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THE MAGMATIC ARC OF THE EAST CARPATHIANS: DISCUSSION AND A PROPOSAL FOR INTERPRETATION[1)]

(1 Fig.)

Łuk wulkaniczny Karpat Wschodnich: dyskusja i propozycja interpretacji

(1 fig.)

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A b s t r a c t: Geotectonic evolution of the magmatic arc of the East Carpathians has been discussed in relation to the plate tectonic model. The eruptive arc formed as a result of subduction proceeding from the east to the west. The subducted plate (100 Ma) was dismembered and lost a lithospheric slab (65 Ma). 35 Ma ago a new subduction below the western plate took place, being followed by the formation of the Moldavian Nappes. The slow moving lithospheric slab arrived in the melting zone (20 Ma) and caused the ascent of magmas (18 – 1 Ma). The sunken lithospheric slab, not yet consumed by the asthenosphere, produces Vrancea earthquakes.

K e y w o r d s: magmatic arc, plate tectonics, East Carpathians

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T r e ś ć: Na podstawie modelu tektoniki płyt przedyskutowano ewolucję geotektoniczną łuku wulkanicznego Karpat Wschodnich, będącego wynikiem subdukcji płyty Morza Czarnego pod płytę europejską. Subdukcja, zapoczątkowana 100 Ma temu, doprowadziła do pogrążenia krawędzi płyty wschodniej (35 Ma), a następnie pod płytą zachodnią uformowała się kolejna strefa subdukcji. Pogrążająca się powoli krawędź płyty osiągnęła (20 Ma) strefę przetopienia, powodując rozwój magm (18 – 1 Ma). Pogrążony fragment litosfery, nie zasymilowany przez astenosferę, stanowi strefę generowania wstrząsów sejsmicznych w regionie Vrancea.

One of the first applications of global tectonics to Europe was connected with the volcanic arc on the inner border of the East Carpathians, related to the subduction of the Black Sea plate under the European plate (Roman, 1970a, b). The

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presence of an andesite type volcanic arc behind a folded belt ("behind" with respect to the direction of the fold vergency) left no room for doubting the existence of a subduction zone here. Many Romanian (Bleahu *et al.*, 1973, Bleahu, 1974, 1976; Hertz and Savu, 1974) and foreign geologists (Bocaletti *et al.*, 1973a, b; Szadeczky-Kardoss, 1973, 1974; Balla, 1979; Burchfiel, 1980) supported this idea. Some authors, however, doubted as to the existence of a subduction here, without providing another valid explanation for this volcanic arc (Książkiewicz, 1977; Trunkö, 1977).

The strongest argument in favour of the existence of a subduction in the East Carpathians is the presence of the Vrancea seismic area in the Carpathian orocline zone. It is marked by earthquakes of medium depth (up to 200 km) that can only be interpreted in connection with a Benioff plane. The first to make a connection between the Vrancea earthquakes and the subduction was Roman (1970), whose idea has been developed and improved by Constantinescu *et al.*, (1973), through the construction of a slab containing the hypocentres. A 55 – 60° west-dipping slab was thus obtained, its upper end being situated east of the Siret river and the lower one beneath the Vrancea Mountains. If the Benioff plane means a plate margin, the plane generating earthquakes can only exist beneath the Moldavian platform. The continuity of such a plane is geologically and geophysically proved by boreholes, from beyond the Dniester till deep under the East Carpathian nappes. This continuity cannot be splitted by arbitrary creation of two collisional plates.

The earthquake of March 4, 1977 revealed the discontinuity of the Benioff plane (Müller *et al.*, 1978) which presents a gap at a depth of 30 – 80 km. This fact is interpreted as having been caused by a breaking of the subducted slab, a detached and isolated block of which was left at a depth of 60 – 160 km, and underwent assimilation by the mantle. It is worth noting that the focal mechanism of the fault plane is that of underthrusting, from the SE towards NW. We can suppose, however, that the movement is a present-day one and that it is determined by vertical sinking of the block during its assimilation. Hence, it does not reflect active horizontal movements of some plates. The Benioff plane belongs to a palaeosubduction zone that ceased to exist long time ago.

What did the block belong to and what is the significance of this subduction? There are two hypotheses concerning this problem:

1. The subduction plane belongs to the Easteuropean plate but after the block had been detached and the collision had taken place, the whole suture ensemble was pushed towards the west, slipping over the block which was left in the mantle. This implies a shift of the lithosphere over the asthenosphere.

2. The block does not belong to the Easteuropean plate but to the Black Sea plate, intercalated between the Moldavian and the Moesian Platforms, as shown by Airinei (1977). This would explain why the Vrancea seismic area is so restricted and why it does not continue towards the north, along the East Carpathians.

According to the second hypothesis we have to make a clear distinction between the two phenomena: the Vrancea seismic area as the sign of a subduction and the East Carpathian volcanic arc.

Concerning interpretation of this arc, a few temporal and spatial elements should be taken into account.

1. The arc is over 1400 km long and of different age. Thus, the magmatic activity started in the Lower Miocene in the northern part, in the Middle Miocene in its central part and in the Pliocene in the southern part.

2. The magmatism is of the andesitic type, chiefly rhyolitic at the beginning and mainly basaltic at the end. Geochemical data indicate a similarity of these rocks to those in the arcs which were formed on the continental crust due to subduction (Radulescu *et al.*, 1981).

3. It seems that there is no petrological and geochemical polarity perpendicular to the arc. Instead, a modification of the parental magma with age is noticed. For a given SiO_2 content, the K_2O content decreases in the younger rocks. This fact, pointed out by Bleahu *et al.*, (1973) and confirmed by Lexa and Konečny (1974) and Balla (1979), indicates the origin of the magmas from an ever greater depth as the age increases. This can be explained by the subduction of a plate that got fused at an ever greater depth with the passage of time. Thus, in the Calimani Mountains, the depth from which the magmas originated increased from 133 km (for stage I) to 193 km (for stage II, Peltz *et al.*, 1973).

All these facts support the idea that the eruptive arc formed as a result of subduction processes. This means that there existed a plate with oceanic crust that was subducted. Considering the general structure of the Carpathian arc and its eastern vergencies, it was supposed that the subduction proceeded from the east towards the west, i.e. the European Platform was subducted beneath a plate named Centraleuropean, Inter-Alpine, European etc. Therefore, between the two plates there existed an ocean which disappeared completely after the collision. It was the Siret Ocean of Hertz and Savu (1974), the Eastern Basin of Radulescu and Sandulescu (1973) and the one supposed, but not named, by Bleahu *et al.* (1973) and Bleahu (1974).

Where and when did this ocean exist? The only proof of its existence in the East Carpathians is the presence of mafic rocks in the Cretaceous flysch, namely in the Black Flysch Nappe of Maramureş and in the Ceahlău Nappe. In the Black Flysch Nappe there occur Jurassic – Lower Cretaceous basalts, forming massive flows and pillow lavas which are crossed by dykes and doleritic sills. These are accompanied by tuffs and stromatites (Bleahu, 1962). Geochemical analyses show that they are intermediary between the calc-alkaline and the alkaline basalts, being situated in the field of the within-plate basalts on the Pearce and Cann's diagrams and therefore originating, according to Sandulescu *et al.*, (1981), "from a within-plate continental area". "There occurs a thinned oceanized crust, mainly due to large rifting processes." Besides the difficulty of accepting an "oceanization" process and of admitting that obviously submarine basalts came from a continental area, we see that the most convincing proofs of the existence of an ocean in the East Carpathians are doubted by Sandulescu. Morever, the basalts of the Ceahlău Nappe are rather sporadic, extremely few and insignificant, although on their basis this zone was called a eugeosyncline, being considered as a zone with simatic crust (Sandulescu, 1975).

For the lack of real tholeiites, the existence of the supposed Siret Ocean cannot be proved. That is the reason why Bleahu (1976) gave up the idea of an ocean with subduction towards the west. He presumed the existence of a marginal basin with incipient opening in the zone of the external Dacides, and considered it to be a result of a subduction from the west towards the east, being marked by the banatitic magmatism.

Besides the mentioned Jurassic – Cretaceous mafic magmatites, there are no other traces of an ocean in the East Carpathians which could have been subducted and generating the volcanic arc. Supposing, however, that the basins in which the Black Flysch and the flysch of the Ceahlău Nappe were deposited were of oceanic nature, being the leading edge of the Easteuropean plate that was subducted beneath the Carpathians, where is the suture of this subduction to be found? It can only be situated between the Easteuropean platform and the plate supporting the East Carpathians, i.e. in the zone out of which the oceanic formations were ejected as nappes towards the east. The suture itself is covered by the Dacidic nappes which came from the west, while the rocks of the supposed ocean floor were overthrust towards the east. The thrust of the Black Flysch and the Ceahlău Nappes took place during the Laramian movements, but it began in the Meso – Cretaceous orogenesis.

The suture is not manifested geophysically, although some authors state that it can be observed on the international seismic profile IX (Radulescu *et al.*, 1976), but this is only an assumption, not a fact. In the same paper it is said that in this zone the simatic and sialic basements of the External Dacides were consumed through a subduction process and that this process also generated the magmatism of the Neogene volcanic arc. This statement comprises the essence of one interpretation variant of the volcanic arc genesis, but it faces two difficulties: The first one regards the very subduction notion, a process in which the sialic basement of the External Dacidic Nappes is supposed to have been consumed. But it is known that the sialic subduction is generally doubted. The second statement, relating the origin of the Neogene magmatism to the Cretaceous subduction, casts some doubts on space and time mechanisms. Concerning the space, the suture would be much too close to the eruptive arc, for the distance between the margin of the eruptive arc and the axis of the Internal Dacidic Zone is of 30 – 50 km. If we consider that these nappes were pushed towards the east, the distance gets still shorter, reaching about 20 km. It is mechanically impossible for a plate, 100 km thick, to be bent and pushed to a depth of at least 160 km (the depth at which the melting zone begins), over a distance of only 20 km. A vertical fall does not correspond to a Benioff plane and the ascending magmas would pass through the very plate from which they arose, thus being not able to generate andesitic magmatism.

Concerning the time, it is found that the last moment when oceanic subduction could have taken place was the Lower Cretaceous (over 130 Ma), while the magmatic activity started in the Miocene (25 Ma). What happened during the 100 Ma that separated the two events?

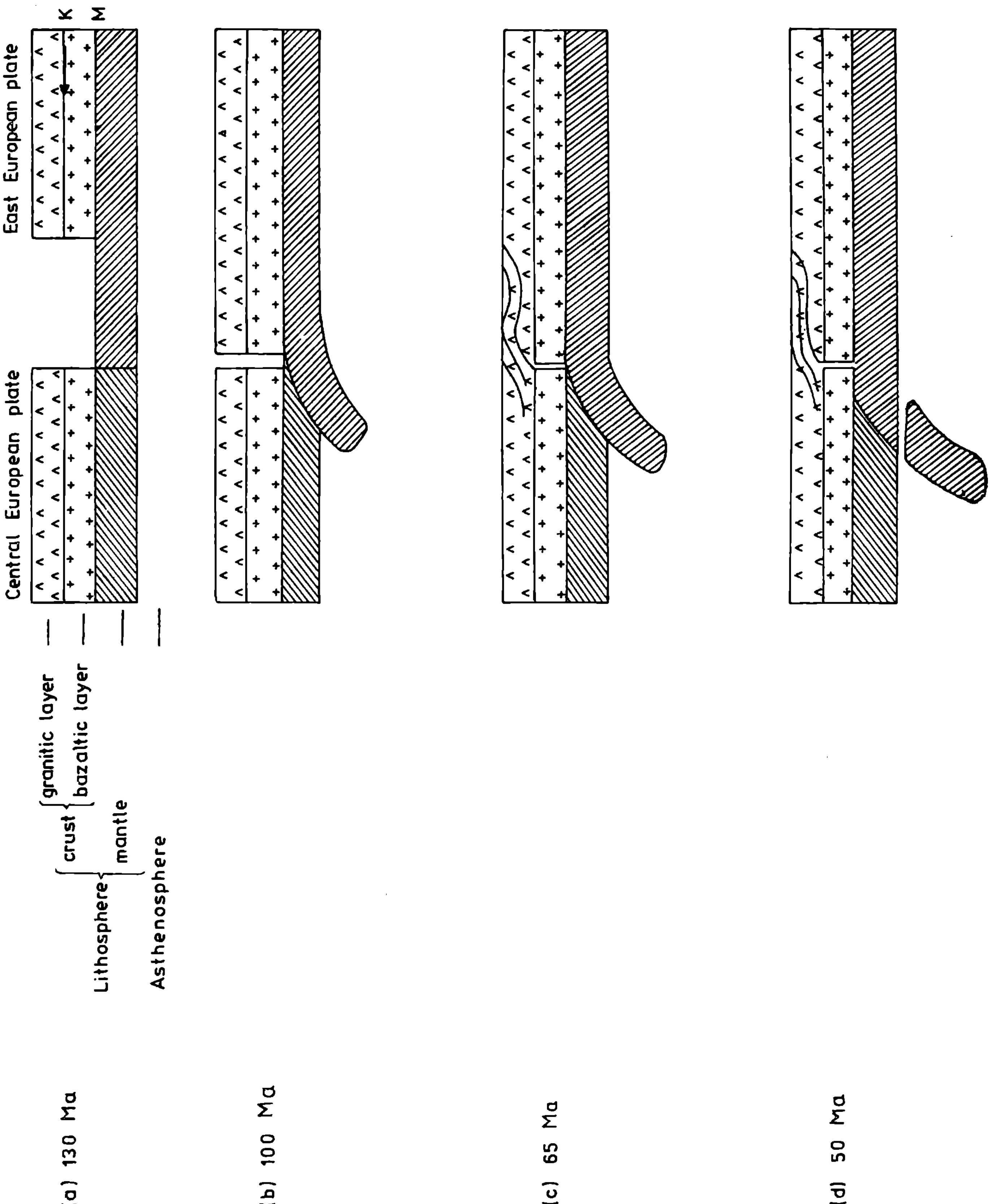
Between the beginning of the subduction and the formation of a magmatic arc at its expense, there must be a time interval necessary for the descending of the subducted plate to a depth at which the fusion by heating takes place. Modelling of this process revealed that the time interval depends on the velocity of the subducted plate and the dip of the subduction plane (Toksöz and Bird, 1977). It is known that the subducted plate melts only when it reaches the temperature of 600°C, i.e. at a depth of at least 160 km. At a speed of 1 – 10 cm/year and at a variable dip of 12 – 45°, the plate reaches the necessary depth in 10 – 40 Ma. At a dip of 27° and a velocity of 1 cm/year, the depth of 160 km is reached in about 40 Ma. However, the subducted plate remains a cold body which is gradually heated by the surrounding mantle. Therefore, another period of time elapses, in which the plate gets heated and, still another one, in which the generated magma gets out to the surface. Even so, the interval of 100 Ma is difficult to be covered and we must assume either that the advancement of the subducted plate was stopped for a long time, or that another mechanism, for instance another subduction, gave rise to the magmatic arc.

If the collision took place at the end of the Neocomian (Fig. 1b), we have to find the manner in which the eastern plate might have gone up to the melting zone, in spite of the suturing that blocked its advancement. We suppose that it was a decoupling process of the crust from the mantle, so that only the former was blocked by the continent/continent collision, while the latter continued to advance. Such a mechanism is also admitted for the Himalayas (Bird, 1977), and on its basis we can trace the further evolution of the East Carpathians.

Due to the blocking of the crust, the External Dacidic Nappes were formed during Laramian movements (Fig. 1c). Furthermore, within a period of immobility of the Easteuropean plate during the Palaeogene, it broke its distal end remaining isolated in the asthenosphere (Fig. 1e). Because the plate did not reach the melting depth connected with this subduction no corresponding volcanic arc was formed.

During Eocene or Oligocene times, the movement of the Easteuropean plate was resumed, but it involved only the lower part of the lithosphere. The latter advanced considerably beneath the crust (Fig. 1e), its end reaching the melting zone and generating magmas (Fig. 1f). At this moment the crust started to slip horizontally towards the west. The suture at the level of the crust reached almost the magmatic heart, from which the magmas were getting out to the surface and gave rise to the magmatic arc (Fig. 1g).

This is how four strange facts connected with the present structure of the East Carpathians can be explained: 1) the existence of a seismic centre without an apparent link to any plate margin, 2) the short distance between the interplate suture and the roots of the magmatic arc, 3) the fact that the Moho is situated 4 km deeper under the western part of the East Carpathians in respect to the Moldavian Platform, the crust being thickened up to 30 km, 4) the existence of some ore bodies in the deposits of the Moldavides that cannot be related to any volcanic processes, they


East European plate
K
M
Central European plate
granitic layer
bazaltic layer
crust
mantle
Lithosphere
Asthenosphere
(a) 130 Ma
(b) 100 Ma
(c) 65 Ma
(d) 50 Ma

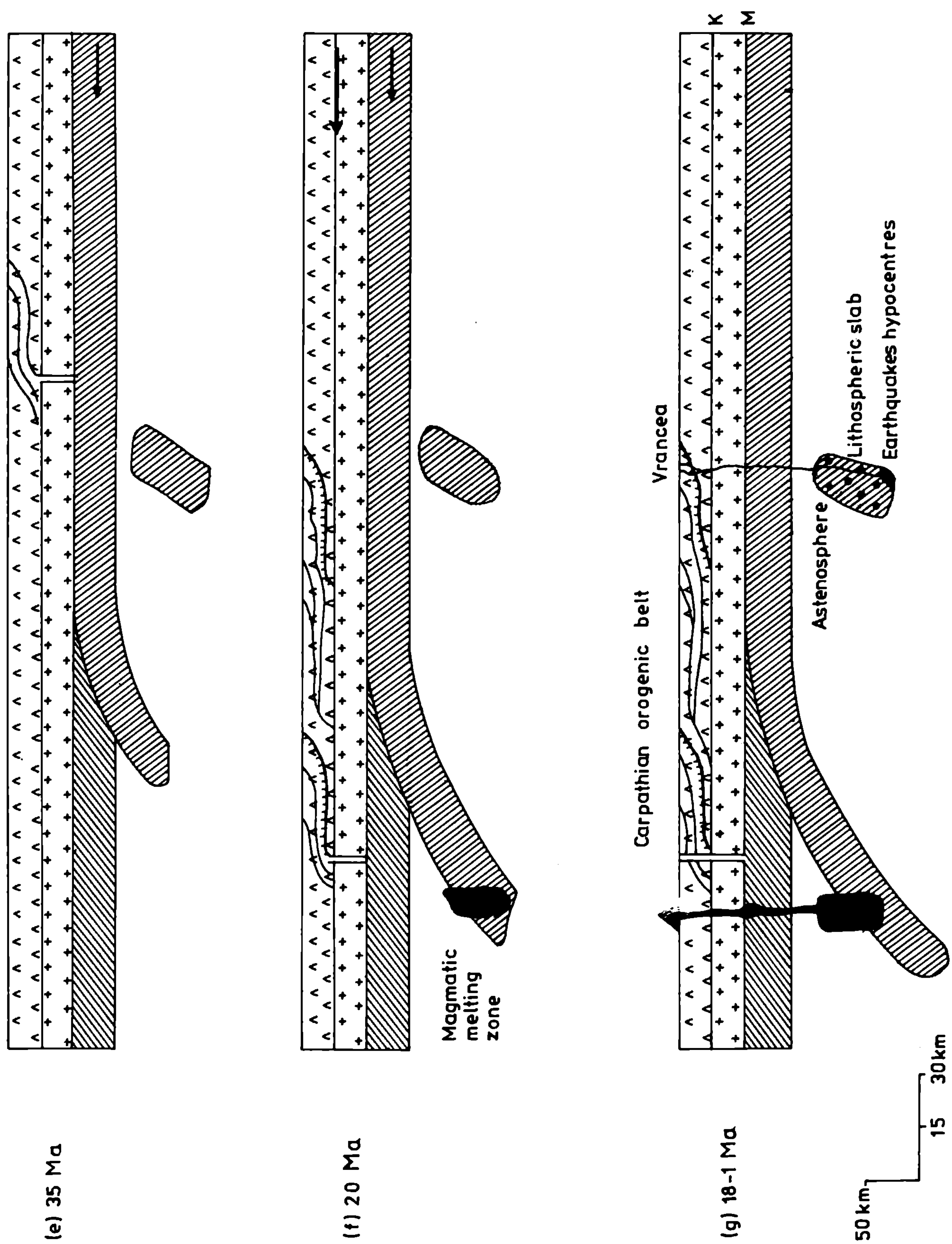

(e) 35 Ma
(f) 20 Ma
Magmatic melting zone
(g) 18-1 Ma
K
M
Carpathian orogenic belt
Vrancea
Astenosphere
Lithospheric slab
Earthquakes hypocentres
50 km
15
30 km

Fig. 1. Sketch showing the evolution of the East Carpathians. *a* – initiation of a basin with oceanic crust, *b* – closing of the basin by the subduction of the eastern plate, *c* – suturing of the plates and the formation of the Outer Dacidic Nappes, *d* – dismembering of the subducted plate loosing a lithosphere slab, *e* – decoupling of the lithospheric mantle from the crust of the eastern plate and initiation of a new subduction below the western plate, *f* – shift of the crust of the two sutured plates and the formation of the Moldavian Nappes; the slow moving lithospheric mantle arrives in the melting zone where magma is formed, *g* – the ascending magma gives rise to the magmatic arc. The sunken lithospheric slab, not yet consumed by the asthenosphere, produces the Vrancea earthquakes

Fig. 1. Szkic obrazujący ewolucję Karpat Wschodnich. *a* – otwarcie basenu o skorupie oceanicznej, *b* – zamknięcie basenu przez subdukcję płyty wschodniej, *c* – kolizja płyt i utworzenie Zewnętrznych Dacydów, *d* – podział pogrążonej płyty i zanurzenie jej fragmentu w astenosferze, *e* – pod płytą zachodnią tworzy się nowa strefa subdukcji, *f* – przemieszczenie skorupy dwóch kolidujących płyt i utworzenie płaszczowin mołdawskich; powoli przemieszczający się płat litosfery osiąga strefę przetapiania i tworzenia magmy, *g* – migrująca ku górze magma daje początek łukowi wulkanicznemu. Pogrążony płat litosfery, nie zasymilowany przez astenosferę, stanowi strefę generowania wstrząsów sejsmicznych w regionie Vrancea

could be connected with a partial and very limited melting of the detached block which reached the melting zone only by gravitational sinking.

The above-proposed model is only a working hypothesis and requires further improvements to solve some still open questions. Thus, for instance, we have to find the mechanism whereby the Moldavide Nappes of eastern vergencies formed on the background of a continental shift of the crust towards the west. The manner in which the movements of the plates involved in the suture of the East Carpathians should be associated with the major events of this part of Eurasia, the spreading in the Atlantic, plate movements in the Eastern Mediterranean and in the Black Sea region, should also be explained.

translated by the author

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