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AN ATTEMPT TO PALINSPASTIC RECONSTRUCTION OF NEOGENE BASINS IN THE CARPATHIAN FOREDEEP

(13 Figs.)

Próba palinspastycznej rekonstrukcji neogeńskich basenów zapadliska przedkarpackiego

(13 fig.)

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Abstract: On the basis of the considerable underthrusting of the European plate under the Carpathians an attempt to palinspastic reconstruction of the Carpathian Foredeep during the Miocene have been presented. Lateral and longitudinal migration of the tectonic movement has been discussed. The importance of the blocky character of the S part European plate has been underlined.

Key words: Alpine chain, Carpathian Foredeep, European platform, palinspastic reconstruction, tectonic movements, underthrusting, plate tectonic, Miocene.

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Treść: Przedstawiono próbę palinspastycznej rekonstrukcji zapadliska przedkarpackiego w miocenie z uwzględnieniem ruchu podsuwczego platformy europejskiej pod górotwór karpacki. Przeanalizowano migrację ruchów nasuwczych podłużnych i poprzecznych do orogenu karpackiego. Zwrócono uwagę na znaczenie blokowej budowy południowej części platformy w procesie rozwoju orogenu karpackiego.

INTRODUCTION

During our preliminary works on the atlas of Neogene palaeogeography for the Carpathians we have faced with a fact of the scarcity of palaeogeographic reconstructions considering palinspastic restorations. Available reconstructions commonly ignore the location of the internal (southern) border of the Carpathian Foredeep. This problem has been, however, recently treated at length by Wdowiarz

(1983) for the East Carpathians and Oszczypko and Tomaś (1985) for the Polish Carpathians.

In recent years a wealth of new data derived from cores and geophysical profiling has significantly improved our understanding of the development of Miocene successions and their relationships to the platformal basement under the Carpathian overthrust. Basing upon these data, for the purpose of the present analysis, we have assumed some minimum extent of the Miocene rocks and of the West

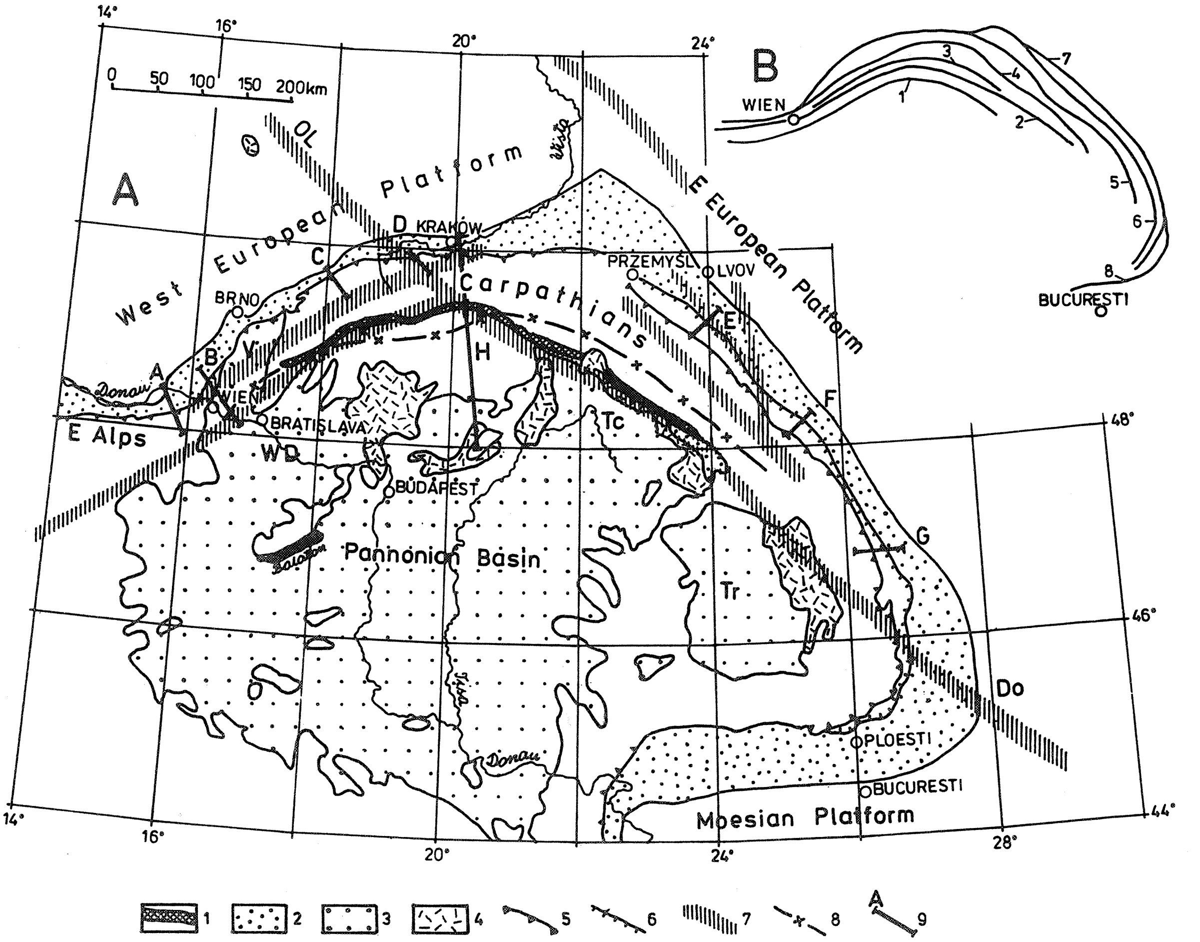

Fig. 1A. Sketch map of Carpathians (partly after Khain and Leonov, 1979). *1* – Pieniny Klippen Belt, *2* – Carpathian Foredeep, *3* – Neogene inter- and intramontane basins, *4* – Neogene volcanics, *5* – Carpathian Overthrust, *6* – overthrust of Sambor – Rożniatów and Subcarpatica Units, *7* – fractures in Mohorovičic surface (after Beranek and Zounkova, 1979), *8* – zero line of anomaly of geomagnetic soundings (after Jankowski *et al.*, 1982), *9* – locations of cross sections, V – Vienna Basin, WD – West Danube Basin, Tc – Transcarpathian Basin, Tr – Transylvanian Basin, OL – Odra Lineament

1B. Migration of fold and thrust movements in Carpathians. *1* – Subhercynian, *2* – Laramian, *3* – Pyrenean, *4* – Helvetian, *5* – Savian, *6* – Styrian, *7* – Moldavian, *8* – Attican

Fig. 1A. Szkic geologiczny Karpat (częściowo wg Chaina i Leonowa, 1979). *1* – pieniński pas skałkowy, *2* – zapadlisko przedkarpackie, *3* – neogen zapadlisk śródgórskich, *4* – neogeńskie wulkanity, *5* – nasunięcie karpackie, *6* – nasunięcie jednostek Sambor – Rożniatów i Subcarpatica, *7* – nieciągłości w powierzchni Mohorovičica (wg Beranka i Zoukovej, 1979), *8* – linia zerowa anomalii sondowań geomagnetycznych (wg Jankowskiego *et al.*, 1982), *9* – usytuowanie przekrojów, V – basen wiedeński, WD – basen zachodnio-dunajski. Tc – zapadlisko zakarpackie, Tr – basen transylwański, OL – lineament Odry

1B. Migracja ruchów fałdowych i nasuwczych w Karpatach. Ruchy: *1* – subhercyńskie, *2* – laramijskie, *3* – pirenejskie, *4* – helweckie, *5* – sawskie, *6* – styryjskie, *7* – mołdawskie, *8* – attyckie

European Platform (Epivariscian) and the East European Platform (Precambrian) under the flysch nappes (fig. 1A). Clearly, we are fully aware that the width of the platform under the overthrust was originally much greater. In our palaeogeographic considerations we have reffered to an old view linking the origin of the Carpathian nappes with underthrusting of the East European Platform beneath flysch trough (Mrazec, Popescu-Voitesti, 1914; Teisseyre, 1921). This concept has now become very timely in light of a number of approaches to explain the tectogenesis of the Carpathian fold belt in plate tectonics terms (Radulescu, Sandulescu, 1973; Ney, 1976; Książkiewicz, 1977b; Prey, 1980; Burchfiel, 1980; Balla, 1982; Burchfiel, Royden, 1982; and others).

In working out palinspastic maps a certain difficulty arises from the fact that different stratigraphic standards are being in use for the Neogene in various regions of the Carpathians. Thus, for example, regional stages of the Central Patethys are distinguished in Neogene sections of the Inner Carpathians and of the West Carpathian Foredeep, whereas a stratigraphic scheme close to the Mediterranean one is applied for the Romanian Carpathians (Micu, 1982). Recent radiometric data suggest that a part of the youngest flysch units in the Polish Carpathians may be coeval with molasse sediments of the foredeep (Couvering van *et al.*, 1981). However, this notion remains still unsupported on biostratigraphical grounds (Olszewska, 1982). In this paper we follow the time scale of Rögl and Steininger (1983).

MIGRATION OF FOLD MOVEMENTS IN THE OUTER CARPATHIANS

There is much evidence indicating a diachronity in thrust movements within the Carpathian chain. The thrusting migrated in time both across the orogen, i.e., from the Internal Zone towards the foredeep (Książkiewicz, 1965; Ślączka, 1969; Mahel, 1974) and along the entire Alpine-Carpathian belt toward the east (Alexandrowicz, 1965; Mahel, 1974; Wdowiarz, 1976; Jiriček, 1979; Oszczypko, Ślączka, 1980). A recognition of palaeodynamic picture of these processes has, however, never been attempted. The prerequisite for Neogene palinspastic reconstructions is to define the age of late folding in the Outer Carpathians and the onset and end of thrust movements in the foreland.

The closing stage of deformation in the Flysch Carpathians is but crudely dated by undisturbed Miocene sediments developed above folded portions of the orogene. Thus, the folding was completed in Vienna Basin prior to the Eggenburgian (Oberhauser, 1980; Vass, 1982), in NE Moravia prior to the Karpatian (Jurkova, Novotna, 1974), and in Polish Outer Carpathians prior to the early Badenian (Oszczypko, 1973). In the latter case, some new evidence suggests that this might have occurred prior to Karpatian ora even Ottnangian times (Oszczypko, Tomaś, 1985). In the Ukrainian Carpathians, the folded Skole Unit is transgressively overlain by the lower Badenian Dobromil Conglomerate (Shakin, 1976). Bacause the more external Boryslaw – Pokucice Unit does not contain sediments of a Karpatian age it may be presumed that folding was here terminated before the Karpatian.

Instead, the tectonic deformation involved the outermost Sambor – Rożniatów Unit probably prior to early Badenian times and the latest push took place before the early Sarmatian (see Shakin, 1976). In the Romanian Carpathians the Tarcau Unit was folded probably during early Miocene times and this preceded deposition of the Brebu Conglomerate. Timing of deformation of flysch sediments in the outermost Marginal Fold and Subcarpatica Units is rendered due to the presence of continuous transitions from flysch to molasse facies in these areas. It is assumed that the Marginal Folds Unit was initially folded during the Burdigalian, whereas the Subcarpatica Unit in Burdigalian and Badenian times (Sandulescu *et al.*, 1981).

AGE OF THRUSTING IN THE CARPATHIAN FORELAND

In the northern Alpine the main phase of thrusting on foreland occurred in the late Eggerian (23 – 24 Ma) and the late phase of deformation was accomplished after the Eggenburgian (ca. 19 Ma; Fig. 2; Kollman, 1977). In the vicinity of Vienna (Fig. 3) these phases took place after early Ottnangian (18 Ma) and after Karpatian times (ca. 16.8 Ma), respectively (Brix *et al.*, 1977). In NE Moravia (Fig. 4) the final emplacement of units comprising the Subsilesian and Silesian Nappes was accomplished after early Badenian times (ca. 15.5 Ma; Jurkova, 1979). In the Polish Carpathians the thrusting was completed after early Badenian times (ca. 15.5 Ma) in their western part (Fig. 5), during the late Badenian (ca. 14 – 15 Ma) in the middle, and after early Sarmatian times (ca 11 – 12 Ma) in the eastern part of the chain (Ney, 1968; Oszczypko, Ślączka, 1980). From the foreland of the Ukrainian Carpathians (Fig. 6) there comes an evidence that the thrust movements occurred here within a period of at least 6 Ma and propagated eastwards in time. They began with the emplacement of the Skole Unit over the Borysław – Pokucie Unit, and took place

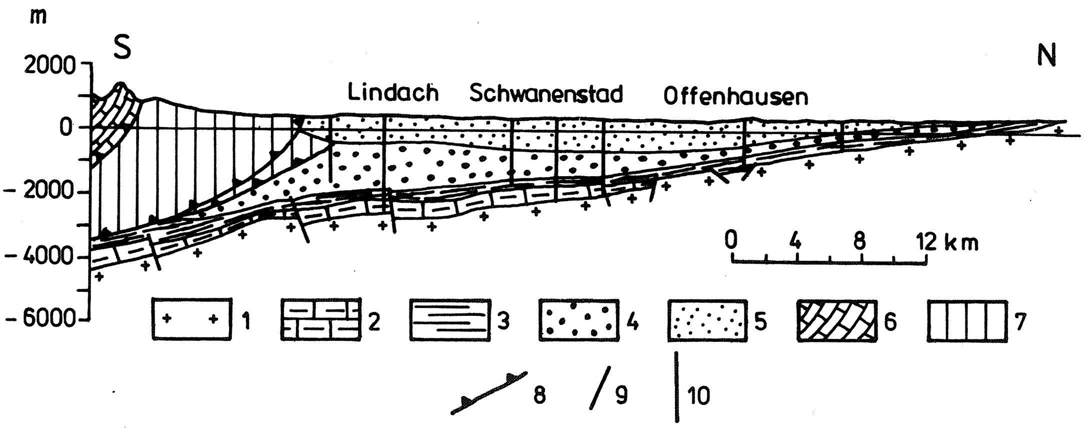

Fig. 2. Cross section through Alpine foreland in vicinity of Linz (modified after Kollman, 1977). *1* – crystalline core of Bohemian Massif, *2* – Paleozoic and Mesozoic, *3* – Palaeogene, *4* – Egerian, *5* – Eggenburgian – Ottnanagian, *6* – Northern Calcareous Alps, *7* – flysch and Helveticum, *8* – thrusts, *9* – faults, *10* – boreholes

Fig. 2. Przekrój geologiczny przez przedpole Alp w pobliżu Linzu (wg Kollmana, 1977, uproszczony). *1* – krystalinik masywu czeskiego, *2* – mezozoik i paleozoik, *3* – paleogen, *4* – eger, *5* – eggenburg – ottnang, *6* – północne Alpy wapienne, *7* – flisz i helwetikum, *8* – nasunięcia, *9* – uskoki, *10* – wiercenia

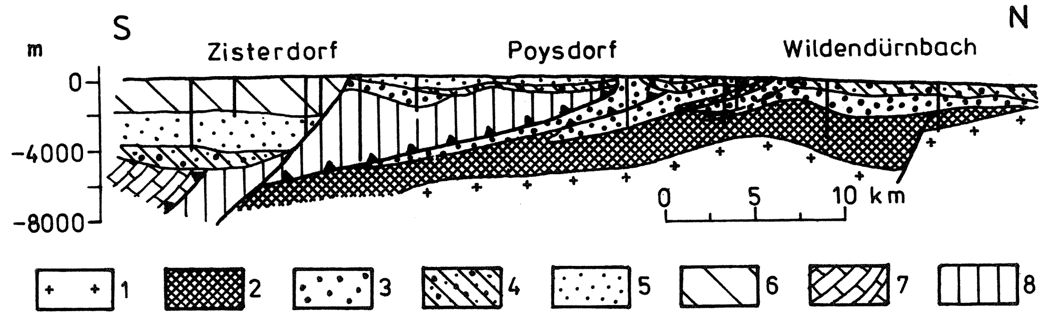

Fig. 3. Cross section through Vienna Basin (modified after Kapounek, Kröll *et al.*, 1965). *1* — crystalline core of Bohemian Massif, *2* — Mesozoicum, *3* — Eggenburgian—Ottnangian, *4* — Karpatian, *5* — Badenian, *6* — Sarmatian, Pannonian, *7* — Northern Calcareous Alps, *8* — flysch. For other explanations — see Fig. 2

Fig. 3. Przekrój geologiczny przez basen wiedeński (wg Kapounka, Krölla *et al.*, 1965, uproszczony). *1* — krystalinik masywu czeskiego, *2* — mezozoik, *3* — eggenburg—ottnang, *4* — karpat, *5* — baden, *6* — sarmat—pannon, *7* — północne Alpy wapienne, *8* — flisz. Pozostałe objaśnienia jak na fig. 2

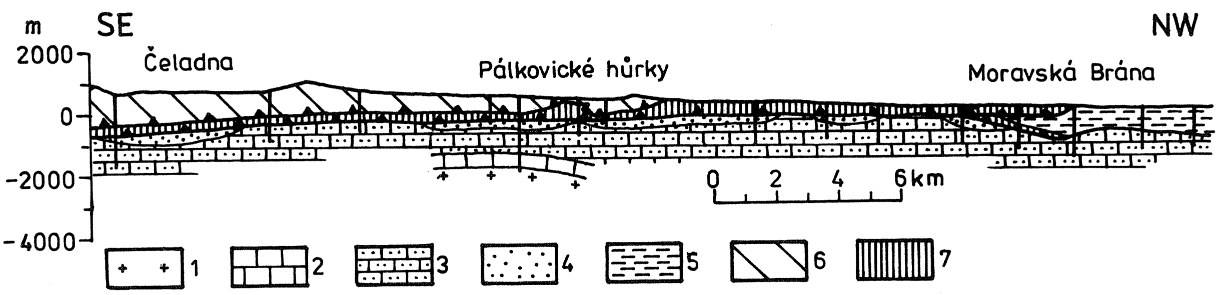

Fig. 4. Cross section through outer part of Moravo-Silesian Beskid Range (modified from Jurkova, 1979). *1* — crystalline zone, *2* — Devonian, *3* — Carboniferous, *4* — Karpatian, *5* — Badenian, *6* — Silesian Unit, *7* — Subsilesian Unit. For other explanations—see Fig. 2

Fig. 4. Przekrój geologiczny przez brzeżną część Beskidów śląsko-morawskich (wg Jurkovej, 1979, uproszczony). *1* — krystalinik, *2* — dewon, *3* — karbon, *4* — karpat, *5* — baden, *6* — jednostka śląska, *7* — jednostka podśląska. Pozostałe objaśnienia jak na fig. 2

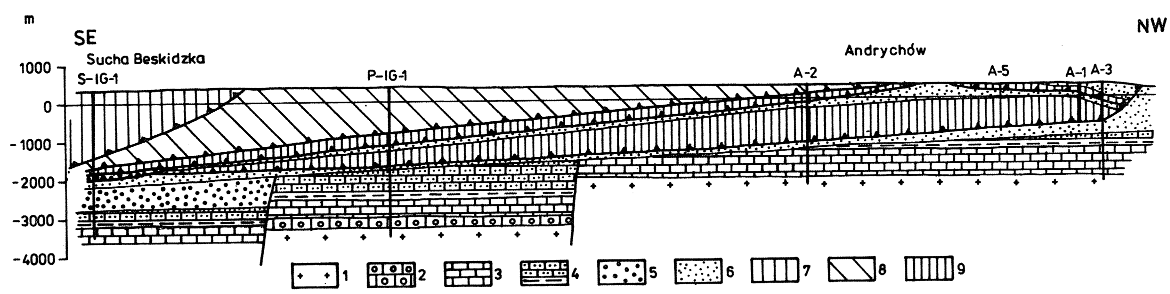

Fig. 5. Cross section through western part of Polish Flysch Carpathians. *1* — crystalline zone, *2* — old Palaeozoic, *3* — Devonian, *4* — Carboniferous, *5* — Lower Miocene (Karpatian—Ottnangian), *6* — Lower Badenian, *7* — Magura Unit, *8* — Silesian Unit, *9* — Subsilesian Unit. For other explanations — see Fig. 2

Fig. 5. Przekrój geologiczny przez zachodnią część polskich Karpat fliszowych w pobliżu Andrychowa. *1* — krystalinik, *2* — starszy paleozoik, *3* — dewon, *4* — karbon, *5* — dolny miocen (ottnang—karpat), *6* — baden dolny, *7* — jednostka magurska, *8* — jednostka śląska, *9* — jednostka podśląska. Pozostałe objaśnienia jak na fig. 2

after deposition of a lower part of the Stebnik Formation (ca. 18 Ma). Next stage involved of the Borysław – Pokucie Unit over the Sambor – Rożniatów Unit after deposition of the Balice Formation (ca. 16.8 Ma). The final emplacement of thrust slices over outer segments of the foredeep was after early Sarmatian (11 – 12 Ma; Fig. 7).

A similar spatial-temporal succession of thrust events can also be recognized in the Romanian East Carpathians (Fig. 8). Thus, the Telejan and Audia Nappes were emplaced during early Miocene times (intra-Burdigalian phase) and the

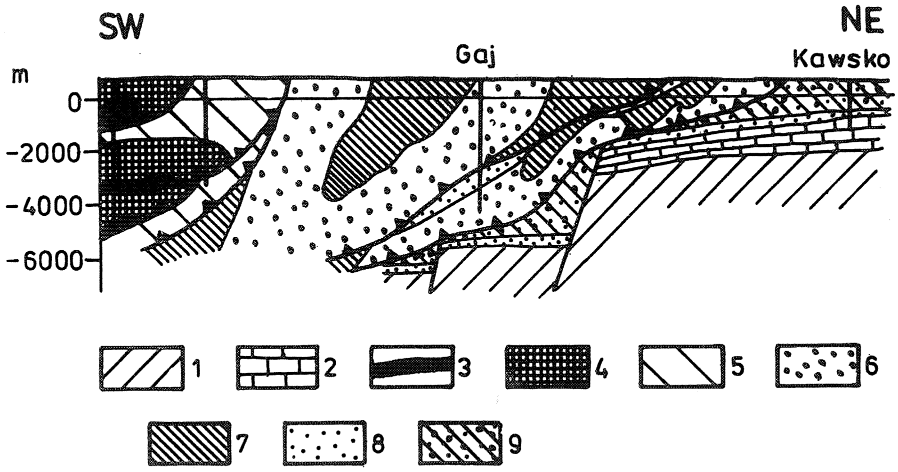

Fig. 6. Cross section through inner part of Carpathian Foredeep west of Stryj River in Ukrainian Carpathians (modified after Burov and Wul, in Glushko and Kruglov, 1977). *1* – Cambrian, *2* – Jurassic and Cretaceous, undifferentiated, *3* – Upper Cretaceous flysch, *4* – Palaeogene flysch, *5* – Burdygalian salts, *6* – Stebnik Formation (Burdygalian), *7* – Balice Formation (Burdygalian-Badenian ?), *8* – Badenian, *9* – Lower Sarmatian. For other explanations – see Fig. 2

Fig. 6. Przekrój geologiczny przez wewnętrzną część zapadliska przedkarpackiego na zachód od Stryja (wg Burowa i Wula *in*: Glushko, Kruglov, 1977, uproszczony). *1* – kambr, *2* – jura i kreda, nierozdzielone, *3* – flisz górnokredowy, *4* – flisz paleogeński, *5* – formacja solonośna (burdygał), *6* – formacja stebnicka (burdygał), *7* – formacja balicka (burdygał-baden), *8* – baden, *9* – sarmat dolny. Pozostałe objaśnienia jak na fig. 2

Tarcau Nappe and Marginal Folds Unit during middle Badenian times (ca. 15 Ma). The most external Subcarpatica Unit, corresponding to the Sambor – Rożniatów Unit in the Ukrainian Carpathians, was pushed during Besarabian times (10 – 11 Ma). Accordingly, the main thrust plane in the West Carpathians conforms to that which separates the Sambor – Rożniatów and Subcarpatica Units. South of Trotus River the overthrust of this latter unit fades away under neo-Sarmatian and Pliocene sediments. Remnant fold and thrust movements persisted in this outermost part of the East Carpathians until Pliocene times (3 – 5 Ma).

The foregoing review indicates that there was a considerable difference in the duration of thrust movements between the West and East Carpathians. In the westermost West Carpathians (vicinity of Vienna) the thrusting events were completed within 5 – 7 Ma, while in the East Carpathians they comprised much of the Neogene Period (11 – 12 Ma). This suggests that during Neogene times a consumed portion of the East European Platform beneath the Carpathian orogen, should

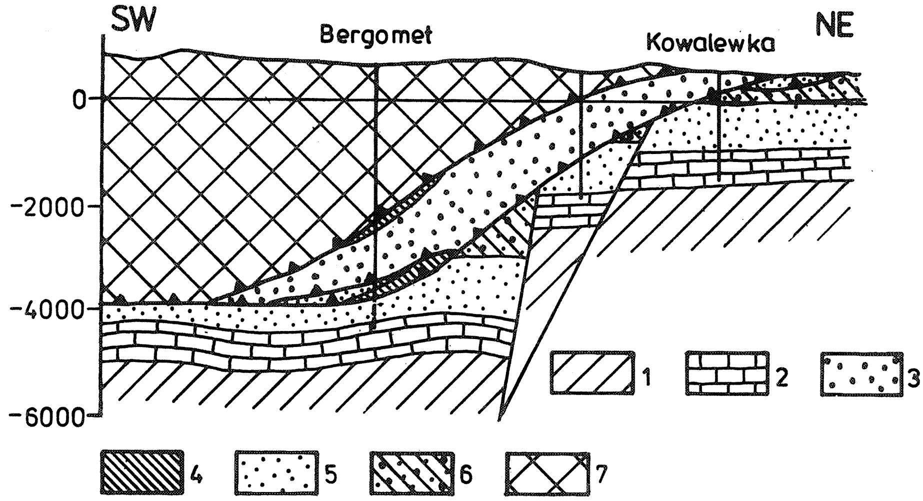

Fig. 7. Cross section through outer part of Ukrainian Carpathians west of Czerniowce (after Wul, in Glushko and Kruglov, 1977). *1* – old Palaeozoic, undifferentiated, *2* – Upper Jurassic – Upper Cretaceous, undifferentiated, *3* – Stebnik Formation (Burdygalian), *4* – Balice Formation (Burdygalian – Badenian ?), *5* – Badenian, *6* – Lower Sarmation, *7* – Skole Unit. For other explanations – see Fig. 2

Fig. 7. Przekrój geologiczny przez brzeżną część Karpat ukraińskich na zachód od Czerniowiec (wg Wula, *in*: Glushko, Kruglov, 1977, uproszczony). *1* – starszy paleozoik nierozdzielony, *2* – jura górna i kreda górna, nierozdzielone, *3* – formacja stebnicka (burdygał), *4* – formacja balicka (burdygał – baden), *5* – baden, *6* – sarmat dolny, *7* – jednostka skolska. Pozostałe objaśnienia jak na fig. 2

be much greater in the eastern part of the chain than in its western segment. Moreover, in the east the downgoing plate was steeply dipping, as suggested by enormous thicknesses of the molasse deposits (up to 10 km), so that it could have reached depths enough for melting and creation of volcanic arc. These phenomena are lacking in the West Carpathians.

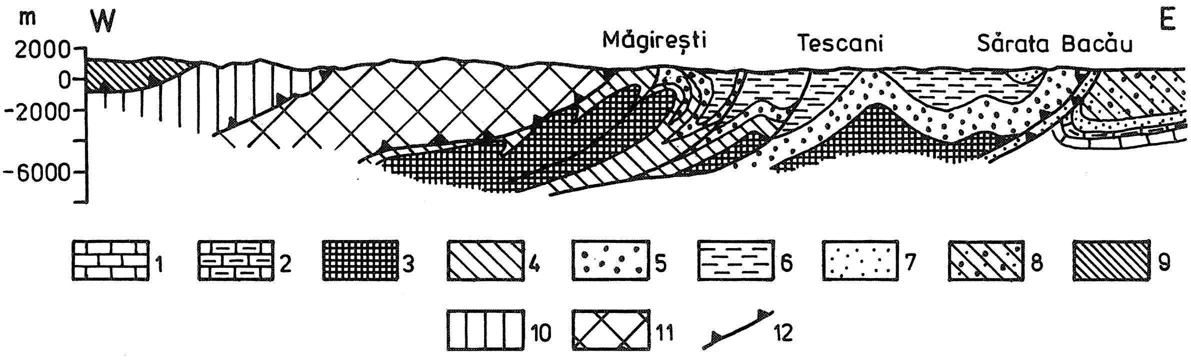

Fig. 8. Cross section through Romanian Carpathian in vicinity of Bucau (modified after Dumitrescu *et al.*, 1970), *1* – Triassic, *2* – Upper Cretaceous – Eocene, undifferentiated, *3* – Eocene – Oligocene, undifferentiated, *4* – Akwitanian – Burdygalian rocksalt, *5* – Magiresti Formation (Burdygalian), *6* – Grey Formation (Burdygalian – Badenian?), *7* – Badenian, *8* – Sarmatian, *9* – Ceahlău Unit, *10* – Teleajen Unit and Audia Unit, *11* – Tarčau Unit, *12* – thrusts

Fig. 8. Przekrój geologiczny przez Karpaty rumuńskie w pobliżu Bucau (wg Dumitrescu *et al.*, 1970, uproszczony). *1* – trias, *2* – kreda górna i eocen, nierozdzielone, *3* – fliszowy eocen i oligocen, nierozdzielone, *4* – formacja solonośna (akwitan – burdygał), *5* – formacja Magiresti (burdygał), *6* – formacja Grey (burdygał – baden ?), *7* – baden, *8* – sarmat, *9* – jednostka Ceahlău, *10* – jednostki Teleajen i Audia, *11* – jednostka Tarčau, *12* – nasunięcia

OUTER MARGIN OF THE CARPATHIAN OROGEN

In the previous sections we have summarized evidence indicating that deformational processes proceeded in the Carpathians both across of the chain and along its strike. The first strong deformation involved the Outher Carpathians during Early Miocene times (intra-Burdigalian phase in the East Carpathians; Sandulescu *et al.*, 1981). In view of the fact that the East Alps, including the Helvetic and Ultrahelvetic Flysch, were first folded prior to late Oligocene times, there is an apparent timelag with respect to the onset of deformation in the Carpathians (Fig. 1B). This can be related to an echelon structure of the Carpathian front which is formed toward the east of increasingly outer units. Such a structural pattern may have resulted from an interaction between the NW – SE trending tectonic structures in the East European Craton with the E – W trending Carpathian trough. The discrepancy between these trends desappears in the East Carpathians and just there a number of uninterrupted vertical transitions from flysch into molasse can be observed. Thus, the outer margin of the Carpathian orogen is a complex product which originated in several stages. It was formed through a gradual, south-eastward accretion of successive flysch basins.

The Carpathian Overthrust and the northern limit of the orogen acquired their present positions due to Miocene phase of thrusting, after full detachment of flysch sediments from the basement. A north and north-eastward migration of a compression wave was followed by tensional stresses. This was accompanied with a shifting of intra-Carpathian molasse basins toward the east and south. Consequently, during the Tertiary the northern margin of the orogen was simultaneously also a southern boundary to sedimentary basins which initially received flysch and subsequently were filled with molasse. After the earliest Miocene the molasse basin shifted northwards an involved mainly platform basement. Occasionally sedimentation extended upon folded orogen (post tectonic cover of the Vienna Basin, Nowy Sącz Basin and Rzeszów "Embayment").

GEODYNAMIC RECONSTRUCTIONS

Geodynamic reconstructions given below, have been carried out for three time periods which preceded major phases of Neogene thrusting (Fig. 9 – 11). These periods comprise: Karpatian (ca. 17 Ma), early Badenian (ca. 15.5 Ma), and early Sarmatian (ca. 12 – 13 Ma).

KARPATIAN

In front of the Flysch Carpathians, Karpatian basin extended between the vicinity of Vienna (to the west) and the Moesian Platform (to the south-east), reaching its maximum width up to 100 km (44 – 47 km, after Wdowiarz, 1983) in the East Carpathians. In western part of the chain this basin developed on both the platform basement and folded flysch (e.g., Vienna Basin) and was connected by several passages with coeval intra-Carpathian basins (Fig. 9). Further east, the southern margin of the Karpatian basin was adjusted approximately to the contemporaneous edge of the orogen, although minor transgressions of the Karpatian sea over the deformed flysch might locally have taken place (Szymakowska, 1976). Data from deep-borehole Sucha IG 1 (Ślączka, 1977) and from drillings in Moravia (Jurkova and Novotna, 1974) indicate that this part of the Carpathians was already folded and partly subjected to erosion during Karpatian times. Between Sucha and Przemyśl, the Karpatian basin was relatively narrow and its presence in that area is proved by only thrust slices containing Karpatian sediments (Balice and Stebnik formations) below and in front of the Carpathian Overthrust. Beginning from the vicinity of Przemyśl the basin widened considerably towards the south

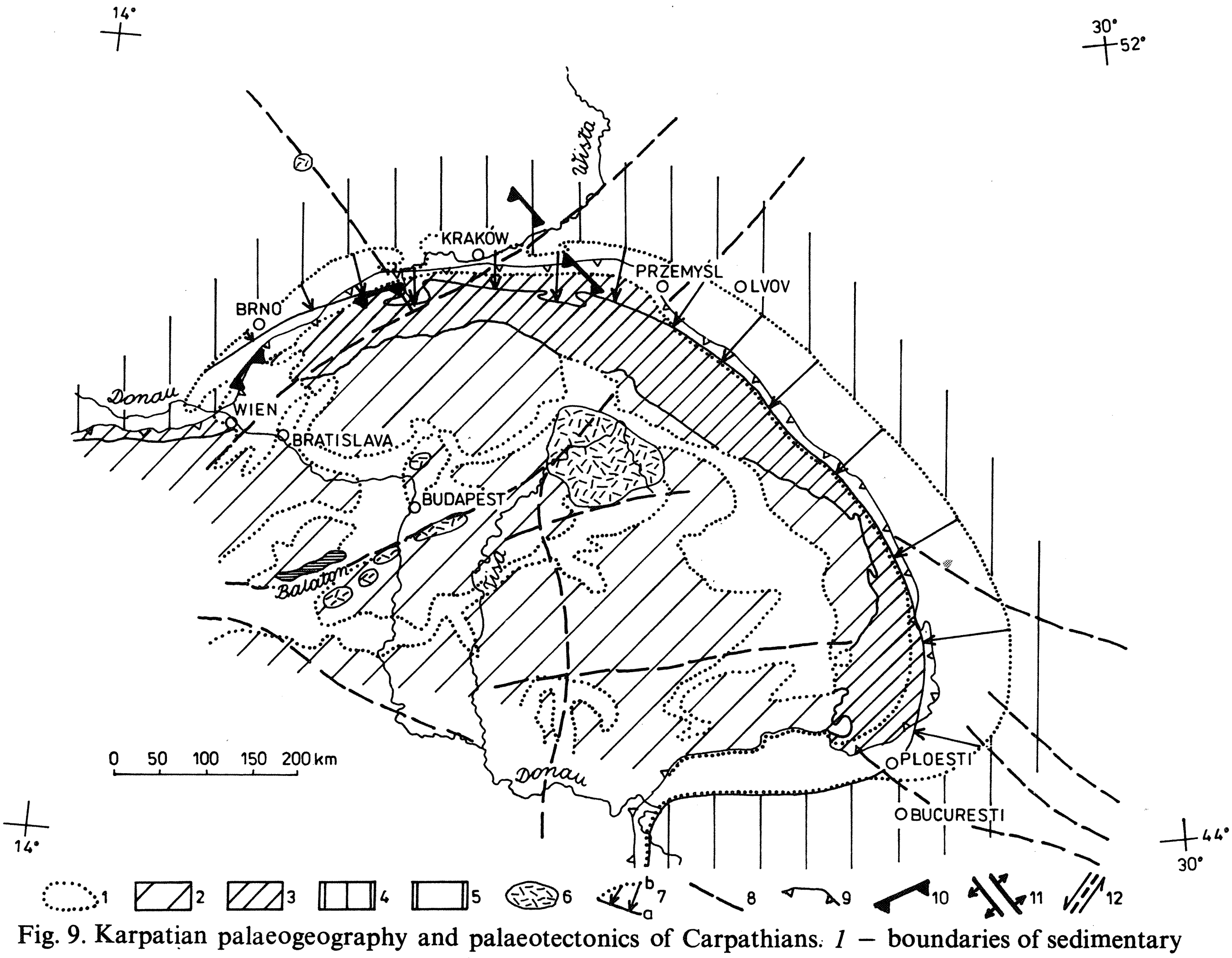

Fig. 9. Karpatian palaeogeography and palaeotectonics of Carpathians. *1* — boundaries of sedimentary basins (partly after Gašparik, 1978; Jambor, 1981; Saurea, 1969), *2* — Inner Carpathians, *3* — Outer Flysch Carpathians, *4* — under thrust portion of European Platform, *5* — European Platform, *6* — volcanics, *7* — recent (*a*) and contemporary (*b*) northern margin of foredeep and direction of underthrusting, *8* — major dislocations, *9* — front of Carpathian Overthrust, *10* — Neogene thrusts of platform rocks, *11* — post-Middle Badenian tensional troughs, *12* — faults in external part of Outer Carpathians and dislocation directions

Fig. 9. Szkic paleogeograficzno-paleotektoniczny karpatu. *1* — granice basenów sedymentacyjnych (częściowo wg Gašparika, 1979; Jambora, 1981 i Saurea, 1969), *2* — Karpaty wewnętrzne, *3* — zewnętrzne Karpaty fliszowe, *4* — podsunięta część platformy europejskiej, *5* — platforma europejska, *6* — wulkanity, *7* — współczesny (*a*) i ówczesny (*b*) północny brzeg zbiornika oraz kierunek podsuwania się platformy, *8* — ważniejsze dyslokacje, *9* — czoło nasunięcia karpackiego, *10* — neogeńskie nasunięcia utworów platformowych, *11* — rowy tensyjne, pośrodkowobadeńskie, *12* — uskoki brzeżnej części Karpat oraz kierunki przemieszczeń

east. In the foreland of the Ukrainian Carpathians the southern margin of the basin followed the edge of the uplifted Borysław – Pokucie Unit and, locally, of the Skole Unit in such areas where the latter unit formed the northern boundary of the Carpathians (Fig. 7). In the Romanian segment of the chain, Karpatian sediments developed mainly on marginal units of the Flysch Carpathians (Subcarpatica and Marginal Folds Units) and probably also on the platform. Around the great twist of the East Carpathians, Karpatian sediments spread deeply into the chain as far southwestward as the Teleajan Unit. In the Getic Basin upper Burdygalian (Karpatian ?) deposits accumulated unconformably above lower Miocene gipsum. According to some authors (e.g., Saurea *et al.*, 1969), Karpatian sedimentation covered the entire Tarcau Unit.

The Karpatian sediments consist mainly of shales and marly shales with intercalations of friable sandstones. In the East Carpathians there are also gipsum and tuffs. These sediments were laid down in open-marine and partly brackish-lagoonal conditions, locally enhancing evaporation. The basin was fed both from the orogen and from the platform. Karpatian sediments are also known from the intra-Carpathian basins; their presence in the Transylvanian Basin is still debated. The foreland basin was connected with those of the Internal Zone through the Vienna Basin and possibly via the South Carpathians. Karpatian magmatism took place only in the Internal Carpathians and resulted in widespread calc-alkaline products in the Middle Hungarian – Transcarpathian volcanic belt and Cserhát – Matra area (Balla, 1982).

Contemporaneously, in the Ukrainian Carpathians folding and erosion started in the Sambor – Rożniatów Unit and its internal part was overridden by the Borysław – Pokucice Unit. In the Romanian Carpathians this period wittnessed an end of deposition in the Marginal Folds Basin as well as beginning of folding and thrusting.

At the end of the Karpatian the European Platform moved under the Carpathian orogen. The available evidence indicates that this motion was particularly substantial in Moravia where part of the Bohemian Massif, contained between the Danube and Odra rivers, drifted south-eastwards and rotated clockwise. In our palinspastic picture (Fig. 9), the eastern boundary of this block follows the Odra Lineament. We believe that fold and thrust deformations in the northern and eastern foreland were caused mainly by south and westward shifting of a segments of West and East European Platform, enclosed between the Odra Lineament and a dislocation zone bounding the Moesian Craton to the north. This fragment of the platform consisted of a number of smaller blocks which might have behaved partly freely of each other during the emplacement. Our reconstructions suggest that an amount of underthrusting of the platform beneath the Carpathian orogen due to pre-Badenian movements, varied considerably in space. It ranged few km in the vicinity of Vienna, through 25 km in Moravia; in the Polish Carpathians minimum extent of after Karpatian overthrusts – 25 – 30 km has been estimated (Oszczypko, Tomaś, 1985); up to 50 – 75 km in the eastern part of the chain and, then, it practically vanished in the South Carpathian foreland.

BADENIAN

The tectonic activity during latest Karpatian resulted in a northward shift of the molasse foreland basin, giving rise to drastic palaeogeographic changes at the beginning of the Badenian Age (Fig. 10). The lower Badenian sea covered vast areas of the platform and it was partly extended over the Moesian Block and peneplenized Carpathians. In the West Carpathians the transgression reached the Magura Nappe. In Ukraine it covered the Sambor – Rożniatów Unit and locally also the Borysław – Pokucie and Skole Units. In the Romanian Carpathians sedimentation was still taking place in the Subcarpathian Basin and in the Doftana "Bay", locally with overlapping contacts.

Much of the lower Badenian is represented by marly and clayey-sandy sediments which were deposited at neritic depths. In nearshore zones developed conglomerates and organogenic limestones. Only in the Romanian foreland sea the salinity was sufficient to promote deposition of gypsum. The lower Badenian sea in the foredeep was connected with marine basins in the intra-Carpathians through the Vienna Basin and the South Carpathians. Marine links might also have existed via the Nowy Sącz Basin and eastern Slovakian basins.

During early Badenian times volcanic activity was continued in the Middle

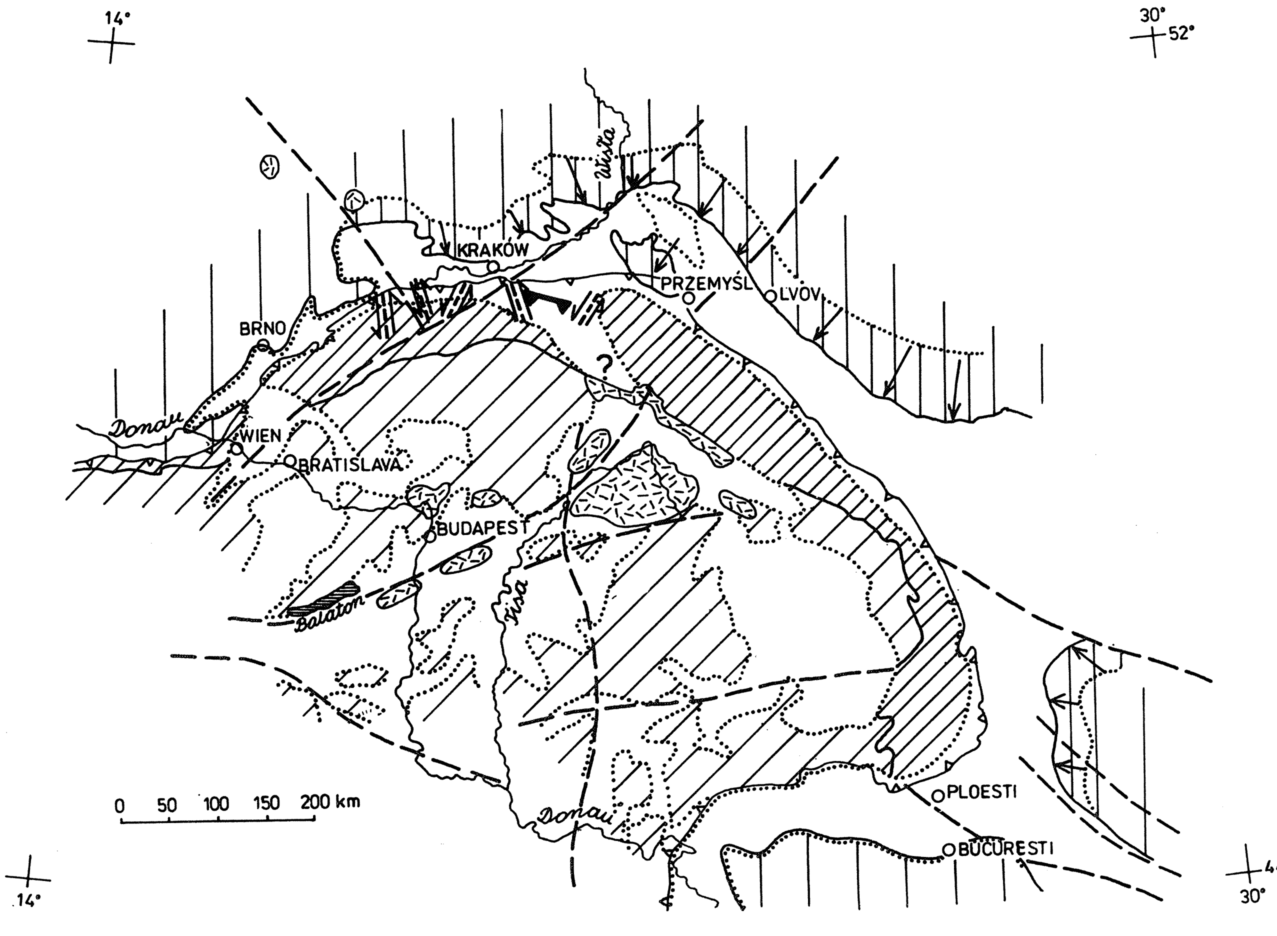

Fig. 10. Early Badenian palaeogeography and palaeotectonics of Carpathians. For explanation see Fig. 9

Fig. 10. Szkic paleogeograficzno-paleotektoniczny badenu dolnego. Objaśnienia jak na fig. 9

Hungarian – Transcarpathian Volcanic Belt. A major episode of andesitic activity took place in the Vihorlat – Gutin Chain and in the Dunazug – Börzöny, and Cserhát – Matra areas (Balla, 1982; Fig. 10). Post-early Badenian movements exterted a dominant role in the tectogenesis of the Carpathians. These movements occurred in several pulses and began at the transitions between the early and middle Badenian. They resulted in uplift of the Carpathians, followed by a shallowing and regional withdrawal of the sea towards the south-east. The middle Badenian Salinary Crisis was related to this regression. Precipitation of salt developed along the Carpathian orogen. Further to the north the chloride facies was replaced by the sulphate one (anhidrite and gypsum). The mid-Badenian tectonic activity might also have been responsible for emplacement of olistolithe series in the Wieliczka region (Kolasa, Ślączka, 1985).

After the middle Badenian movements there came again a deepening of the foreland basin and widespread re-establishing of neritic conditions of sedimentation. Clayey-marly sediments with sandy intercalations were predominant. This preceded the onset of the main tectonic phase which began in late Badenian times. These were both fold and thrust movements. The former involved the outer margin of the West Carpathians and resulted in refolding of flysch sediments along with evaporites (Badenian folds of Książkiewicz, 1977a). Probably during the same time folding also affected the Subcarpatica Unit. Effects of the late Badenian thrusting are best seen in the Polish Carpathians where Badenian sediments under the flysch nappes were penetrated by numerous wells (Fig. 5). In the East Carpathians this phase of thrusting resulted in emplacement of the Tarcau and Marginal Folds Units.

The amplitude of underthrusting of the platform increases from almost non-existent in NE Moravia up to nearly 50 km in the middle part of the Polish Carpathians (Fig. 10). The displacement took place probably along a series of discrete dislocations dividing the platform in that area into several blocks. The block between the Odra Lineament and Vistula Zone (Żywiec – Kurdwanów – Zawichost fault) shifted toward the south-east and rotated clockwise, whereas the block contained between the latter dislocation and the southern boundary fault of the northern Dobrogea Massif, moved south-eastwards and probably turned to the right. Significant motions might also have occurred along other dislocations dessecting this block, mainly along a NW – SE trending fault zone close to the Przemyśl sigmoid. A successive, more southern block, comprising northern part of the Moesian Platform and bounded to the south by the Mangalia – Ploesti Fault Zone, drifted to the west.

EARLY SARMATIAN

During early Sarmatian times a significant marine regression involved the West Carpathian foreland. The western limit of the Sarmatian sea ran approximately along the Wisła Line. A isolated marine basin persisted in Upper Silesia. Sarmatian deposits in the eastern segment of the platform were of transgressive character.

The shoreline shifted to the north and east. The early Sarmatian foreland basin was characterized by shallow depths and brackish waters. Its sedimentary infill consists mainly of shales with intercalations of mudstones and fine-grained sandstones. Locally, in littoral zones originated biogenic limestones. The zone of maximum subsidence lay in the East Carpathians. The clastic material was supplied mainly from the orogen; the platform source was subordinate. Of marine passages linking the foreland basin with the intra-Carpathian ones, persisted only via the South Carpathians. The Badenian volcanic centres were active also during Sarmatian times (Balla, 1982).

Post-Sarmatian thrust movements involved only segment of the Carpathians, enclosed between rivers Dunajec to the west and Trotus to the south. The amplitude of the post-Sarmatian underthrusting is significantly shorter than that of the Badenian age. It approaches to its maximum of a 20 km at the southeastern part of the Sarmatian basin. The main thrust plane of the orogen conforms the bases of the Skole Unit (Polish Carpathians) and of the Sambor – Rożniatów and Subcarpatica Units (Ukrainian and Romanian Carpathians).

After the early Sarmatian the main depocenter in the foreland basin migrated south of the Trotus River. During neo-Sarmatian and Pliocene times remarkably rapid accumulation took place in area between the rivers Putna and Buzau, where the comulative thickness of Pliocene sediments attains 9000 m (Dumitrescu *et al.*, 1976 – Tectonic Map), and where tectonic activity still alive. High sedimentation rate was also characteristic for the Panonian Basin at that time. Volcanic activity began in the Calimani – Harghita region and persisted till the Pleistocene (Balla, 1982). Tectonic activity is still existing in the Romanian Carpathians.

DISCUSSION

Numerous geological, geophysical and palaeogeographical data indicate that the substratum of the Carpathian Foredeep basins was a southern part of the West and East European Platforms. The foregoing considerations have shown that the motion of the European Craton towards the Carpathian orogen varied in time and space. It can therefore be expected that the platform was dissected by a series of major dislocations which formed boundaries to several blocks. During Neogene times these blocks experienced to differential movements which were directed toward the south-east in the western part of the chain, south-westwards in the east, and westwards in the south. A number of data suggests that this motion was transmitted through several minor dislocations, that caused a seeming continuity in the course of emplacement of particular blocks beneath the Carpathians. Apart from few cases it is difficult to establish which dislocations were active in this process.

The above model depends on the assumption that this inwarddirected shifting of the blocks was accompanied with a shortening of the internal edge of the platform, probably simultaneously with a longitudinal stretching of the Carpathian arc. This is not unlikely in view of the fact that there is a 10% difference in present lengths between the outer margin of the Carpathians and the internal edge of the platform recognised under the Carpathian Overthrust.

It is difficult, however, to establish a manner of shortening. It may have occurred through development of transverse undulations and overthrusts which diminished in their amplitude down the platform. Such features apparently associated the formation of the Lower San Anticlinorium which derivered large quantities of clastic material to Lower Miocene basins in the Ukrainian Carpathians (Pre--Badenian overthrust is known to occur in the southwestern edge of the anticlinorium – Moryc, 1971). This is also suggested by a diagonal shift of the axis of gravimetric minimum southwest of Przemyśl (Ślączka, 1975). Other manifestations of compressional movements are strike-slip and back faults which caused the emplacement of Neogene deposits beneath the platform rocks. In the vicinity of Vienna the underthrusting involved Mesozoic cover of the Bohemian Massif. Other similar examples, related to late Styrian movements, were reported from the Moravian and Silesian Beskids (Roth, 1979; Jurkova, 1979; see also Połtowicz, 1962). It is possible that submarine canyons, known from the basement of the Polish Carpathians (Karnkowski, 1978) originated due to the post-middle Ba-

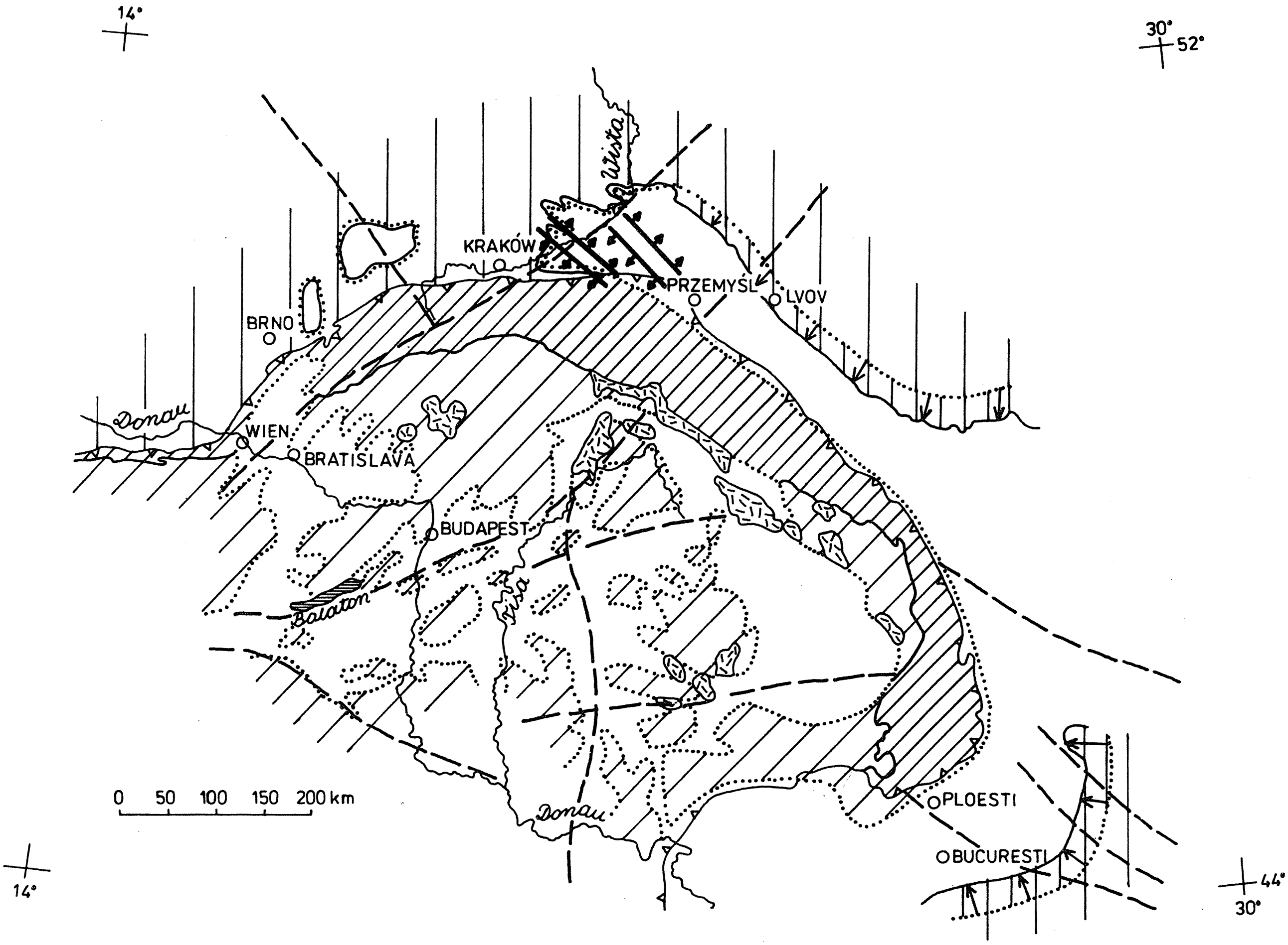

Fig. 11. Early Sarmatian palaeogeography and palaeotectonics of Carpathians. For explanation see Fig. 9

Fig. 11. Szkic paleogeograficzno-paleotektoniczny sarmatu dolnego. Objaśnienia jak na fig. 9

denian tension in the eastern portion of the West European Platform which in this time underwent rotation and displacement toward the southeast (Fig. 11).

Compression in the Carpathian arc resulted from a continental collision of the southeastward drifting Euro-Asiatic Craton (Talwani, Pitman, 1972) with the Pannonian, Apulian Microplates and Afroarabian Continent (Smith, 1971; Trümphy, 1975). Since the Eocene till Early Miocene there began a strong folding of the Flysch Carpathians and, afterwards, their thrusting onto the foreland molasses (Fig. 12). Earlier deformational phases were much less intense and confined areally. The southernmost zone of shortening originated in the latest Eocene at the junction between the Pieniny Klippen Belt and Magura Basin. A more northern zone developed in front of the Silesian "Island" during Pyrenean movements. According to several authors a present trace of this zone (Fig. 1A) is delimited by zero-line of anomaly of geomagnetic soundings (Jankowski *et al.*, 1982). Yet, the most important was a regional subduction zone, situated at the boundary between the platformal and geosynclinal substratum in the East Carpathians (Fig. 9), and

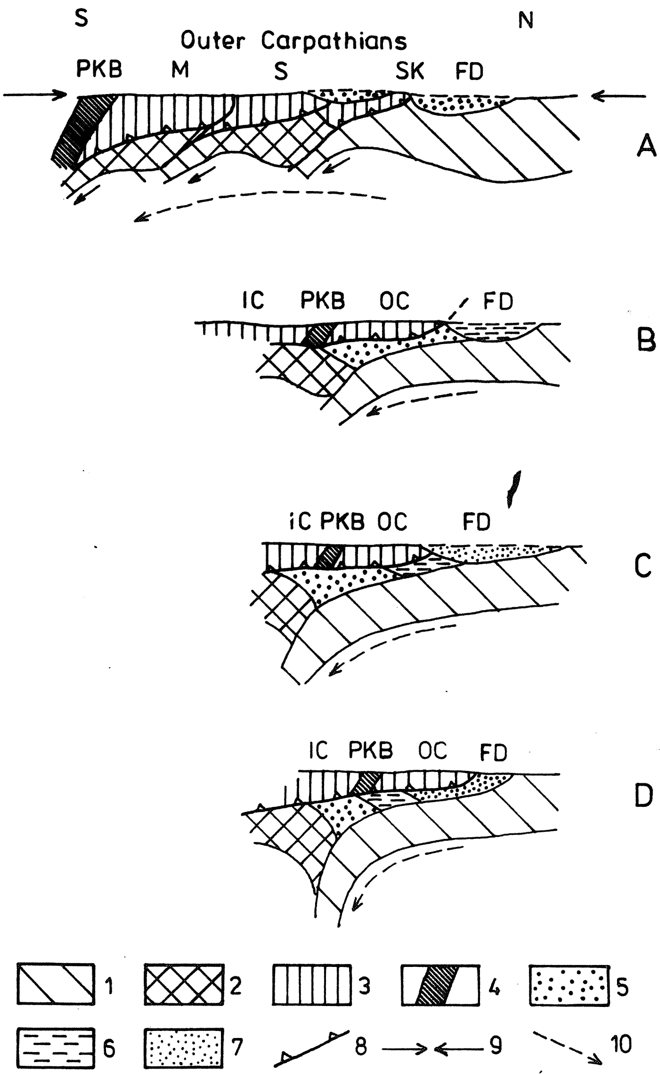

Fig. 12. Schematic palinspastic cross section through Carpathians along meridian of Cracow. A – lower Lower Miocene, B – upper Lower Miocene, C – Badenian, D – recent situation; *1* – platform basement, *2* – Carpathian basement, *3* – thrust sheets of Carpathians, *4* – Pieniny Klippen Belt, *5* – lower Lower Miocene sediments (Eggenburgian – Ottnangian ?), *6* – upper Lower Miocene Sediments (Karpatian), *7* – Badenian sediments, *8* – Carpathian Overthrust, *9* – compression directions, *10* – direction of underthrusting of European Platform. FD – Carpathian Foredeep, Sk – Skole Unit, S – Silesian and Subsilesian Units, M – Magura Unit, PKB – Pieniny Klippen Belt, OC – Outer Carpathians, IC – Inner Carpathians

Fig. 12. Schematyczny przekrój palinspastyczny przez Karpaty wzdłuż południka Krakowa. A – miocen dolny, niższy, B – miocen dolny wyższy, C – baden, D – sytuacja współczesna; *1* – podłoże platformowe, *2* – podłoże Karpat, *3* – allochtoniczne utwory Karpat, *4* – pieniński pas skałkowy, *5* – osady miocenu dolnego (eggenburg – ottnang), *6* – osady wyższego miocenu dolnego (karpat), *7* – osady badenu, *8* – nasunięcie karpackie, *9* – kierunki kompresji, *10* – kierunek podsuwania się platformy, FD – zapadlisko przedkarpackie, SK – jednostka skolska, S – jednostka śląska i podśląska, M – jednostka magurska, PKB – pieniński pas skałkowy, OC – Karpaty zewnętrzne, IC – Karpaty wewnętrzne

active during the entire Neogene. Location of this subduction zone during Neogene times (Radulescu, Sandulescu, 1973; Burchfiel, Royden, 1982) can be read in the Eastern part of the Carpathians from a welldeveloped, coeval volcanic arc which consists of two ranges: Vihorlat – Gutin and Calimani – Harghita. The volcanicity in the former took place in Badenian – Sarmatian times, in the latter – since Pannonian till Quaternary (Balla, 1982). In the Alps and West Carpathians there are no signs of volcanism which could be related to subduction, except rare andesitic rocks in the Szczawnica region (Birkenmajer, 1978). The lack of calc-alkali volcanism in the Eastern Alps and Western Carpathians could perhaps be interpreted in terms of a shallow underthrusting of the European Plate (see also Hesse, 1982).

It follows from the above that in Early Miocene times the West Carpathians were already folded. During the latest Early Miocene a further underthrusting of the European Craton resulted in a total detachment of the Flysch Carpathians from the underlying rocks in the western part of the arc (Figs. 12, 13). To the east, the detachment occurred later on and was caused by folding in the Borysław – Pokucie and Sambor – Rożniatów Units. The border line between the West and East Carpathians is a so-called Przemyśl sigmoid. The development of this sigmoid could be explain by the fact that underthrusting of the platform beneath the segment of the Carpathians situated W from Przemyśl was flat due to smaller thickness of

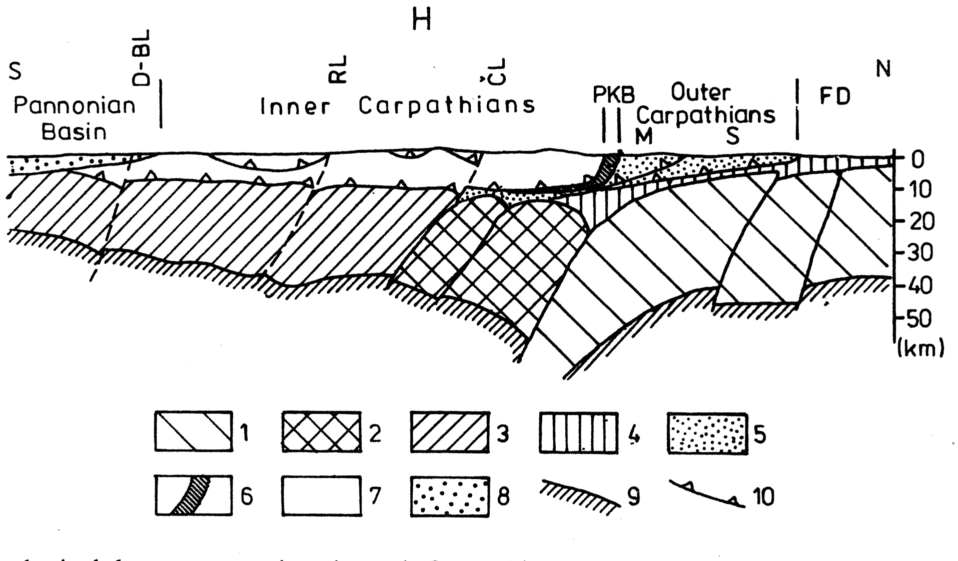

Fig. 13. Hypothetical deep cross section through Carpathians along meridian of Cracow. *1* – Basement of European Platform, *2* – basement of Outer Carpathians, *3* – basement of Inner Carpathians, *4* – Neogene molasses in Carpathian Foredeep, *5* – Outer Carpathian flysch, *6* – sediments of Pieniny Klippen Belt, *7* – rock successions of Inner Carpathians, *8* – Neogene sediments of intramontane basins, *9* – Moho discontinuity, *10* – thrusts: D – BL – Darno – Balaton line, RL – Raba line, ČL – Čertovica line, FD – Carpathian Foredeep, S – Silesian Unit, M – Magura Unit

Fig. 13. Hipotetyczny głęboki przekrój geologiczny wzdłuż południka Krakowa. *1* – utwory platformy europejskiej, *2* – utwory podłoża Karpat zewnętrznych, *3* – utwory podłoża Karpat wewnętrznych, *4* – neogeńskie molasy zapadliska przedkarpackiego, *5* – flisz Karpat zewnętrznych, *6* – utwory pienińskiego pasa skałkowego, *7* – utwory Karpat wewnętrznych, *8* – neogeńskie utwory basenów międzygórskich, *9* – nieciągłość Mohorovičica, *10* – nasunięcia: D – BL – linia Darno – Balaton, RL – linia Raby, ČL – linia Čertovic, FD – zapadlisko przedkarpackie, S – jednostka śląska, M – jednostka magurska

lower Miocene deposits than E from Przemyśl. In this late segment folding of thick lower Miocene deposits of Sambor – Rożniatów and Borysław – Pokucie units caused pushing the marginal part of the East Carpathians towards SW. As an effect the W segment is situated now farther to the North than E one. After detachment from the basement the Carpathians behaved more or less passively with respect to the underthrusting platform. During that time there began tensional movements in the outer part of the West Carpathians (Burchfiel, Royden, 1982). Consequently, particular segments of the Carpathians might have been involved a strike-slip motion with sense of rotation opposite to that of movement and rotation of the platform. Palaeomagnetic data indicate that the West Carpathians rotated anticlockwise (Krs, *et al.*, 1978; Bażenov *et al.*, 1981) while for the middle and East Carpathian clockwise rotation is characteristic (Fig. 2, Unrug, 1980). In the East Carpathians, tensional deformations leading to the developments of the intra-Carpathian molasse basins (Burchfiel, Royden, 1982), caused a significant migration of the orogen towards the east as well as its stretching. The process of migration began in the Karpatian and persisted till the Pliocene. This may partly explain large differences in length of the internal margin of the platform and the outer and inner limits of the Carpathian arc.

The East European Platform as a whole rotated clockwise, as suggested by palaeomagnetic data (Krs, 1979). This is also consistent with an overall drift of the Euroasian Plate postulated by Talwani, Pitman (1972). There is a view that the motion of the platform was anticlockwise (Khain *et al.*, 1980), however, in light of the preceding discussion this seems to be hardly probable.

During overthrust movements the outer part of the uplifting Carpathians was subjected to large-scale gravity processes which emplaced fragments of the Carpathian nappes into the Miocene basin. Most liable to these processes was the Subsilesian Unit due to its specific lithological developments (Fig. 6).

Translated by dr Szczepan Porębski

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STRESZCZENIE

Fałdowanie łuku karpackiego wywołane zostało kolizją płyty europejskiej z płytą afrykańską wraz z mikropłytą apulijską oraz panońską. Proces nasuwania się i fałdowania Karpat fliszowych został spowodowany kilkakrotnym skróceniem się podłoża geosynklinalnego w jego paraoceanicznych częściach. Najbardziej południowa strefa skracania powstała przy końcu eocenu na styku pienińskiego pasa skałkowego i basenu magurskiego. Dalej na północ położona strefa rozwinęła się w czasie ruchów pirenejskich na przedpolu "wyspy śląskiej". Dla procesu nasuwczego Karpat najważniejszą rolę odegrała jednak regionalna strefa subdukcji usytuowana na styku platformy europejskiej i podłoża geosynklinalnego Karpat zewnętrznych; strefa ta rozwijała się przez cały neogen. Jej obecny ślad w postaci kontaktu podłoża geosynklinalnego i platformowego w Karpatach Zachodnich wyznacza anomalia Wizego (fig. 1). W Karpatach Wschodnich przebieg neogeńskiej strefy subdukcji wyznacza dobrze wykształcone pasmo wulkaniczne. Tworzą je łańcuchy wulkaniczne Vihorlat—Gutin oraz Calimani—Harghita. Wiek tego wulkanizmu w pierwszym przypadku jest badeńsko-sarmacki, w drugim przypadku panońsko-czwartorzędowy (Balla, 1980). W Karpatach Zachodnich zasadniczo brak jest wapienno-alkalicznego łańcucha wulkanicznego, który można by wiązać wprost ze strefą subdukcji. Spowodowane to zostało prawdopodobnie zbyt płaskim podsuwaniem się platformy europejskiej pod orogen karpacki.

Jak wynika z istniejących danych Karpaty Zachodnie zostały sfałdowane w wyniku kompresji już w miocenie dolnym. W wyższej części dolnego miocenu dalszy ruch podsuwczy platformy europejskiej spowodował odkorzenienie się tej części Karpat fliszowych od ich położa. W Karpatach Wschodnich odkorzenienie nastąpiło później na skutek fałdowania jednostki borysławsko-pokuckiej i samborsko-rożniatowskiej. Strefę graniczną między Karpatami Zachodnimi i Wschodnimi stanowi tak zwana sigmoida przemyska. Po odkorzenieniu się Karpaty fliszowe zaczęły się zachowywać biernie w stosunku do podsuwającej się platformy. W brzeżnej części Karpat Zachodnich w tym czasie zaznaczały się ruchy rozciągające (Burchfiel, Royden, 1982). W ich następstwie poszczególne segmenty tej części Karpat mogły wykonać względny ruch przesuwczy z rotacją przeciwną do kierunku ruchu i rotacji platformy. Potwierdzają to badania paleomagnetyczne (Krs, Pruner, 1978; Bażenov *et al.*, 1981).

W Karpatach Wschodnich w wyniku odkształceń tensyjnych związanych z powstawaniem wewnętrznokarpackich basenów molasowych (Burchfiel, Royden, 1982) od karpatu do pliocenu trwało aktywne przemieszczanie się Karpat ku wschodowi. W ten sposób można tłumaczyć, przynajmniej częściowo, duże różnice pomiędzy długością wewnętrznej krawędzi platformy a zewnętrznym brzegiem Karpat, a także między tym ostatnim a wewnętrznym obwodem Karpat fliszowych.

Ruch podsuwczy platformy europejskiej pod orogen karpacki odbywał się przypuszczalnie wzdłuż szeregu dyslokacji poprzecznych, dzielących platformę na liczne bloki. Bloki te w neogenie wykonały zróżnicowane ruchy: blok zachodni (masyw czeski) ku południowemu wschodowi, blok centralny ku południowi, a blok wschodni ku południowemu zachodowi oraz zachodowi (fig. 9, 10, 11, 12). Platforma europejska w całości wykonała ruch prawoskrętny, na co wskazują dane paleomagnetyczne (Krs, 1979). Ruch ten jest zgodny z kierunkiem dryftu kry euroazjatyckiej (Talmani, Pitman, 1972).