Geodetic Signs of the Recent Kinematical and Geodynamical Deformation of the Carpathian Arc

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Abstract. Up to now, 4 to 5 models have been presented describing the development of the Carpathian-Pannonian region in terms of subduction processes that took place during the tertiary. All these models are limited to the period between the Paleocene and the Pliocene. None of these, however, explains the Quaternary and Recent phenomena in relation to the post-subduction stage. Several neotectonic models refer to the development of basaltic volcanism [53] or Quaternary basins in the south-eastern part of the Pannonian basin. However, the latest geodetic measurements based on GNSS monitoring show a significant kinematics of the internal Carpathian blocks and considerable vertical movement tendencies in the Transylvania, Moldavian and Romanian parts of the platform. The question is the cause of these phenomena and how they are related to earlier processes of subduction. The answer can be found in a comprehensive analysis of geodetic and geophysical data. The main reason for such effort is aspiration to isolate the residual segment of the subduction plate located under the Transylvanian region. The article presents derived geodynamic model based on the combination geodetic with geophysical data, which explain the kinematical tendencies in the eastern and southern Carpathians.

1. Introduction

The paper describes the development of the Carpathian-Pannonian region, from the point of view of the post-subduction processes that took place during the Recent period. All Geodynamical Models Pannonian-Carpathian area (delamination/break off) are limited to the development of the Pannonian to the Pliocene period - Figure 1. None of these, however, explain the Quaternary and Recent phenomena in relation to the post-subduction stage. Several neotectonic models refer to the development of basaltic volcanism [53] or Quaternary basins in the south-eastern part of the Pannonian Basin. However, the latest geodetic work based on GNSS monitoring shows a considerable kinematics of the internal Carpathian blocks and considerable upward tendencies in the area of Transylvania, the Moldavian and Pannonian parts of the platform.

Question arises what is the cause of these movements and how they are related to the earlier subduction processes. The answer can be found in the complex analysis of geodetic and geophysical...
data. The article presents some geodetic data and derived models in combination with geophysical data that explain recent movement tendencies in the area of the eastern and Southern Carpathians. The main cause compared to previously published models can be seen in the uplifting of the residual segment of the subducting plate that remained after the deep seated slab, located under the Transylvanian region.

Figure 1. The Carpathian model of the “roll-back” subduction, “break-off” destruction of the lithosphere and following “rebounding” interpreted from geological-geophysical data [36], [35]

Legend: Scheme of ALCAPA and TISZA Units (green) – Alps (blue color), Inner Western Carpathians (red) and Drauzug-Bükk Units with Gémer Paleozoic; 1—platform, 2—foredeep, 3—a) last stage of foreland basin deposition (in Ma), b) last thrust movements of the Outer Carpathians (in Ma), 4— a) areal volcanisms with ages (roll-back), b) linear volcanisms with ages (tear break-off), 5—ophiolite complex, 6—final (basalt) volcanism, 7—high conductive boundary, 8—anomalous trends of recent vertical movements, 9—pre-Cenozoic complexes and the Outer Carpathian units, 10—sources of magnetic anomalies from the pre-tertiary subsurface, 11—axis of abscission of subducting oceanic lithosphere, 12—13—delineation of remaining parts of oceanic lithosphere (rCFB), 14—deepest parts of foredeep, 15—principal fracture zones, 16—foci of earthquakes with magnitude 5–8

2. Geotectonic model of the modelled area
The main evolutionary stages of the subduction-collision process leading to the development of the Carpathian arc are as follows. The western (Alpine) part of the Alpine–Carpathian convergent system underwent a change from subduction to collision during Eocene. The end of the subduction was accompanied by a break-off of the subducting oceanic slab and by a break-off-related volcanism of the Eocene–Eggenburgian age (43–19.7 Ma). The break off propagated eastward. Collision in the Alps was synchronous with the closure of the main Tethyan Ocean in the Alpine–Carpathian region. The rCFB was the only leftover of this ocean, left in front of the overriding plate to the east of the colliding Alps.
The eastward propagation of the slab detachment continued from the Alps into the area of the rCFB
(Figure 1), which was affected by subduction since the early Miocene. From the late Oligocene to
middle Miocene, crustal wedges, moving eastward from the Alpine collision zone, became parts of the
Carpathian–Pannonian overriding slab. The rCFB underwent passive subduction, characterized by
passive sinking of the slab under its own body forces, steep dip of the subducting slab, strong
hinterland extension, extensive areal magmatism and Asthenosphere up-welling in the orogeny
hinterland. The subducting slab break-off ran along the whole Carpathian arc, from the early Miocene
to its present position in the bend between the Eastern and Southern Carpathians (Figures 1 and 2).

The synthetic interpretation of geophysical and geological data on the Carpathian–Pannonian
region allows us to define [43], [46]:

- the present-day subduction zone, which is located to the west of the Vrancea region
- the area above an up-welling asthenosphere located in the overriding slab, indicated by the
  extent of the intermediate calcalkaline areal magmatism, positive heat flow anomalies and
  positive anomalies in a stripped gravity map [6], [7], [36], [44]
- a location of the slab break-off, roughly indicated by linear intermediate volcanism
- an approximate location of the passive continental margin, interpreted from magnetic
  anomalies which have different character for the platform and orogeny and from the high-
  conductivity zone that outlines the whole Carpathian arc.

Figure 2. A lithospheric cross section based on the geophysical data combined with the Tertiary
model of the Carpathian subduction (modified after [35]). Location of the section is at Figure 4 (heavy
lines). Above a part of current measured quantity (all information) lower part – model of
development, [35]
The slab break-off-related linear volcanism terminates about 50 km north of the Vrancea seismoactive area, having Holocene age. Some of data (specially magnetotelluric - MT) indicate that the subduction hinge zone could be as far to the west from the Vrancea zone as along the Gutii–Apuseni–Vardar line, but these speculations requires further elaboration. The subducting oceanic slab underneath the Southern Carpathians is attached to the Moesian Platform, further along the arc as the youngest age.

3. Geodetic data – subsidence or rebounding

In this paper we are using the homogenized velocity fields available from various national and regional GNSS geo-kinematics projects and an attempt to evaluate with regards to geophysical and geological data from chosen areas. Important role plays also the data of the Recent Vertical Movements (RVM) processed for area of the Central Europe by [28], [44], [62], [64] and [30] (Figure 3).

3.1. GPS data

Since 1994 the region of Carpathians and Pannonian Basins is subject to regular monitoring using the GPS technique. Initially, the epoch campaigns on annual basis were performed. Later a set of permanent GPS stations was progressively established. Recently the region is covered by several epoch networks and by tens of permanent GPS stations. The epoch and permanent sites have served originally for different purposes (geodesy, geokinematics, local deformation areas, etc.). The repeating period of observing campaigns was not uniform, and the instrumentation and equipment were subjects of gradual changes. Therefore, simple gathering of published data does not provide site coordinate time series, which can be treated as fully homogeneous and mutually compatible. Moreover, the analysis software, GPS modelling and coordinate and velocity adjustment procedures were developing gradually. The time series which were analysed using a specific strategy are not fully consistent and have serious discontinuities.

3.2. Combination of regional and local horizontal velocity fields.

The method for alignment of individual local or regional networks to the reference velocity field applied in [22] (Figure 3) is based on the adjustment of Euler pole and angular velocity of rotation for horizontal velocities of a set of identical points in the pairs of networks. Consecutively, the adjusted parameters are used for transformation of the velocities at non-identical points to the common reference. The feature of RVM in the Carpathian region can be described as follows. The same is true for the Carpathian arc generally undergoes or uplifts the Apuseni Mountains and mountainous areas in Hungary. The Great Hungarian Plain, the Little Hungarian Plain and also the Transylvanian Basin show significant subsidence. The uplift tendencies of the Alps extend into the south-western part of Hungary.

The largest vertical movements are observed in the triangle area among the towns Chernivtsi, Belgrade and Bucharest (Figure 3). In this area, which comprises the East Carpathians and adjacent margin of the East European and Moesian platforms, the uplift reaches up to 6–7 mm/yr whereas the Northeastern Carpathians are undergoing an uplift of up to 4.4 mm/yr.

3.3. The Recent vertical movements

The vertical movement tendencies are presented in the map of RVM of the Central European region (Figure 3), which has been compiled from the published maps and data from several sources. The main source comes from [28] in [44], which represents the 20 years of repeated precise levelling measurements. The Western Carpathians and Bohemian Massif areas were evaluated on the basis of the RVM maps and the results from [62], [60], [30] and [64].
4. Methodical, analysis and data interpretation

The present-day geophysical data on the Carpathian–Pannonian lithosphere have the following characteristic features (Figure 2). Details about the data can be understood from the Tran-Carpathian cross-section. This cross section, runs from the Polish part of the West European Platform to the East European platform, crossing the Pannonian Basin system, the Apuseni Mountains, and the Transylvanian Basin. It indicates a thermal erosion of the platform margins, which are in contact with the overriding orogeny formed by the Carpathians in its front and the Pannonian Basin system in its hinterland. The thermal erosion is documented by the heat-flow map [44]. It is also indicated by increased depths of the L/A boundary interpreted at different depth either levels from seismological or magnetotelluric data [37]; [59]; [4], which react to increased temperature differently. Seismological interpretations assume that a depth of the peridotite melting isotherm coincides with the zone of the P-wave velocity decrease or the change in the S-wave velocity, whereas magnetotelluric interpreters put this isotherm at a zone of the electrical conductivity increase [5]. During last decade the new interpretation approach for determination of the continental lithospheric thermal structure has been applied along regional transects [66], [14]. This approach is leading to different results from the seismological one. Even though these results are compared with gravity data, our approach to interpretation of gravity data in the Western Carpathians do not confirm lithospheric thickness 130-150 km below the Western Carpathians. This discrepancy between both opinions is one of the import problem for solution lithosphere in the Carpathian territory.

Figure 3. Intraplate velocities obtained from combination of regional and local velocity fields [22] and the map of the Recent vertical movement tendencies (RVM) compiled, from [44], re-arranged and complemented by the latest results of the horizontal and vertical velocity vectors from the GPS measurements. Area influence of the rebounding process is shown by white circle. Radial extension movements, with dominant southern tendency, are provoked by rebound of the remnant oceanic lithosphere (rCFB) combined with a uplifting of marginal parts of continental lithosphere represented by EEP and Moesian platforms.

An interesting comparison emerges when we overlap

- the heat-flow map [44],
- the crustal thickness maps derived from gravity data and gravity data stripped off the sediment effect [6], [7], [8]; [58]; [44],
- the map of recent vertical movements [42],
• the lithospheric thickness map compiled from MT and seismological data (Figure 4 – [5], [37], [38], [56], [57] and [61]), and
• the map with contour of the ALCAPA and Tisza–Dacia units.

This comparison indicates that the ALCAPA unit roughly overlaps with the thermally active part of the Carpathian–Pannonian region and areas of thinnest crust determined from both types of gravity data. The larger part of the Tisza–Dacia overlaps with the area of the cooler heat flow, with the extent of the normal to thicker crust and with the area affected by recent uplift.

This correlation documents a different origin and development character of the ALCAPA and Tisza–Dacia units. The thinnest lithosphere is present in the Pannonian area overlapping with the ALCAPA unit. It forms two minima of 60 km separated by an elongated area of normally thick lithosphere (100–120 km) located between Budapest and Košice [37]. A lithospheric root is developed only in two areas: in the Eastern Alps along the northern boundary of the ALCAPA unit and in the Southern Carpathians along the southern boundary of the Tisza–Dacia [37].

The lithosphere bellow ALCAPA unit with thinned crust can be further characterized by
• high seismic velocities [9]; [59]; [41],
• by high conductivities [44], [5], and
• by the occurrence of the extensive and continuous volcanism that lasted from early Miocene to Pliocene–Quaternary [40].

Figure 4. Overview of magnetotelluric profiles in Central Europe. Heavy dotted line represents MT profiles at Figure 2, thin grey lines in Poland – proposed profiles. Map is supplied by the model of the thickness lithosphere compiled by authors on the base of seismological [37] and magnetotelluric data (based on the geometric mean of the depth values derived from Rhomax and Rhomin Pannonian Basin, [5].
The crustal thickness below ALCAPA unit reaches values of 22–25 km [65]; [58]. It is characterized by a large number of extensional basins, belts of magnetic anomalies [26] and high values of the gravity field [58]. The whole Pannonian region overlapping with the ALCAPA unit is characterized by relatively high values of the heat flow [15]; [13]; [38]. The Outer Carpathians of the ALCAPA have heat-flow values lower than other ALCAPA regions [10]. All these properties characterize the ALCAPA unit, which experienced a lateral extrusion from the ancestral Eastern Alpine realm and travelled as far as to the contact with the West and East European platforms in Poland and Ukraine.

In comparison to ALCAPA unit the lithosphere below the Tisza–Dacia unit, including areas of the Apuseni Mountains, the Transylvanian Basin, and the Eastern and Southern Carpathians, can be characterized by variable thickness of crust [65]; [58], lower values of gravity field [58] and lower heat-flow values [10]. Furthermore, higher seismicity is in its southeast corner Zsíros in [42] where its lowest heat-flow values are recorded in the Transylvanian Basin [10]; [13]; [38]. A broad zone along its contact with East European and Moesia platforms, including also Apuseni Mts., undergoes characteristic uplift movements Jóó in [42].

All these properties characterize the Tisza–Dacia unit, which did not experience the level of extension and large-scale faulting comparable to the ALCAPA unit but only underwent a large clockwise rotation during the later stages of its movements – Upper Miocene to Recent [32]; [38].

4.1. The Magnetotelluric Data - Conductivity boundary

The high conductivity layer, determined from MT data, is one of the most important constrains on presence and character of Lithosphere/Asthenosphere (L/A) boundary. The high lithospheric temperatures and the top of the conductive layer in the mantle can be associated with that of the Asthenosphere of low seismic velocity [1], [3]. This relation is clearly shown by an empirical relation between the depth of the conductive Asthenosphere and the regional heat flow values [3]. That is, magnetotelluric data suggest thin and hot lithosphere below the Pannonian Basin.

In the Carpathian-Pannonian region this L/A boundary was interpreted at 50-60 km depth [2] in Pannonian Basin and at 100-150 km in the Western Carpathians [39]; Kucharski P., pers. com.. The boundary reaches a depth of 140 km in the Bohemian Massif and 200 km in East European Platform [59].

There is a high conductivity layer present at a depth of 100 km in certain parts of the eastern Bohemian Massif [39]. It correlates with low velocity zone detected by seismological analysis. This high conductivity layer disappears at the contact of Bohemian Massif with Western Carpathians. Another high conductivity zone exists underneath the Rimava-Lučenec Depression, at the contact of the Pannonian Basin and the Western Carpathians, at a depth of 40/50 km [61]; [3].

Most recently, a Top of Asthenosphere map has been constructed for the Hungarian part of the Pannonian Basin [5] with the aid of new very deep magnetotelluric soundings. Map clearly shows a deepening of the Asthenosphere towards the Carpathians, the Eastern Alps, the Variscan Europe and East European Platform. On the basis of this map and seismological model of [37], the new map of the lithospheric thickness has been constructed (Figure 4). The MT data suggest much higher position of the Asthenosphere and active role of the upper mantle in Pannonian basin. Its extension to area of the Apuseni and Transylvanian Depression very well correlates with positive anomaly in the stripped gravity map, heat flow data and support the interpretation of slab break offs model with rebounding part of separated rCFB lithosphere.

The next important linear conductivity feature is located at the contact of the Carpathian orogeny with the Eastern European platform. The systematic investigation of the areal distribution of geomagnetic field variations with several minutes to 2 – 3 hour periods [27]; [47] in the Western Carpathians and 20-minute periods in the Eastern Carpathians [51] revealed two important conductivity zones with zero variation of Z-component of the geomagnetic field (Figure 4). The conductivity zone follows the Carpathian arc. The conductor lies at a depth of 16 – 26 km [51]; [47].

For the analyses of the supposed rebounded area in the Eastern and Southern Carpathians, important MT data were gained by [56], [55], [57]. The MT profiles 2T, PBN, H and C (Figure 5 and Figure 6)
have been used for demonstration of the conditions in space where the rebounding process of lithosphere is interpreted.

5. Discussion
The southeastern corner of the Carpathian Mountains in Romania provides a unique opportunity to study the very final, short-lived stage of plate convergence when a plate of subducted lithosphere finally detaches from the upper rigid parts and begins to sink into the mantle. Research efforts commonly focus on trying to image the cold lithospheric slab (topographic techniques) and on trying to understand the tearing process from the earthquakes it generates. We should like to concentrate on answering the question - Where is the problem and which data can be used to prove the rebounding process? The answer can be found in following results and conclusions:

- Sedimentary and volcanic development in space and time enable to determinate the effects of the gradual break off of the remnant oceanic plate and simplify earlier complicate subduction models (e.g. [45], [11]; [31], [35].
- This is in agreement with the spreading, movement and break off of the subducting slab (Compare with the modified model of [54]).
- Upper Badenian and younger sedimentary depocenters and existence of so called a flexural fore-bulge ([35], [29]) in foredeep and marginal parts of platform indicate former bending of the subducting lithosphere on its margin, their destruction probably indicate reality, that drawing in of the fore-bulge zone to the orogeny matches to the detachment of submerged part of plate. E.g. there is possible to estimate that time between origin of the lithosphere fracture and followed linear volcanism is about 1,6 mil years!!
- Migration of the linear intermediary volcanism represents trend from W to E [36], [35], [40]. Recent position of the Late Miocene - Quaternary intermediary volcanism that finished is approx. 100 km from the Vrancea area.
- The Vrancea earthquakes are located in the continental lithosphere and mainly in very narrow zone 40 x 50 km [35], [16], [21].
- Breaking off the subducted plate is replaced by compensation and balancing of the rebounded parts of passive continent with remnant oceanic plate and combined with the intensive thermal heating of the Pannonian basin area where income the new lithosphere (Figure 2).
- Depocenters of the Pliocene – Quaternary basins (Békes, Makó basins, Jászág, Derecske and next) with their perpendicular orientation to zone of rebounding give evidence that to subsidence help wrenching of the Eastern margin of Pannonian basin to horst and graben system [24], [25], [12] by rapid uplifting of the zone Gutii - Apuseni – Turnu Severin (the W margin of the rebounding area).
- In addition, such interpretation is supported and indicated by the gravity and MT data interpreted as uplifted mantle masses in centers of this depression [42], [8] – Figure 4).
- Recently on the bases of geodetic data (GPS, RVM), the effects of the rebounding can be observed and interpreted too (see Figure 3 – [28], Joó, in [44], [22].
- The topography of southeast Carpathians is extremely low considering the crustal thickness in comparison with other mountains (e.g. the Apennines, the Alps – see [18]). Although the crust there is almost as thick as the crust of the Alps (50-55 km), the elevation is less than one half of the elevation of the Alps.

There are few following features that could be analyzed in more detail, e.g. seismologic studies indicate that the cold mantle body under the southeast Carpathians is already partly detached from the subducting lithosphere and its position could be located from seismological and magnetotelluric data in continental lithosphere [36], [59].

A particularly interesting finding is that the seismically active region is shifted ~ 100 km east from the place of maximum pull-down, indicating that lithospheric tearing is now occurring at one side of
the detaching root and not above it. This interpretation is consistent with that of [18] who introduced the idea of lateral delaminating of the lower lithosphere.

Figure 5. The location of the studied MT profiles supplied by movement tendencies, risk tectonic zones and recent uplifted blocks. Profile H and C is at Figure 2 and 4. Explanations: 1- Platform, 2- Foredeep, 3- Inner Neogene molasse, 4- Neovolcanics, 5- Ofiolite, 6- area of maximal rebounding, 7- axes of supposed slab break off, 8- transcurrent tectonic zone, 9- Heigh Conductivity zone, 10- areas with maximum of recent vertical movements, 11- direction of block movement, 12- Latest Miocene-Quaternary (6-0 Ma), 13- Quaternary active fault, 14- Quaternary –Pliocene sedimentary centres, 15- axes of anticline, 16- MT profile

Figure 6. The elements of the rebounding process interpreted along the Magnetotelluric profiles H and C. Location of profiles see at Figures. 4, 5.
6. Conclusion

The Vrancea segment is located below outward migration orogeny, which is blocked by the collision with the eastern European continental crust, resulting in uplift as evidenced by fission-track data [52] and geodetic data [28]. In this case, however, evidence concerning the action of a slab pull force can be found in the focal mechanisms of the intermediate depth earthquakes. As were presented in the past by many authors e.g. [16], [63], [35] they uniformly exhibit nearly vertical tensional axes [48], which favors a continuous slab at least down to the maximum focal depth of nearly 200 km. The pull force required to produce the tension is provided by the corner effect of environment where remnant part of slab balance strain during rebounding. This seismoactive zone of Vrancea is relatively very narrow zone (40 x 60km) and presents in the tomographic images at depths between about 60 and 350 km only on sections [63]. Other results [20], [21]; did not confirm this conclusion ambiguously.

The deformation field, as deduced from the available fault plane solutions [48], is drastically reduced in the crust, where the maximum magnitude is below 6.5 (except Shabla zone, in Bulgaria). The system of major faults developed in a NW-SE direction in the Carpathians foredeep area is certainly linked to the subduction process in Vrancea, although they seem not to play a significantly active role, as could be expected for an active subduction process. The existing data indicate an extensional deformation regime over the foredeep area and Southern Carpathians, while a predominant compressive regime is outlined at the contact between the eastern margin of the Pannonian Depression and Carpathians orogeny, in agreement with the bending tendency of the maximum horizontal compression orientation of the crustal stress field from NE-SW, in western and central Europe, to E-W, in the intra-Carpathian region [17].

Most authors prefer process delamination, but without more detail specification. In the Carpathian arc, slab detachment is nearly completed; only for the Vrancea region is necessary to find better solution after our meaning. It can be conclude for the Carpathian arc as a whole, that migrating slab detachment is in its final stage but its position is probably bellow Apuseni ("Apulian block"). Slab detachment is after [63] the natural last stage in the gravitational settling of subducted lithosphere in a terminal stage subduction zone. We consider to be necessary to take into account the post subduction process. The Vrancea seismoactive structure is combined with processes in block among the tectonic zones - Peceneaga-Camera, Trotus a Intramoesian [33], [34] and is broadly consistent with models based on either delamination of mantle lithosphere or lithospheric gravitational instability occurring beneath the SE corner of the Carpathians [49], [50].

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