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PALINSPASTIC RECONSTRUCTION OF THE CARPATHIAN ARC BEFORE THE NEOGENE TECTOGENESIS

(2 figs.)

Rekonstrukcja palinspastyczna łuku karpackiego przed tektogenezą neogeńską

(2 fig.)

Abstract: The Carpathian arc has a heterogeneous structure formed during Cretaceous and Paleogene tectogenetic phases. Before the Neogene tectogenesis, flysch sediments were deposited in the Outer Flysch Belt and in the Pieniny Klippen Belt. The palinspastic reconstruction of these flysch basins based upon facies analysis and sedimentological data leads to the conclusion that the outward displacement of the Western and the Eastern Inner Carpathian Blocks during the Neogene tectogenesis was differential. This differential movement caused the deformation of the Szolnok Flysch Belt extending in the basement of the Great Pannonian Basin. A clockwise rotational component in the displacement of the Inner West Carpathians and resulting sinistral strike-slip shearing is probably responsible for the peculiarities of the tectonic structure of the Pieniny Klippen Belt.

INTRODUCTORY REMARKS

Numerous papers proposing various plate tectonic models for the Carpathian arc were published recently (Dewey and Bird 1970, Smith 1971, Dewey et al. 1973, Radulescu and Sandulescu 1973, Bleahu et al. 1973, Szadeczky Kardoss 1973, 1975, 1976, Boccaletti et al. 1973, Hertz and Savu 1974, Grubić 1974, Ney 1975, 1976, Birkenmajer 1976, Sikora 1976, Książkiewicz 1977). Some of the proposed models are burdened by assumptions based on misinformation or inprecise use of terminology, as indicated by Hertz and Savu (1974) and Książkiewicz (1977).

Nearly all these papers consider the problem of crustal shortening in the Carpathian arc and discuss the paleogeographic zonation, but no palinspastic reconstructions were presented. However the problem of spatial relations of various parts of the Carpathian arc is of great

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importance for critical evaluation of the proposed geodynamic models. The task of palinspastic reconstructions in the Carpathian arc is complicated. Specific estimates of crustal shortening were published only for some parts of the Carpathians, i.e. for the Polish part of the Outer Flysch Belt (Książkiewicz 1962) and for the Pieniny Klippen Belt (Scheibner 1963).

The Carpathian arc was formed during several tectogenetic phases of the Alpine orogeny. The present paper proposes a palinspastic reconstruction of the paleogeography of the Carpathians during Paleogene time, that is after the Cretaceous tectogenetic phases which deformed the inner regions of the Carpathians — and before the Neogene tectogenetic phases which deformed the outer regions of the Carpathians. The reconstruction is based largely on detailed sedimentological and facial studies of flysch deposits. These studies are developed in an unequal degree in the various parts of the Carpathians, thus leading to major generalizations in some areas. Two points of major importance are incorporated in the presented palinspastic reconstruction. First, the eastern extremity of the Pieniny Klippen Belt was found to pass south of the western extremity of th Inner East Carpathians (Patrulius et al. 1960, Sandulescu 1975b). Secondly, the opinion that the main deformation of the Pieniny Klippen Belt is post-Paleogene is receiving an ever growing support as geological evidence is accumulating (Książkiewicz 1972, Leško and Samuel 1968, Marschalko et al. 1976). The consequences of these findings for the evolution of the Carpathian arc are discussed in some detail.

STRUCTURAL DIVISION OF THE CARPATHIAN ARC

Although the Carpathians are forming a geometrically nearly perfect arc, their structure is markedly non-uniform (Fig. 1). The following major structural units are distinguished in the Carpathian arc and its interior:

- the Foreland,
- the Foredeep, with an inner zone folded and thrust over the outer zone,
- the Outer Flysch Belt,
- the Inner East Carpathians,
- the Pieniny Klippen Belt,
- the Inner West Carpathians,
- the Apuseni Mts,
- the Southern Carpathians,
- the Neogene basins superposed on various older structural units.

The following brief description of these units is based on recent structural syntheses by Andrusov (1965, 1968), Książkiewicz (1972), Sandulescu (1975b) and Mahel (1974).

The Foreland

The western extremity of the Carpathian Foreland is formed by the Bohemian Massif, and farther east extend several structural units representing pre-Cambrian and epi-Variscan platforms. The Carpathians are thrust outward on their Foreland. Drilling exploration brings accumulating evidence of prolongation of various Foreland units under the outer zone of the fold belt. Recent summaries of this problem for the Polish part of the Carpathians were published by Ślączka (1976a) and Wdowiarz (1976).

The Foredeep

The Foredeep forms a continuous zone along the whole Carpathian arc, and is filled with sediments of Miocene-Pleistocene age, lying on Proterozoic, Paleozoic and Mesozoic rocks of the Foreland. The upper age limit of the sedimentary fill of the Foredeep is progressively younger towards the East and South, ranging to the end of Early Badenian in the western sector of the Foredeep, to the end of Badenian in the central sector, and to Pliocene and Pleistocene in the eastern and southern sectors.

The sedimentary fill of the Foredeep Basin consists of predominantly detrital rocks ranging in grain size from coarse conglomerates to marly clays, with two saliferous horizons. Its thickness ranges from 600 m in the western sector, to c. 4000 m in the northern part of the eastern sector, and c. 10 000 m at the south-eastern bend of the Carpathian arc.

The autochtonous sedimentary fill of the Foredeep is downfaulted and overriden by the inner zone of the Foredeep, deformed in the Neogene tectogenesis, and by the Outer Flysch Belt.

The belt of folded Miocene rocks thrust over the autochtonous fill of the Foredeep is present in front of the nappes of the Outer Flysh Belt in the Eastern Carpatians. In the innermost part of this zone the Borislav—Pokuty nappe consists of Lower Miocene rocks overlying the Cretaceous-Paleogene flysch. In the western Carpathians the zone of folded Miocene rocks at the front of the Outer Flysch Belt is discontinuous and poorly developed. Late folding affected the Pliocene sediments in the south-eastern part of the Foredeep.

The Outer Flysch Belt

The Outer Flysch Belt forms a continuous zone extending along the whole Carpathian arc. The age of the Flysch sequence ranges from Late Tithonian to Late Oligocene (Earliest Miocene). Both longitudinal and transverse facial diversity is conspicuous especially during Late Cretaceous and Eocene. The major part of the flysch sequence consists of detrital rocks whose material was supplied from marginal and intrabasinal tectonic lands (cordilleras) intermittently uplifted and eroded.

The folded flysch rocks form several décollement nappes thrust outwards, with minor backward thrusts present at the inner margin of the Outer Flysch Belt. The tectonic deformations operated in two phases, the first one Early Miocene (pre-Badenian), the second one post-Early Badenian. The latter phase migrated in time from the western to the eastern part of the Outer Flysch Belt, where progressively younger Miocene rocks are folded at the front of the Flysch Belt. The whole Flysch Belt was pushed outward en bloc during these movements, as indicated by the presence of undeformed Late Badenian sediments overlying the Flysch nappes.

The Inner East Carpathians

The Inner East Carpathians (Dacides orientales of Sandulescu, 1975 b), are contiguous to the inner margin of the Outer Flysch Belt. They consist of several nappes thrust eastward, composed of continental-volcanogenic Permian — marine Triassic-Jurassic-Early Cretacecous sedimentary cover, and crystalline pre-Alpine basement present in some of the nappes. The eastern zone of the Inner East Carpathians consists of nappes with Late Jurassic-Early Cretaceous flysch, partly resting upon and intercalating with Jurassic basic effusive rocks. The outermost nappe of this zone (the Ceahlau nappe) was emplaced during Late Senonian tectogenetic phase, while all other nappes of the Inner East Carpathians were emplaced during the mid-Cretaceous, pre-Cenomanian phase. The post-tectonic cover of Cenomanian-Oligocene age begins with conglomerates followed by red marls, limestones (Late Cretaceous) and Paleogene Flysch.

The Pieniny Klippen Belt

The Pieniny Klippen Belt, flanking from the south the western part of the Outer Flysch Belt, is forming a very narrow and elongated unit (width locally inferior to 1 km, maximum c. 20 km, length c. 600 km), with an extremely complex tectonic structure. No crystalline basement rocks are involved in the structure of the Pieniny Klippen Belt. The marine sedimentary sequence comprises Jurassic, Cretaceous and Paleogene rocks. Triassic rocks are present only locally.

The structure of the Pieniny Klippen Belt is very irregular, but in some areas it is possible to distinguish two major nappes. The main tectogenetic phase is post-Paleogene, while earlier mid-Cretaceous and late Cretaceous phases produced local tectonic deformations. The extent of these earlier deformations is a matter of debate.

The Inner West Carpathians

The Inner West Carpathians consist of a pile of nappes thrust northward, and composed of a sedimentary cover comprising continental-volcanogenic Permian — marine Triassic-Jurassic-Cretaceous up to Cenomanian inclusive (marine Carboniferous is present in the southern nappes), and a crystalline basement existing in some of the nappes. The crystalline basement consists of pre-Cambrian and Early Paleozoic parametamorphic rocks and Variscan granitoids. Small granitoid plutons of Late Cretaceous age and coeval epizonal metamorphism are present in the southern part of the Inner West Carpathians (Varček 1973).

The tectogenesis is pre-Senonian. The post-tectogenetic cover consists of Senonian and Paleogene rocks, the latter developed mostly in nummulitic limestone and flysch facies.

The Apuseni Mts.

The Apuseni Mts. consist of two structural units, forming the northern and the southern part of this zone. The Northern Apuseni comprise the Bihor Massif composed of a pre-Alpine crystalline basement and a sedimentary cover including continental volcanogenic Permian — marine Triassic-Jurassic-Cretaceous (up to Lower Turonian), with epizodic continental sedimentation in Early Jurassic and Early Cretaceous. The Bihor Massif is overriden by a pile of nappes thrust northward, consisting of pre-Alpine crystalline basement and continental-volcanogenic Upper Carboniferous-Permian and marine Triassic-Jurassic-Lower Cretaceous sedimentary cover. The deformation is pre-Senonian. The post tectogenetic cover begins with the Lower Senonian.

The Southern Apuseni (Metaliferi Mts.) are composed of Jurassic ophiolites and a Tithonian-Lower Cretaceous sedimentary cover. The tectogenesis is polyphase with mid-Cretaceous and Late Cretaceous deformations. The post-tectogenetic cover of Late Cretaceous age is developed partly in flysch facies.

The Southern Carpathians

The Southern Carpathians consist of nappes thrust southward on the autochtonous Danubian domain. The sequence of continental-volcanogenic Permian and marine Triassic-Jurassic-Lower Cretaceous (with a major lacune in Late Triassic and continental Lower Jurassic), and slices of crystalline and sedimentary pre-Alpine basement are forming the nappes emplaced during the Late Senonian tectogenetic phase. Earlier deformations attributed to mid-Cretaceous tectogenetic phase are also present.

The Neogene Basins

Three major basins downfaulted and filled by Neogene and Quaternary sediments and volcanic rocks are superposed on various structural units of the Carpathians. These are, listed from the west to the east: the Vienna basin, the Pannonian Basin and the Transylvanian Basin.

The Vienna Basin is superposed on the Outer Flysch Belt, the Pieniny Klippen Belt and the Inner West Carpathians. The basement of the Transylvanian Basin is incompletely known because of the large thickness of the sedimentary fill (Sandulescu 1975 a).

The basement of the Pannonian Basin is fairly thoroughly investigated (Balogh and Korossy 1968, 1974), and this area provides important data for the palinspastic reconstruction of the Carpathians.

The basement of the Pannonian Basin is composed of Pre-Cambrian and Lower Paleozoic crystalline rocks, covered by Upper Paleozoic and Mesozoic marine sedimentary rocks. Marine sedimentation persisted since the Carboniferous through the Permian with minor breaks in continuity and lasted into Mesozoic time. Basic submarine volcanic rocks of Triassic and Early Cretaceous age reach locally great thickness. The area was subject to pre-Senonian folding, but in contrast with other structural units no nappes were formed.

The Senonian is post-tectogenetic in the major part of the area, with predominant marl and limestone facies, while an elongated basin filled with flysch sediments was formed in Late Cretaceous in the Debrecen—Szolnok—Szeged area. The flysch sequence known from subsurface data comprise the Senonian, Eocene and Oligocene. This Szolnok Flysch is intensely folded in post-Paleogene (and possibly also Late Senonian) tectogenetic phase.

Neogene faulting strongly affected the area, producing horsts in which Mesozoic and Paleozoic rocks are exposed, forming the Bükk, Bakony—Vertes, Mecsek and Villany ranges.

Some relations of the Inner Carpathian Units

The Northern Apuseni Mts. show facial and structural affinities with the Inner West Carpathians during Late Paleozoic and Mesozoic times until the pre-Senonian tectogenetic phase (Sandulescu 1975 b), although the proposed correlations are debatable. The Szolnok Flysch Basin, since its formation in Senonian time, formed the zone separating the structural units situated to the west (Inner West Carpathians and the western part of the basement of the Pannonian Basin, including the Bükk, Mecsek and Villany zones), and to the east of it (Apuseni Mts., basement of Transylvanian Basin, Inner East Carpathians, Southern Carpathians). The regions situated on the two sides of the Szolnok Flysch Basin behaved differently during the Neogene tectogenetic phases, and for that reason they are termed here the Inner West Carpathian Block and the Inner East Carpathian Block.

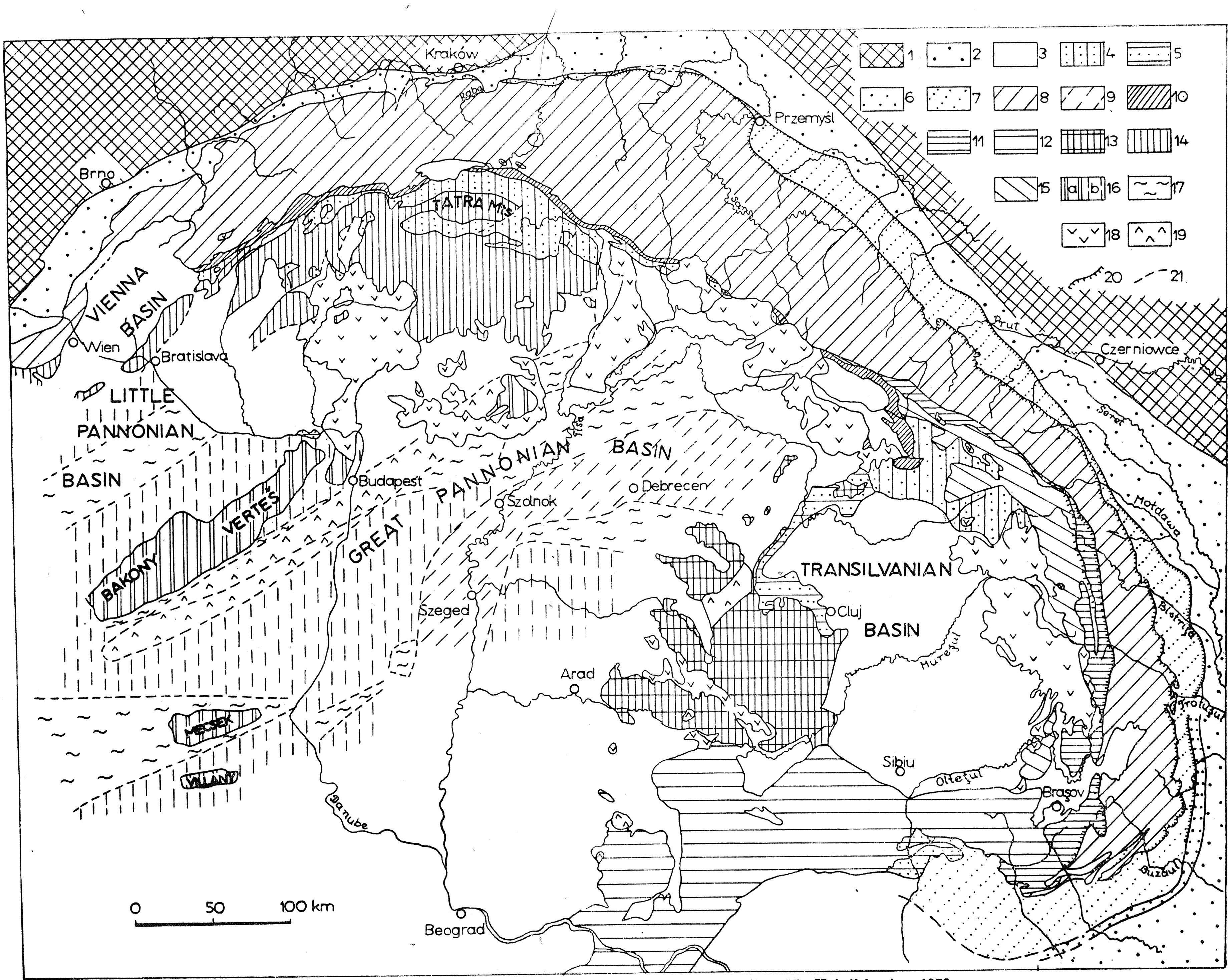

Fig. 1. Principal structural units of the Carpathians. After M. Książkiewicz 1972, Sandulescu 1975b, Balogh and Korossy 1968. Foreland and foredeep: 1 — Foreland; 2 — Foredeep: Neogene and Quaternary not folded. Post tectogenetic cover: 3 — Neogene and Quaternary in intramontane basins, not folded. (Basement of sedimentary fill shown in parts of the Little Pannonian Basin and the Great Pannonian Basin); 4 — Paleogene flysch, weakly folded (Central Carpathian Flysch around the Tatra Mts., Maramures Flysch north of the Transilvanian Basin); 5 — Paleogene in epicontinental marine facies. Structural units formed in Neogene tectogenesis: 6 — folded Pliocene; 7 — folded Miocene, partly overlying Cretaceous — Paleogene Flysch; 8 — Outer Flysch Belt; 9 — Szolnok Flysch Belt (folded Senonian — Paleogene flysch in the basement of the Great Pannonian Basin); 10 — Pieniny Klippen Belt. Structural Units formed in Late Senonian tectogenesis: 11 — The Ceahlau nappe of the Inner East Carpathian Flysch; 12 — South Carpathians. Structural units formed in pre-Senonian tectogenesis: 13 — Apuseni Mts.; 14 — Inner West Carpathians. Structural units formed in pre-Cenomanian tectogenesis: 15 — Inner East Carpathians. Basement of the Little Pannonian Basin and Great Pannonian Basin: 16 — Upper Permian and Mesozoic, weakly folded, a — cropping out, b — under Neogene sedimentary cover; 17 — metamorphic rocks. Volcanic belts: 18 — Neogene and Quaternary; 19 — Late Cretaceous and Paleogene; 20 — major overthrusts; 21 — approximate boundaries

Fig. 1. Główne jednostki strukturalne Karpat. Według: Książkiewicz 1972, Sandulescu 1975b, Balogh i Korossy 1968. Przedgórze i rów przedgórski: 1 — Przedgórze; 2 — rów przedgórski: neogen i czwartorzęd nie sfałdowany. Pokrywa post-tektoniczna: 3 — neogen i czwartorzęd w zapadliskach śródgórskich, nie sfałdowany (podłoże post-tektonicznego wypełnienia osadowego przedstawione dla Małej i Wielkiej Niziny Węgierskiej); 4 — flisz paleogeński, słabo sfałdowany (flisz Podhala i Zachodnich Karpat Wewnętrznych, flisz marmaroski); 5 — paleogen w facji morskiej epikontynentalnej. Jednostki utworzone podczas tektogenezy neogeńskiej: 6 — pliocen sfałdowany; 7 — miocen sfałdowany, częściowo leżący na fliszu kredowo-paleogeńskim (w fałdach pokucko-borysławskich); 8 — flisz Karpat Zewnętrznych; 9 — flisz Szolnok (sfałdowany flisz senońsko-paleogeński w podłożu Wielkiej Niziny Węgierskiej; 10 — Pieniński Pas Skałkowy. Jednostki utworzone podczas tektogenezy późno-senońskiej: 11 — płaszczowina Ceahlau fliszu Wschodnich Karpat Wewnętrznych; 12 — Karpaty południowe. Jednostki utworzone podczas tektogenezy przed-senońskiej: 13 — Góry Apuseni; 14 — Zachodnie Karpaty Wewnętrzne. Jednostki utworzone podczas tektogenezy przed-cenomańskiej: 15 — Wschodnie Karpaty Wewnętrzne. Podłoże Małej i Wielkiej Niziny Węgierskiej: 16 — górny perm i mezozoik słabo sfałdowany, a — na powierzchni, b — pod neogeńską pokrywą osadową; 17 — skały metamorficzne. Skały wulkaniczne: 18 — neogeńskie i czwartorzędowe; 19 — późnokredowe i paleogeńskie oraz banatyty; 20 — nasunięcia rozgraniczające jednostki strukturalne; 21 — granice przybliżone

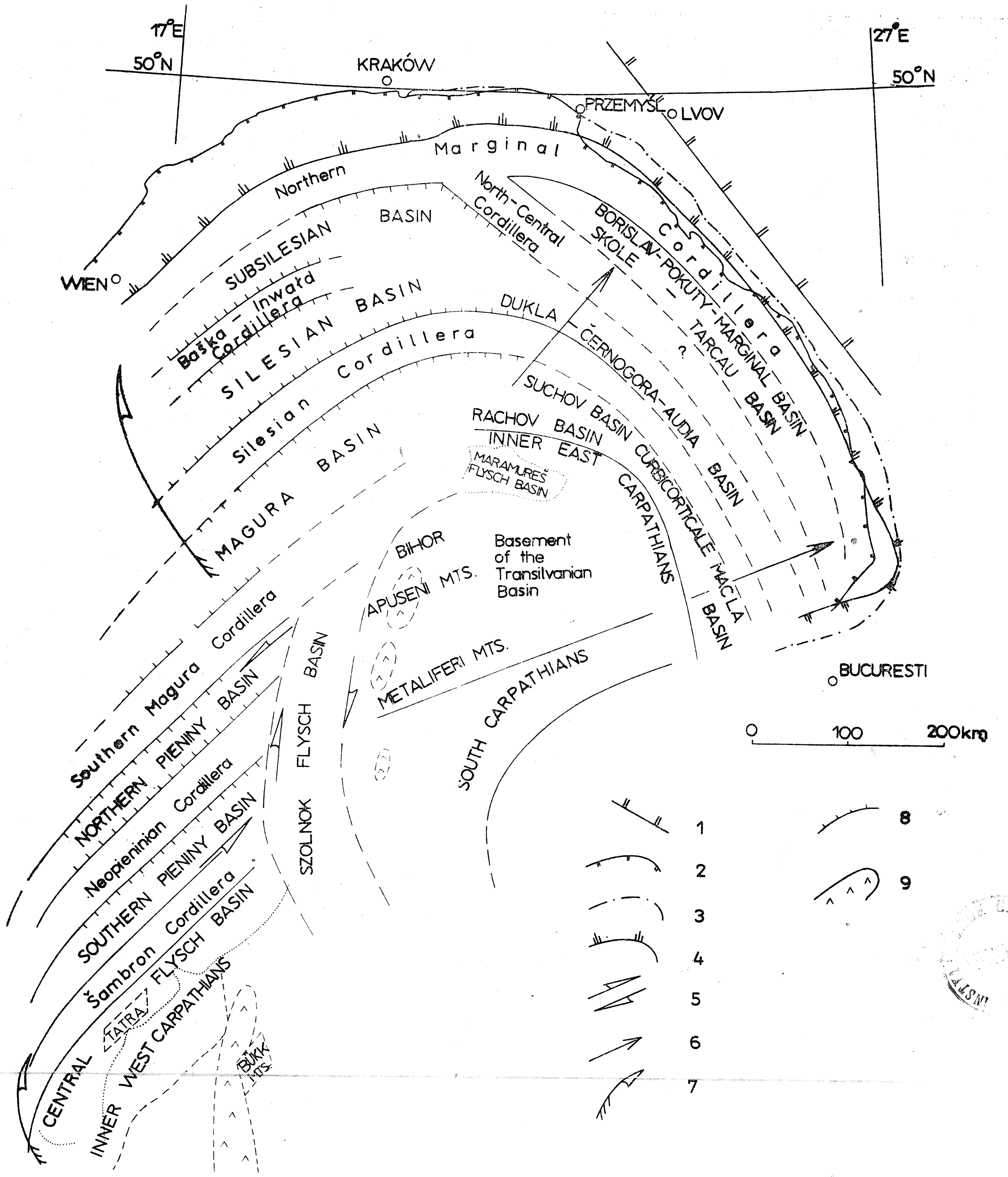

Fig. 2. Palinspastic reconstruction of the Carpathians before the Neogene tectogenesis. The reconstruction is made with reference to the present position of the foreland of the Carpathians for which the geographic coordinates are given. 1 — South-western margin of the East-European platform; 2 — Northern and Eastern boundary of the Outer Flysch Belt consisting of nappes thrust outwards; 3 — Northern and Eastern boundary of the belt of folded Neogene sediments in front of the Outer Flysch Belt; 4 — Southern and South-Western boundary of the Foreland platform, indicated by the axis of the negative granimetric anomaly; 5 — Strike-slip displacement and shearing; 6 — Direction of thrusting in Neogene tectogenesis; 7 — Direction of thrusting and clockwise rotation in Neogene tectogenesis; — 8 — Zones of insular shelfs associated with cordilleras with shallow-water sedimentation during Cretaceous and Paleogene; 9 — Late Cretaceous and Paleogene kalk-alkaline volcanism and plutonism (andesites between the Inner West Carpathians and the Bükk Mts., banatites in the Apuseni Mts.)

The sedimentary sequences of the basins are forming the individual nappes of the Outer Flysch Belt. The positions of the basins are reconstructed from data on the tectonic structure of the Outer Flysch Belt and the Pieniny Klippen Belt. The positions of the cordilleras are reconstructed on the basis of facial and sedimentological data.

Fig. 2. Rekonstrukcja palinspastyczna Karpat przed tektogenezą neogeńską. Rekonstrukcję opracowano w odniesieniu do obecnej pozycji przedgórza Karpat. 1 — południowo-zachodnia krawędź platformy wschodnio-europejskiej; 2 — północna i wschodnia granica nasuniętego fliszu Karpat Zewnętrznych; 3 — północna i wschodnia granica sfałdowanych osadów neogeńskich; 4 — południowa i południowo-zachodnia granica platformowego przedgórza Karpat wyznaczona przebiegiem ujemnej anomalii grawimetrycznej; 5 — strefy przemieszczeń przesuwczych i ścinania; 6 — kierunek nasunięć podczas tektogenezy neogeńskiej; 7 — kierunek nasunięć i rotacji zgodnej z ruchem wskazówek zegara podczas tektogenezy neogeńskiej; 8 — strefy szelfów wyspowych wokół kordylier — miejsce płytkowodnej sedymentacji węglanowej; 9 — późnokredowy i paleogeński wulkanizm wapienno-alkaliczny (andezyty w podłożu Wielkiej Niziny Węgierskiej) oraz banatyty w Górach Apuseni.

THE PALINSPASTIC RECONSTRUCTION

General remarks

The palinspastic reconstruction presented in this paper shows the inferred paleography of the basins deformed in the Neogene tectogenetic phases, and the presumed position of various Inner Carpathian Units after the Cretaceous tectogenetic phases, during Paleogene time.

The zones for which the paleography of the sedimentary basins is reconstructed in some detail are: the Outer Flysch Belt and the Pieniny Klippen Belt. The reconstruction is possible owing to the continuity of these two belts and the advanced state of basin analysis research in these two zones of the Carpathians. Some geophysical data and informations provided by deep bore-holes are also used.

The southern margin of the Foreland Platforms

The Precambrian, Paleozoic, Mesozoic and Tertiary rocks of the Carpathian Foreland and Foredeep are step-faulted and downthrown towards the Carpathians along the whole arc. Bore-holes reached these platform deposits under the overriding Outer Flysch Belt at distances up to c. 30 km south of the outer front of the flysch nappes in the area south of Kraków (Ślączka 1976a).

The southern margin of the Foreland Platforms is indicated presumably by the negative gravimetric anomaly extending along the whole Carpathian arc. This anomaly runs along the axis of the Vienna basin and along the northern boundary of the Pieniny Klippen Belt up to the meridian of Kraków, then continues due east across the Outer Flysch Belt, intersecting its external boundary south of Przemyśl. Farther east, the anomaly continues along the outer margin of the Outer Flysch Belt, then re-enters the area of the Outer Flysch Belt, leaving it again in the area of the Vrancea seismic zone, and bending along the outer margin of the South Carpathians (Fig. 2).

In the sectors where the negative gravimetric anomaly runs in the Foredeep area it marks the zone of the greatest thickness of the sedimentary fill. Deep seismic sounding indicated that the Moho discontinuity reaches the greatest depth of c. 50 km at, or near the line of negative gravimetric anomaly. Along the Pieniny Klippen Belt the Moho discontinuity rises stepwise to the depth of 30—35 km. This is a common feature of the Deep Seismic Sounding Profiles III/IV, V, and VI (Sollogub et al. 1973, Szenas 1972).

The Outer Flysch Basin

The northern margin of the Outer Flysch Basin is placed in the palinspastic reconstruction along the line of the negative gravimetric anomaly, that is at the presumed boundary of the Foreland Platforms.

The palinspastic reconstruction of the Outer Flysch Basin should provide space for three types of paleogeographic units, namely:
— the sedimentary basins of the various flysch sequences forming the individual nappes of the Outer Flysch Belt;
— the tectonic lands — cordilleras — active as source areas of detrital material;
— the belts of shallow water carbonate sediments, found in the flysch sequences as olistoliths, pebbles in conglomerates, resedimented bioclastic arenite material and carbonate matrix in sandstones.

The amount of evidence available for these three types of paleogeographic units is unequal. Instead, their mutual relations are reasonably well established. The Flysch sequences of the individual nappes are generally different, and it is concluded that they were deposited in individualized sedimentary basins. Nearly uniform conditions of sedimentation existed only during the early and final stages of evolution of the Outer Flysch Basin, in Early Cretaceous and Oligocene time. Studies of facies distribution, thickness of sediments and paleocurrent systems indicate the position of source areas of clastic material — the cordilleras — at the margins of the Outer Flysch Basin and within it, where they separated the individual basins of the various flysch sequences. Presumably each cordillera had an insular shelf zone, and carbonate sediments formed there were redeposited in deeper flysch basins by turbidity currents and various types of gravity sediment flows (Książkiewicz 1956, 1960, 1962, 1965, Dumitriu and Dumitriu 1968, Eliaš 1963, Ślączka 1976 b, Unrug and Wendorff 1976, Malik 1978).

The most realistic estimate can be made concerning the original width of the sedimentary basins of the flysch sequences. The present width of the pile of the flysch nappes forming the Outer Flysch Belt ranges from c. 60 to c. 110 km. After pushing back the overthrusts and stretching out the folds, the original width of the basins of the flysch sequences is estimated on purely geometric ground as not less than 120—220 km (Świdziński 1971). Yet, taking into consideration the facial belts destroyed during tectonic deformations and subsequent erosion, and known only from exotic blocks, e.g. the Bachowice facies (Książkiewicz 1954), the width of the flysch basins is estimated as not less than 300 km (Książkiewicz 1962, Geroch et al. 1967).

The location of major cordilleras is evidenced in detail for the western part of the Outer Flysch Belt (Książkiewicz 1962, 1965). Five major cordilleras are reconstructed there:
— the northern marginal cordillera,
— the north-central cordillera,
— the Baška — Inwałd cordillera,
— the Silesian Cordillera
— the southern (marginal) Magura cordillera.

The cordilleras were intermittently uplifted and supplied large amounts of detrital material to the flysch basins. There are no data permitting to estimate directly the dimensions of the cordilleras. The volume of turbidite submarine fans recognized in the flysch sequences provide some guidance for evaluation based upon the amount of detrital material supplied by the individual cordilleras. Some time ago the present writer (Unrug 1968) supposed that the cordilleras were extremely narrow (width in the range of 20 km). However an estimate of width of a cordillera close to 50 km seems now to be more realistic. The sum of width of the cordilleras in the western part of the Outer Flysch Belt is estimated as c. 200 km.

The width of the belts of shallow water sediments can not be estimated directly. Petrographically these sediments are represented by biogenic limestones (lithotamnium and nummulitic limestones), foraminiferal marls, and calcareous algal detritus fairly ubiquitous (Książkiewicz 1958, 1965, Eliaš 1963, Alexandrowicz et al. 1966, Bieda 1968, Unrug 1968, Ślączka 1971, Malik 1978). The carbonate matrix of flysch sandstones is also derived from shallow water carbonates (Unrug and Wendorff 1976).

The cumulative width of the insular shelves fringing the cordilleras in the western part of the Outer Flysch Basin is estimated as c. 60 km.

The total width of the western sector of the Outer Flysch Basin is estimated therefore as 500—600 km. This value is considered as a minimum. The same criteria can be applied to the eastern part of the Outer Flysch Basin. The width of the Outer Flysch Belt is smaller there, and the number of intrabasinal cordilleras was probably lower than in the western part of the basin. The total width of the eastern sector of the Outer Flysch Basin is estimated as c. 250—300 km.

The Pieniny Klippen Basin

The reconstruction of the Pieniny Klippen Basin is based upon two main premises:
— the continuation of the Pieniny Klippen Belt on the inner side of the Inner East Carpathians in the Poiana Botizei area (Patrulius et al. 1960, Sandulescu 1975b);
— the Neogene age of the major tectogenetic phase in the Pieniny Klippen Belt.

It should be recalled that according to some opinions mid-Cretaceous and late-Cretaceous folding phases were supposed to be of great importance in the structure of the Pieniny Klippen Belt (Andrusov 1965, 1968, Birkenmajer 1960, 1963, 1970). However, stratigraphic research proved the presence of a continuous Cretaceous sequence and of a continuous Cretaceous-Paleogene passage (Birkenmajer 1953, Sokołowski 1954, Książkiewicz 1956, 1958b, 1960—63, Książkiewicz and Mitura 1964, Alexandrowicz 1966, Alexandrowicz et al. 1962, Salaj and Samuel 1966, Leško and Samuel 1968, Sikora 1971). According to Książkiewicz (1972) pre--Paleogene tectogenetic phases were marked chiefly by faulting and some uplifts, but no large scale thrusts.

An important consequence follows from the above: while the inner border of the eastern sector of the Outer Flysch Belt was contiguous to the folded belt of the Inner East Carpathians, the Pieniny Klippen Basin was situated between the western part of the Outer Flysch Basin and the folded belt of the Inner West Carpathians.

The evolution of the Pieniny Klippen Basin is Late Cretaceous and Paleogene time is dominated by deposition of flysch sediments accompanied by red marls and shales. Recent research proved the presence of a continuous flysch sequence of Albian-Middle Eocene age (Książkiewicz and Mitura 1964, Leško and Samuel 1968, Andrusov and Samuel 1973, Marschalko 1973, Marschalko et al. 1976, Sikora 1971, Radwański 1978). During Paleogene time the Pieniny Klippen Basin was divided into two troughs separated by a tectonic land which supplied detrital material to the both troughs. This tectonic land is termed "Neopieninian Cordillera" by Slovakian geologists (Marschalko et al. 1976). Reef limestones of Cretaceous and Paleogene age doposited in a shallow water zone fringing in the south the Neopieninian Cordillera form an important constituent of the clastic material and olistoliths of the southern flysch trough of the Pieniny Klippen Belt (Birkenmajer and Lefeld 1969, Borza 1966, Marschalko et al. 1976).

The palinspastic reconstruction of the Pieniny Klippen Basin should accomodate therefore, similarly as in the case of the Outer Flysch Basin, the width of the sedimentary basins of the flysch sequences, the width of the Neopieninian cordillera and the width of the shallow water zones. Estimates of the width of the sedimentary basins of the flysch sequences are highly uncertain because of the complicated tectonic structure. An estimated value of 60 km as the width of the basins was published (Książkiewicz 1972). Assuming the width of the Neopieninian cordillera as 50 km, and the width of the shallow water zones on both sides of the cordillera as 30 km, a total width of 140 km is obtained for the whole Pieniny Klippen Basin, as a conservative estimate.

Paleogene flysch basins in the Inner Carpathians

Two sedimentary basins filled with flysch sediments of Paleogene age were formed on the folded ranges of the Inner East Carpathians (the Maramureš Flysch) and of the Inner West Carpathians (the Podhale Flysch of the Polish authors, called Central Carpathian Flysch in Slovakia). A third flysch basin persisted since Senonian time on the area of the future substratum of the Pannonian Basin.

The Maramures Flysch of Eocene-Oligocene age had its source area of detrital material west of the sedimentary basin (Contescu et al. 1966). The West Central Carpathians Flysch of Middle Eocene — Early Oligocene age received the clastic material from the Šambron cordillera which formed the northern margin of the folded Inner West Carpathians, and from several local sources within the Inner West Carpathians (Marschalko and Radomski 1960, Marschalko 1968). The flysch sediments, exposed at the surface in these two basins are only slightly deformed.

The third flysch basin of the Szolnok Flysch of Senonian-Paleogene age, known from subsurface data in the substratum of the Neogene fill of the Pannonian Basin, is strongly deformed. This basin, elongated North-East — South-West is 30—60 km wide (Balogh and Korossy 1968). There are no data allowing to estimate the original width of the Szolnok Flysch Basin. It was certainly larger than the present width of the folded basin, and in the palinspastic reconstruction it has been assumed as c. 80 km.

The relation of the Outer and the Inner Carpathians

The relation of the Outer zones of the Carpathians folded during the Neogene, and of the Inner zones folded during Cretaceous time is different in the eastern and the western part of the Carpathian arc. The Inner East Carpathians were separated from the margin of the Foreland Platforms by the Outer Flysch Basin, while the Inner West Carpathians were separated from the margin of the Foreland Platforms by the Outer Flysch Basin and the Pieniny Klippen Basin. Therefore, the Inner West Carpathians were situated during Paleogene time at a greater distance from the margin of the Foreland Platforms than the Inner East Carpathians. During Neogene tectogenetic phases the two Inner Carpathian Blocks were pushed outwards while the Outer Flysch Belt and the Pieniny Klippen Belt were deformed into thrust sheets and folded. The Szolnok Flysch Basin was deformed then by differential movement of the two blocks, and associated large-scale dextral strike-slip displacement.

From the inferred position of the Inner West Carpathians during Paleogene time it follows that a rotational component was included in the movement of this block in relation to the Outer zone of the Carpathian arc. Paleomagnetic data indicate post-Permian clockwise rotation of the Inner West Carpathians by 45° (Kotasek and Krs 1965). If this rotation, or a part of it occurred during Neogene movements, it would fit well in the presented palinspastic reconstruction.

The Inner West Carpathians are contacting with the Pieniny Klippen Belt along a fault, and if a rotation of the Inner West Carpathians is assumed, a sinistral strike-slip displacement along this fault is a geometric consequence. Such a displacement and associated shearing could be responsible for a part of the structural complications of the Pieniny Klippen Belt. Several authors indicated the possibility of interpreting the tectonic structures of some parts of the Pieniny Klippen Belt as mega-boudinage (Świdziński 1961, Scheibner 1961). The idea of boudinage structures in the Pieniny Klippen Belt was proposed first by Lugeon (1903), who associated this style of deformation with northward arching of the Pieniny Klippen Belt. However, the eastern part of the Pieniny Klippen Belt is markedly rectilinear, and just there the boudinage type of deformations is most distinctly developed, thus indicating shearing along a strike-slip fault.

Two opinions pertaining to the problem discussed here were expressed recently, on the basis of detailed studies of mesotectonic structures along a small portion of the southern border of the Pieniny Klippen Belt. Morawski (1972) postulated a sinistral strike-slip component of the displacement along the fault separating the Pieniny Klippen Belt and the Central Carpathian (Podhale) Flysch. Such a displacement fits the clockwise rotation of the Inner West Carpathians. This opinion was contradicted by Mastella (1975), who found both sinistral and dextral strike-slip faults in the area. However, the area studied by both these authors is small and their results can not be extrapolated over the entire length of the Pieniny Klippen Belt.

CONCLUSIONS

The proposed palinspastic reconstruction based on paleogeographic interpretation of data obtained by sedimentological basin analysis, provides a kinematic explanation for several structural peculiarities of the Carpathian arc, first of all for the occurrence of the young folded Szolnok Flysch Belt well inside the Inner Carpathians, and for the structural character of the Pieniny Klippen Belt. Clockwise rotation accompanied also northward translation of the Outer Flysch Belt, and this can explain the greater distance of overthrusting of the Outer Flysch Belt on the Foreland in the western part of the Carpathian arc.

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STRESZCZENIE

T r e ś ć: Rekonstrukcja palinspastyczna Karpat przed tektogenezą neogeńską oparta jest na wynikach badań facjalnych, sedymentologicznych i paleogeograficznych. Uwzględniono w niej przebieg wschodniego krańca Pienińskiego Pasa

Skałkowego po wewnętrznej stronie masywu marmaroskiego oraz występowanie sfałdowanego fliszu Szolnok w podłożu Wielkiej Niziny Węgierskiej.

Podczas tektogenezy neogeńskiej bloki Zachodnich Karpat Wewnętrznych i Wschodnich Karpat Wewnętrznych zostały przesunięte ku północnemu wschodowi ruchem różnicowym, fałdując położony pomiędzy nimi flisz Szolnok na prawym uskoku przesuwczym. Blok zachodni Karpat Wewnętrznych wykonał rotację zgodną z ruchem wskazówek zegara co spowodowało deformację Pienińskiego Pasa Skałkowego na uskoku przesuwczym lewym. Także zachodnia część Karpat Zewnętrznych wykonała rotację zgodną z ruchem wskazówek zegara, czego wynikiem jest nasunięcie fliszu na przedpole, o większej amplitudzie niż w Karpatach wschodnich.

Rekonstrukcja palinspastyczna Karpat w czasie paleogenu przedstawia paleogeografię basenów sedymentacyjnych Karpat Zewnętrznych przed ich deformacją w neogeńskich fazach tektogenicznych, oraz przypuszczalne położenie wewnętrznokarpackich jednostek strukturalnych zdeformowanych w kredowych fazach tektogenicznych. Do basenów zdeformowanych w neogenie należą: basen Fliszu Karpat Zewnętrznych ciągnący się wzdłuż całego łuku karpackiego (z przerwą na odcinku Karpat Południowych) i basen Pienińskiego Pasa Skałkowego przylegający od strony wewnętrznej do zachodniego odcinka basenu Fliszu Karpat Zewnętrznych. Rekonstrukcja paleogeografii i ocena szerokości basenów sedymentacyjnych przed deformacją oparte są na prowadzonych od dwudziestu pięciu lat badaniach zmienności facjalnej i systemów paleotransportu materiału klastycznego w seriach fliszowych Karpat.

Przyjęto, że południowa granica pogrążonego pod nasuniętym łukiem karpackim przedmurza wyznaczona jest przez ujemną anomalię grawimetryczną ciągnącą się wzdłuż całego łuku karpackiego (fig. 1, fig. 2).

Rekonstrukcja basenu sedymentacyjnego Fliszu Karpat Zewnętrznych uwzględnia przestrzeń zajmowaną przez:
— baseny sedymentacyjne poszczególnych serii litostratygraficznych tworzących płaszczowiny fliszowe,
— kordyliery dostarczające materiału klastycznego do basenów serii fliszowych,
— strefy płytkowodne gdzie powstawały osady węglanowe, występujące we fliszu w postaci olistolitów, otoczaków egzotycznych, resedymentowanego materiału bioklastycznego i składników węglanowej matrix w piaskowcach fliszowych (fig. 2).

Obecna szerokość pasa fliszu Karpat Zewnętrznych wynosi w jego zachodniej części 60—110 km. Po cofnięciu nasunięć i rozprostowaniu fałdów ocenia się pierwotną szerokość basenów sedymentacyjnych serii fliszowych na 120—220 km na podstawach czysto geometrycznych. Biorąc pod uwagę zniszczenie pewnych stref facjalnych w wyniku procesów tektogenetycznych i erozyjnych można przyjąć, że pierwotna szerokość basenów sedymentacyjnych była większa i wynosiła co najmniej 300 km.

Szerokość kordylier nie może być oceniona bezpośrednio. Szacunkowo przyjęto, że szerokość jednej kordyliery była rzędu 50 km, a łączna szerokość kordylier występujących w przekroju zachodniej części basenu fliszu Karpat Zewnętrznych była rzędu 200 km.

Szerokość stref płytkowodnych tworzących szelf wokół kordylier nie może być oceniona bezpośrednio. Szacunkowo przyjęto ją na 15 km, a łączną szerokość stref płytkowodnych w zachodniej części basenu oceniono na 60 km.

W sumie szerokość basenu sedymentacyjnego fliszu Karpat Zewnętrznych oszacowano na 500—600 km w jego zachodniej części. Dla wschodniej części basenu ilość danych, które mogły być wykorzystane do rekonstrukcji paleogeograficznej, jest mniejsza. Pas fliszowy jest tu węższy niż w części zachodniej, a liczba kordylier jak można wnioskować, była mniejsza niż w części zachodniej. Całkowitą szerokość wschodniej części basenu fliszu Karpat Zewnętrznych oszacowano na 300 km.

Rekonstrukcja basenu Pienińskiego Pasa Skałkowego oparta jest na występowaniu wschodniego zakończenia tego pasa po wewnętrznej (południowej) stronie masywu marmaroskiego, oraz na ciągłości sedymentacyjnej fliszu Pienińskiego Pasa Skałkowego od albu do środkowego eocenu, z czego wynika, że tektogeneza Pienińskiego Pasa Skałkowego jest głównie neogeńska. Przyjęto, że szerokość basenu paleogeńskiego fliszu Pienińskiego Pasa Skałkowego zrekonstruowana na zasadach podanych wyżej była rzędu 150 km.

Podczas paleogenu istniały również trzy baseny fliszowe na obszarze Karpat Wewnętrznych sfałdowanych w kredzie. Są to: basen fliszu podhalańskiego nałożony na Zachodnie Karpaty Wewnętrzne, basen fliszu marmaroskiego nałożony na północną część Wschodnich Karpat Wewnętrznych, oraz basen fliszowy w podłożu Wielkiej Niziny Węgierskiej ciągnący się na linii Debreczyn—Szolnok—Szeged, nazywany tutaj fliszem Szolnok. Flisz marmaroski i flisz podhalański wieku paleogeńskiego są słabo zdeformowane. Natomiast flisz Szolnok reprezentujący interwał stratygraficzny senon-paleogen jest intensywnie sfałdowany. Szerokość pasa występowania fliszu Szolnok, stwierdzona wierceniami wynosi 30—60 km. Pierwotna szerokość basenu tego fliszu była z pewnością większa, brak jednak danych dla jej bezpośredniej oceny. W rekonstrukcji palinspastycznej przyjęto szacunkowo szerokość pierwotną basenu fliszu Szolnok na 80 km jako wartość minimalną.

Jak wynika z powyższej analizy stosunek Karpat Wewnętrznych sfałdowanych w kredzie, do Karpat Zewnętrznych sfałdowanych w neogenie jest różny w zachodniej i we wschodniej części łuku karpackiego: w części wschodniej między krawędzią platformowego przedgórza a Karpatami Wewnętrznymi rozciągał się tylko basen fliszu Karpat Zewnętrznych, natomiast w części zachodniej między krawędzią platformowego przedgórza a Karpatami Wewnętrznymi mieścił się basen fliszu Karpat Zewnętrznych (szerszy niż w części wschodniej) i basen

Pienińskiego Pasa Skałkowego. Amplituda ruchu mas wewnętrznokarpackich względem krawędzi platformy przedgórza podczas tektogenezy neogeńskiej była zatem większa w zachodniej części łuku karpackiego niż w jego części wschodniej. Blok Zachodnich Karpat Wewnętrznych przemieszczał się ruchem różnicowym względem bloku Wschodnich Karpat Wewnętrznych (obejmującego Masyw Marmaroski, Góry Apuseni, Karpaty Południowe i podłoże basenu Transylwańskiego). W wyniku tego względnego przemieszczenia wymienionych dwóch bloków sfałdowany został flisz Szolnok położony pomiędzy nimi.

Z rekonstrukcji palinspastycznej wynika, że blok Zachodnich Karpat Wewnętrznych znajdował się przed tektogenezą neogeńską na zachód od swego obecnego położenia, w odległości stanowiącej sumę składowej wschodniej przemieszczenia bloku Wschodnich Karpat Wewnętrznych i zmniejszenia szerokości basenu fliszu Szolnok podczas ruchów neogeńskich. Przemieszczenie bloku Zachodnich Karpat Wewnętrznych względem położonych na zewnątrz basenów Pienińskiego Pasa Skałkowego i fliszu Karpat Zewnętrznych miało zatem silnie zaznaczoną składową przesuwczą lewą. W Zachodnich Karpatach Wewnętrznych stwierdzono metodami paleomagnetycznymi po-permską rotację o 45° zgodną z ruchem wskazówek zegara. Rotacja ta, jeśli związana była przynajmniej częściowo z ruchami neogeńskiej tektogenezy, jest zgodna z postulowanym tu lewym ruchem przesuwczym Zachodnich Karpat Wewnętrznych względem bardziej zewnętrznych jednostek.

Można przypuszczać, że naprężenia związane z omawianym ruchem przesuwczym rozładowywały się głównie w strefie Pienińskiego Pasa Skałkowego. Powtarzane w literaturze od czasów Uhliga opinie o megabudinażowym charakterze stylu tektonicznego niektórych części Pienińskiego Pasa Skałkowego można by więc wiązać z przesuwczym charakterem uskoku ograniczającego od południa Pieniński Pas Skałkowy. Szczegółowe badania mezostrukturalne wskazują na istnienie składowych przesuwczych przemieszczenia na tym uskoku, opinie na temat zwrotu tych składowych są natomiast, w dotychczas opublikowanych pracach, rozbieżne.