vrancea zone seismicity, and recording displacement rates of up to 15 mm/yr.

To a first order, the presence or absence of a through-going, dipping crustal fabric beneath the purported Miocene suture would alternatively substantiate or eliminate the subduction-model origin for Vrancea seismicity. Similarly, demonstration of a geometric association of foreland deformation with the Vrancea mantle source region would imply a mechanical coupling of the Vrancea seismogenic body with the overlying crust, and hence argue against a detached slab. Deep seismic reflection data are uniquely suited to address these competing hypotheses by providing a high-resolution image of the structural geometry of the crust, and a direct link of surface geology to upper mantle seismicity.

4. Conclusions

The origin of intermediate depth seismicity in the Vrancea zone of Romania continues to be a subject of
debate. While most workers consider that the Vrancea seismogenic body consists of oceanic lithosphere, either resulting from detachment and lateral migration of an oceanic slab (e.g., Girbacha and Frisch, 1998; Gvirtzman, 2002), or subduction and lateral tearing of a slab beneath the eastern edge of the Eastern Carpathians (e.g., Wenzel et al., 1998; Wortel and Spakman, 2000), such interpretations appear to be inconsistent with geologic constraints from the Eastern Carpathians and adjacent foreland. In particular, petroleum exploration data document that crust of continental affinity extends significantly westward beneath the external thrust nappes (Sub-Carpathian, Marginal Folds, and Tarcau) of the Eastern Carpathians. In addition, Neogene strata of the Eastern Carpathians can be reconstructed much further westward to a position now occupied by the Transylvanian basin. Finally, geologic structure in the Carpathian foreland (including the Moho) is sub-horizontal directly to the east of and above the Vrancea seismogenic zone. Taken together, these geologic relationships imply that the Vrancea zone occupies a region overlain by continental crust and upper mantle, and does not appear to originate from a subducted oceanic slab along the length of the Carpathian orogen.

An alternative model for Vrancea zone seismicity, proposed here, involves active continental lithospheric delamination, resulting from Miocene closure of an intra-continental basin and attendant lithospheric thickening. Such a model is consistent with the presence of seismicity beneath thick continental crust, including the foreland of the Carpathian system, and honors surface and subsurface geologic constraints that appear to preclude the presence of remnant oceanic crust in Tertiary time in the region.

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