Clinoforms as paleogeographic tools: development of the Danube catchment above the deep Paratethyan basins in Central and Southeast Europe

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Abstract

The Miocene marine basins of Central and Southeast Europe, once comprising the Paratethys Sea, were gradually filled with sediments during the Neogene and turned to be the catchment area of the proto-Danube and finally that of the modern Danube. Seismic data from various parts of the large Danube catchment area show that these several hundred meter deep basins were filled by lateral accretion of river-transported sediments, appearing as shelf edge scale clinoform sets in seismic profiles. The direction of shelf edge progradation is NW to SE (N to S, W to E) in each basin, except for the Dacian Basin where NE to SW direction prevails. The age of the clinoform sets is generally younging downstream: 19-18 Ma in the North Alpine Foreland Basin, 14-13 Ma in the Vienna Basin, 10-9 Ma in the Danube (Kisalföld) Basin, 8.6-4 Ma in the Central Pannonian Basin (Alföld), ?9-5 Ma in the Dacian Basin, and 6-0 Ma in the Euxinian (Black Sea) Basin. In spite of this geographical and temporal pattern, only the Danube (Kisalföld) and the western and central part of the Central Pannonian Basins were filled by the proto-Danube shelf accretion. Formation of the Danube, as a longitudinal river of the Alpine foreland that gradually elongated to the east and followed the retreating shoreline of the Paratethys, most probably took place at the beginning of the Late Miocene, ca. 11 Ma ago, thus the Early and Middle Miocene shelf advance in the North Alpine Foreland and Vienna Basins, respectively, cannot be attributed to a „paleo-Danube". The clinoform systems of the Dacian Basin are coeval with those of the upstream Central Pannonian Basin, indicating that by the time the Danube sedimentary system reached the Dacian Basin, it was already a shallow basin. The vast clinoforms of the northwestern Euxinian shelf also significantly overlap in age with the Pannonian Basin ones; only the <4 Ma part of the shelf accretion can be attributed to the Danube *sensu stricto*.

Introduction

During the Neogene, a series of deep marine and Caspian-type lacustrine basins streched across Central and Southeast Europe along the course of the present-day Danube river. Russian geologist Vladimir Dimitrijevic Laskarev coined the name „Paratethys” to describe this large intracontinental Neogene sea, which also included the Black Sea and Caspian Lake basins (Laskarev 1924). He claimed that „during the Miocene, Pliocene and Quaternary epochs, the geological history of southern Europe (especially that of south-eastern Europe) was closely tied to this sea, the place of which was occupied by the gradually developing Danube system and by the remnants of the Paratethys: the Black, Azov, and Caspian Seas.” Indeed, in geographical terms, the modern Danube catchment fairly precisely coincides with the European part of the Neogene Paratethys (with the notable exception of the northern Carpathian foredeep, which is not discussed in the present paper). The North Alpine Foreland Basin, the Vienna Basin, the Danube (Kisalföld) Basin, the central Pannonian Basin and the Dacian Basin all experienced changing bathymetries during their history as part – or remnant – of the Paratethys. In each of these basins and their sub-basins, a significant decrease in water depth took place typically only once, when the several-hundred-meter deep basins were gradually filled by lateral accretion of river-transported sediment packages as a result of shelf-margin growth by progradation. This process, developing at different times in different basins, changed the deep basins into fluvial lowlands, eventually merged together like beads in a string-of-pearl by the modern Danube (Fig. 1). By mapping and dating these clinoform sets, it is possible to reconstruct the paleogeographic changes and to understand the role that the Danube sedimentary system played in the sedimentary filling of the Paratethys basins. In this study we review the shelf edge-scale clinoform systems of the respective basins, with special emphasis on the direction of their accretion and age, and discuss if and how they could be connected to the development of the modern source-to-sink sedimentary system of the Danube.

Shelf edge-scale clinoform systems in the central and southeastern European Paratethys basins

North Alpine Foreland Basin

The North Alpine Foreland Basin (NAFB) is an east-west trending, 900 km long and 100 km wide basin in the northern foreland of the Alps that formed by the load of the Eastern Alps docking onto the Western European foreland (Fig. 1). The Eocene to Miocene sedimentary basin fill reaches 3-4 km thickness close to the Alpine thrust front and gradually decreases towards the north. The sedimentary sequence includes deep marine to shallow marine, lacustrine, and fluvial deposits (Kuhlemann & Kempf 2002).

In the NAFB, large-scale clinoforms are present in the eastern part of the basin, within the Hall Formation (Fig. 2). The down-dip extent of the clinoform set is several tens of kms, the direction of progradation is S to N in the central part (Hinsch 2008) and W to E in the central and eastern part of the basin (Gusterhuber et al. 2012). The height of the clinoforms is 200-250 m. The age of the Hall Formation is late Eggenburgian (early-middle Burdigalian; Fig. 3), ca. 19 to 18 Ma (Grunert et al. 2015).

The Hall shelf formed along the northern margin of the Alps, and it was built into the eastern NAFB which had been a relatively deepwater basin since the Late Oligocene. Following the advance of the shelf-margin across the basin, shallow marine and tidal sedimentation dominated, replaced by freshwater deposition from the early Karpatian (Kuhlemann and Kempf 2002).

Vienna Basin

The Vienna Basin is a NE-SW trending, 100 km long and 50 km wide pull-apart basin that formed between a system of sinistral transfer faults during Miocene lateral extrusion of the Eastern Alps (Fig. 1). The basin fill includes Miocene marine to brackish lacustrine sediments in a thickness of up to 5500 m (Arzmüller et al. 2006).

In the prevailingly shallow water sedimentary fill of the basin, delta scale clinoforms appear at various levels in the strata of the Lower and Middle Miocene (Strauss et al. 2006; Kováč et al. 2004). Clearly visible shelf-edge scale clinoforms, however, were imaged by seismic surveys only in the central part of the basin, around the Matzen high (NE of Vienna; Fig. 4). The direction of progradation is changing from NE-SW to NW-SE, and the clinoform sets extend along depositional dip for ca. 40 km in the latter direction. The highest clinoforms span a vertical height of 400 m from the shelf-break to the toe-of-slope, so their decompacted height, and thus the paleo water depth of the basin, could be on the order of 600-800 m, much higher than suggested by previous paleogeographic reconstructions (Lee & Wagreich 2016). Biostratigraphically, the clinothems belong to the Bolivina-Bulimina benthic foram zone, and thus have an age of ca. 14-13 Ma (Late Badenian; Fuchs & Hamilton 2006; Kováč et al. 2004; Fig. 3).

The shelf-edge clinoforms of the Vienna Basin indicate that a very deep depocenter formed in the central-southern Vienna basin during the late Badenian. The accelerated subsidence at this time (Lee & Wagreich 2016) created a relatively narrow basin into which a shelf was built from the northwest. The source of the clastic material is considered to be the Alps and the Bohemian Massive. When the progradation of the shelf margin completely filled the basin with sediments, shallow-water depositional systems occupied the area. During the rest of the Miocene (latest Badenian, Sarmatian and Pannonian), no deep-water conditions re-established in the Vienna Basin.

Danube (Kisalföld) Basin

The Danube (Kisalföld) Basin is a 200 km long and 100 km wide, NE-SW trending sub-basin of the Pannonian Basin system (Fig. 1). It formed in the Early to Late Miocene along extensional normal faults and as a consequence of post-rift thermal subsidence (Tari 1996). The sedimentary fill of the basin includes Early to Middle Miocene (Karpatian to Badenian) marine sediments, Middle Miocene (Sarmatian) restricted marine sediments, and Late Miocene to Pliocene (Pannonian) brackish to freshwater sediments (Kováč et al. 2011).

The NE-SW trending finger-like depressions in the northern periphery of the Danube (Kisalföld) Basin experienced intense subsidence and shelf-margin accretion in the Middle Miocene. In the central and southern part of the basin, however, shelf-edge clinoforms are ubiquitous in the Upper Miocene deposits of Lake Pannon (Fig. 5). The progradational length of the clinoform sets is 50-60 km, and the direction of their accretion is NW to SE (locally N-S and W-E; Magyar et al. 2007; Sztanó et al. 2016). The typical clinoform height is between 200 and 300 m; decompaction of a 280 m high clinoform gave an original height (and thus a minimum water depth) of 550 m (Balázs et al. 2018). The age of the oldest (northwesternmost) clinoform is estimated to be ca. 10 Ma, whereas that of the youngest (southeasternmost) one is ca. 9 Ma (Magyar et al. 2000, 2007, 2013; Šujan et al. 2016), suggesting a high progradation rate of up to 50-60 km/My.

The rifting and the extensive post-rift (thermal) subsidence of the basin created significant water depth in the early Late Miocene. A powerful sediment input from the Alps and Western Carpathians built a long shelf, parallel with the basin axis, the progradation of which filled the entire basin within ca. 1 million years. The deltaic layers are overlain by fluvial sediments (Sztanó et al. 2016), and deep-water conditions never returned to the Danube (Kisalföld) Basin.

Central Pannonian Basin (Alföld)

The Pannonian Basin is a back-arc basin where extension was driven by subduction roll-back in the Carpathians and Dinarides (Fig. 1). The basement of the Central Pannonian Basin (Alföld, Great Hungarian Plain) includes several Neogene deep depressions, mostly half-grabens, which are typically filled with terrestrial to marine sediments of late Early to Middle Miocene age. The area became a uniform, 500 km long (in SW-NE direction) and 360 km wide (in NW-SE direction) basin in the Late Miocene to Pliocene, when sedimentation took place in a large brackish lake (Lake Pannon) and adjacent deltaic and fluvial environments (Balázs et al. 2016).

Shelf-edge clinoforms are widely spread across the entire basin. From the basin margins, these clinoforms generally prograde towards the basin center (Fig. 1). The central part, and thus the largest portion of the basin, however, was filled with shelf-margin accretion from the NW to the SE (Figs. 1, 6). This NE-SW striking clinoform system has a depositional dip length of ca. 250 km (Vakarcs et al. 1994; Magyar et al. 2013). The vertical height of the clinoforms is 250-450 m, which corresponds to a decompacted height of 370-800 m (Balázs et al. 2018). The age of these clinoforms is estimated as 8.6-4.0 Ma (Magyar et al. 2013).

Much of the Central Pannonian Basin was filled by a sediment transport system that „overspilled" the sill of the Transdanubian Range, separating the Danube (Kisalföld) Basin from the Central Pannonian Basin (Sztanó et al. 2013; Fig. 1). The western and central parts of the Pannonian Basin were filled with sediments derived from the Alps and from the Western Carpathians. The eastern part, however, received sediments from the Eastern Carpathians and from the Apuseni Mountains, thus shelf-edge progradation from the NE (proto-Tisza shelf) and from the SE (proto-Maros shelf) was also significant. In the southern part of the basin, Late Miocene shelf-edge progradation from the west (Alps) and from the south (Dinarides) is displayed in seismic profiles (Magyar et al. 2013; Fig. 1). As the individual shelf-margins merged and prograded through the basin, deep-water conditions ceased to exist by ca. 4 Ma ago and never returned.

Dacian Basin

The Dacian basin is the Miocene to Recent foreland basin of the Southern and Eastern Carpathians. It extends ca. 400 km parallel with the E-W trending Southern Carpathians and ca. 300 km parallel with the N-S trending Eastern Carpathians (Fig. 1). The sedimentary fill of the basin is represented by normal marine (Badenian) to restricted marine (Volhynian, Bessarabian, Khersonian, Meotian), brackish lacustrine and deltaic (Pontian, Dacian) and fluvial and terrestrial (Romanian) deposits (Jipa & Olariu 2009; Fig. 3). In the deepest part of the basin (Focşani Depression), the thickness of the Neogene basin fill exceeds 13 km (Tărăpoancă et al. 2003).

In the Dacian Basin, shelf-edge clinoforms developed in the deepest, axial part. In the western margin of the basin, up to 400 m high clinoforms prograde towards the basin center (i.e. W to E) in a length of ca. 70 km (Leever et al. 2009; Jipa and Olariu 2013; Fig. 7). The age of the clinoforms is Meotian to Pontian (ca. 7.5 to 5 Ma; Fig. 3). Further to the east, between the Jiu and Olt rivers, the shelf margin progrades in the opposite direction, i.e. E to W and NE to SW, in a length of ca. 120 km (Fig. 8). The vertical scale of these clinoforms is the same as in the western clinoforms, but their age is at least Khersonian to Pontian (8-5 Ma) (Leever et al. 2009; Fongngern et al. 2015; Fig. 3). In the eastern part of the Dacian Basin, the main depositional dip direction is N to S (changing between NW to SE and NE to SW), i.e. parallel with the Eastern Carpathians (Fig. 1). The depositional-dip length of the prograding clinoform sets is ca. 200 km, whereas their height is less than 200 m (typically 100-120 m; Fig. 9). The age of the prograding unit is Bessarabian to Meotian (?9-6.0 Ma; Fig. 3).

There are two depocenters within the Dacian basin where deep-water conditions and thus shelf-edge clinoforms formed in the Late Neogene: one in the western part of the basin (Getic depression) and another one adjacent to the Eastern Carpathians, including the Focșani depression (Jipa & Olariu 2009, 2013; Fig. 1). The western depocenter was filled by convergent shelf-margin accretion, where progradation occurred mainly from NE to SW and from W to E towards the middle of the depression, and where most of the sediment was sourced from the Southern Carpathians, although contribution and shelf accretion from the south was also recorded (Leever et al. 2009; Jipa & Olariu 2013; Fongngern et al. 2015). The somewhat older but shallower deep-water basin of the eastern depocenter was filled with a southward progradation of the shelf-margin, where sediments were sourced mainly from the Eastern Carpathians (Jipa & Olariu 2013). Even the largest clinoforms in this system are transitional in size between shelf edge scale and delta scale clinoforms (see the classification of Patruno and Helland-Hansen 2018). In fact, Jipa & Olariu (2013) describe this Eastern Carpathians – Focşani depression source-to-sink system as fluvial-deltaic. It was part of a larger Late Miocene fluvial system that drained the Eastern Carpathians and the Ukrainian Shield and charged into the Dacian Basin in the southwest and into the Euxinian Basin in the southeast (Balta system; Matoshko et al. 2016). Clinoforms prograding from the SE towards the depocenter of the eastern Dacian Basin were also observed Fig. 1).

Euxinian Basin (Black Sea)

The Euxinian basin is an extensional back-arc basin of the Pontides. Its western part opened in the Cretaceous. The Neogene basin fill of the western Black Sea includes Middle

Miocene to Recent sediments in a thickness of more than 3000 m (Dinu et al. 2005; Munteanu et al. 2011).

Shelf-edge clinoforms are imaged below the northwestern Black Sea shelf within the Upper Neogene to Recent basin fill. The length of the clinoform sets, accreted from the NW towards the SE, is more than 100 km (Fig. 10). The height of the clinoforms is 500-800 m. The age of the prograding unit is variously given as Pontian (6-4.7 Ma; Dinu et al. 2005), middle Pontian to early Dacian (5.8-4.5 Ma; Munteanu et al. 2011, 2012), or Pontian to Quaternary (mainly late Pontian: 5.5-0 Ma; Krézsek et al. 2016; Olariu et al. 2017; Fig. 3).

Much of the present-day northwestern Black Sea shelf was built in the Late Neogene, mostly from the NW to the SE. The source of this large sediment influx is thought to have been the Ukrainian shield and the Eastern Carpathians (Balta system, Matoshko et al. 2016), and, with the arrival of the Danube sediment transport system, the Alps.

Discussion: What role did the proto-Danube sedimentary system play in filling up the Paratethyan basins?

As shown above, the progradation of the shelf-margins and thus the filling of the deep depressions of the Paratethyan basins generally took place from NW to SE (or locally W to E and N to S) (Fig. 1). The age of the prograding clinoform sets is gradually decreasing from the 18-19 Ma old clinoforms of the NAFB to the present-day slope of the northwestern Black Sea shelf, as the final sink of the Alpine-derived sediments. This pattern supports the notion that a long-lived and gradually eastward extending sediment transport system was responsible for the consecutive disappearance of the deep marine to lacustrine Paratethys basins. As it is the Danube today that drains the north Alpine foreland and transports Alpine- and Carpathian-derived sediments into the Black Sea, the question of how and when the relatively long and narrow Danube catchment developed and replaced the Paratethys basins is of particular interest.

The Eggenburgian shelf-margin advance in the NAFB indicates an eastward directed drainage system (Fig. 11A). About 17 million years ago, however, the tectonic uplift of the Amstetten Swell some 100 km west of Vienna forced the drainage direction to reverse, and the basin had a westward drainage until ca. 11 Ma (Kuhlemann & Kempf 2002; Winterberg & Willett 2019). The river system that built the Eggenburgian shelf and buried the deep NAFB thus cannot be considered proto-Danube because it has no temporal continuity with the modern Danube system (Fig. 11B).

The „paleo-Danube", however, is often mentioned in the literature as the main agent of the powerful NW-SE sediment transport and shelf margin accretion in the Vienna Basin during the Badenian (e.g. Kováč et al. 2004; Lee and Wagreich 2016). As (much of) the NAFB was drained towards the west during the Middle Miocene (Kuhlemann & Kempf 2002), the Badenian river (or river system) that fed into the Vienna Basin through the Zaya Graben (Jiřiček & Seifert 1990) was either very short, covering only the easternmost tip of the NAFB east of the Amstettem Swell (Fig. 11 B), or it existed parallel with, and south of, the west-directed drainage system (Winterberg & Willett 2019). If the Danube is defined as the orogen-parallel, longitudinal river of the Alpine foreland which elongated to the east following the retreating shoreline of the Paratethys (Winterberg & Willett 2019), then the Badenian river of the Vienna Basin can be identified with the proto-Danube only in the latter – yet unproven – case.

The well-developed and wide clinoform sets of the Danube (Kisalföld) Basin are the product of the proto-Danube beyond any doubt (Magyar et al. 2013; Fig. 11C). After 11 Ma, the thrusting of the Jura blocked the westward drainage of the NAFB and thus created the current eastward drainage system (Kuhlemann & Kempf 2002; Winterberg & Willett 2019). The eastward-directed proto-Danube built only delta scale clinoforms into the shallow-water Vienna Basin. The closest deep-water basin where shelf edge scale clinoforms formed ca. 10 million years ago was the Danube (Kisalföld) Basin. After filling the Danube (Kisalföld) Basin, the prograding proto-Danube delta transversed the sill of the Transdanubian Range (Sztanó et al. 2013) and started to shed sediments into the Central Pannonian Basin. Shelf-edge clinoforms indicate that the Central Pannonian Basin received sediments from various directions from the surrounding Alps, Carpathians, and Dinarides, but the dominant sediment transport system was that of the proto-Danube, being responsible for filling the deep depressions in ca. two thirds of the basin area between 8.6 and 4 Ma (Magyar et al. 2013; Fig. 11 D).

The Dacian Basin is an „outlier" in the consecutively younging basin-fill pattern. The prograding shelf-edge clinoforms filled the deep-water environments of the Dacian Basin within a time frame which is almost identical with the filling of the „upstream" Central Pannonian Basin (ca. 9-5 Ma). The Dacian basin was filled with sediments from the Eastern and Southern Carpathians, with shelf-margins advancing mostly from N-NE to S-SW (Jipa and Olariu 2013), at the time when the paleo-Danube still fed into the water body of the Central Pannonian Basin (see the „concurrent basin fill model" of Olariu et al. 2017; Fig. 11D).

Finally, the large-scale, NW to SE prograding clinoform system of the northwestern Black Sea shelf also shows significant temporal overlap with the filling of the Central Pannonian and Dacian Basins. The Pontian (6-5 Ma) shelf-margin advance thus cannot be attributed to the arrival of the Danube sedimentary system into the Euxinian Basin (Fig. 11D) but belongs to the N to S directed Balta sedimentary system (Matoshko et al. 2016). Recently, Olariu et al. (2017) suggested that an abrupt switch in depositional style, i.e. from sandy basin-floor fans to much larger muddy channel-levees and basin-floor fans, in early Dacian time (ca. 4 Ma) indicates the arrival of the Danube-transported sediments into the Black Sea sink (Fig. 11E). The only available provenance study (de Leeuw et al. 2018) dates the arrival of the Danube to the Black Sea between 4.36 and 1 Ma and thus is in accord with the above hypothesis. Dating of the Late Neogene deposits of the Euxinian Basin still holds significant uncertainty, and more reliable age data are needed to confirm these interpretations.

Conclusions

The present-day Paratethyan basins, strung together by the Danube from the NAFB downstream to the Euxinian (Black Sea) Basin shelf, were transformed from several-hundred-meter-deep marine or lacustrine basins to shallow marine and to fluvial environments during the Neogene. As the shelf-edge clinoform sets of these basins indicate, this process took place generally from NW to SE within each basin, and with a general temporal younging between the basins from NW to SE. The proto-Danube formed in the NAFB as part of an eastward-directed drainage system, and gradually elongated to the east, following the retreating shoreline of the Paratethys. The shelf edge clinoform advance, however, can be attributed to the sediment transport system of the proto-Danube only in the Danube (Kisalföld) and Central Pannonian Basins. The river (system) that fed the shelf edge of the NAFB 19-18 Ma ago has no temporal continuity with the modern Danube. The 14-13 Ma shelf edge accretion of the Vienna Basin was probably sourced from the easternmost part of the Alps, not from the entire length of the orogenic belt. The shelf edge clinoforms of the Dacian Basin could not be sourced by the paleo-Danube because neither their direction (prevailingly NE to SW) nor their age (9 to 5 Ma, coeval with the filling of the upstream Central Pannonian Basin) fits the pattern. The NW-SE prograding clinoform sets of the Black Sea shelf are partly of Pontian age (6-5 Ma), which excludes any relationship with the proto-Danube. The younger part (< 4 Ma) of the shelf accretion, however, can be attributed to the mostly Alpine-derived Danube sediment.

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Table caption

Table 1

The major characteristics of clinoform sets from various Paratethyan basins. *: very rough estimate, indicating the possible maximum rather than a real value.

Figure captions

Fig. 1

The Paratethyan basins with the modern Danube catchment area (black solid line) in Central and Southeast Europe. NAFB: North Alpine Foreland Basin, VB: Vienna Basin, DKB: Danube (Kisalföld) Basin, CPB: Central Pannonian Basin, DB: Dacian Basin, GD: Getic Depression, FD: Focşani Depression, EB: Euxinian Basin, TR: Transdanubian Range. Arrows represent shelf-edge clinoform advance. Yellow/black arrows A to I indicate location and length of seismic profiles in Fig. 2.

Fig. 2

W to E oriented seismic depth section across the eastern part of the North Alpine Foreland Basin. The pre-Cenozoic basement is overlain by the Lower Oligocene Kiscellian and Upper Oligocene – Lower Miocene Egerian Stages (interpretation follows Gusterhuber et al. 2012). The Eggenburgian Hall Formation displays large-scale clinoforms (white arrows). For the age of the Paratethyan regional stages see Fig. 3, for location of the seismic profile see Fig. 1.

Fig. 3

The Neogene chronostratigraphic system of the Paratethys

Fig. 4

NW to SE oriented seismic depth section from the central part of the Vienna Basin. The thrusted Alpine basement is overlain by the late Early Miocene Karpatian Stage, followed by an angular and erosional unconformity below the Middle Miocene Badenian. Clinoforms (white arrows) appear in the upper part of the marine Badenian. In the top of the section, late Middle Miocene Sarmatian and Late Miocene Pannonian layers deposited conformably. For the age of the Paratethyan regional stages see Fig. 3, for location of the seismic profile see Fig. 1.

Fig. 5

NW to SE oriented seismic time section from the Danube (Kisalföld) Basin. Middle Miocene (Badenian and Sarmatian) sediments filled the extensional half-graben that opened in the pre-Neogene (Paleo-Mesozoic and Paleogene) basement. The overlying Pannonian (Upper Miocene to Pliocene) lacustrine to fluvial sequence contains well-developed clinoforms in its middle part (white arrows). For a detailed interpretation of this profile see Sztanó et al. 2016; for the age of the Paratethyan regional stages see Fig. 3, for location of the seismic profile see Fig. 1.

Fig. 6

NW to SE seismic time section from the Central Pannonian Basin (Alföld). The pre-Neogene basement and the Middle Miocene extensional half-grabens are overlain by the Pannonian (Upper Miocene to Pliocene) lacustrine to fluvial sequence, with clinoforms in its middle part (white arrows). For the age of the Paratethyan regional stages see Fig. 3, for location of the seismic profile see Fig. 1.

Fig. 7

W to E seismic time section from the westernmost part of the Dacian Basin (Getic Depression). The pre-Neogene basement is overlain with an unconformity by the Middle to Late Miocene Volhynian to Khersonian Stages and the Late Miocene Meotian and Pontian Stages. Large-scale clinoforms (white arrows) are imaged in the Pontian, in the shallow subsurface. For the age of the Paratethyan regional stages see Fig. 3. Location of the seismic profile is indicated in Fig. 1.

Fig. 8

SW to NE oriented seismic time section from the western part of the Dacian Basin (Getic Depression). The lowermost Neogene unit (Volhynian to Khersonian) is overlain by the Late Miocene Meotian, Late Miocene to Early Pliocene Pontian, and Pliocene Dacian Stages. Shelf-edge clinoforms (white arrows) occur in the Meotian to Pontian. For the age of the Paratethyan regional stages see Fig. 3. Location of the seismic profile is indicated in Fig. 1.

Fig. 9

S to N seismic time section from the northeastern part of the Dacian Basin. The pre-Neogene basement is overlain by the Volhynian to Khersonian Stages, which display southward prograding clinoform sets (white arrows). The prograding unit is overlain by Meotian and Pontian sediments. For the age of the Paratethyan regional stages, see Fig. 3, for location of the seismic profile, see Fig. 1.

Fig. 10

NW to SE directed seismic time section across the northwestern Black Sea shelf (Euxinian Basin). Large-scale shelf-edge clinoforms (white arrows) appear in the Upper Pontian to Quaternary part of the sequence. For a detailed interpretation of this section, see Krezsek et al. (2016). Ages of the Paratethyan regional stages are given in Fig. 3, location of the seismic profile in Fig. 1.

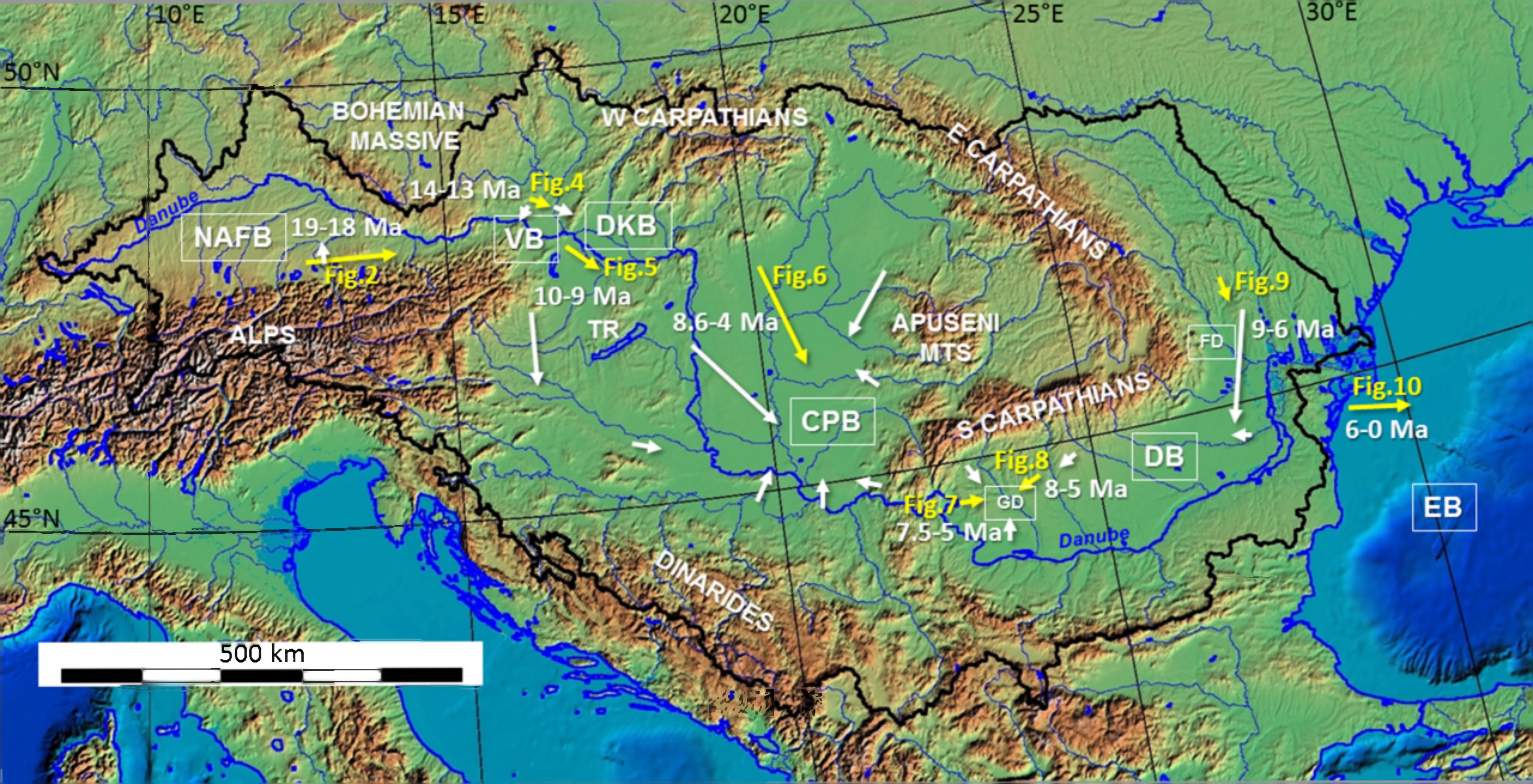
Fig. 11

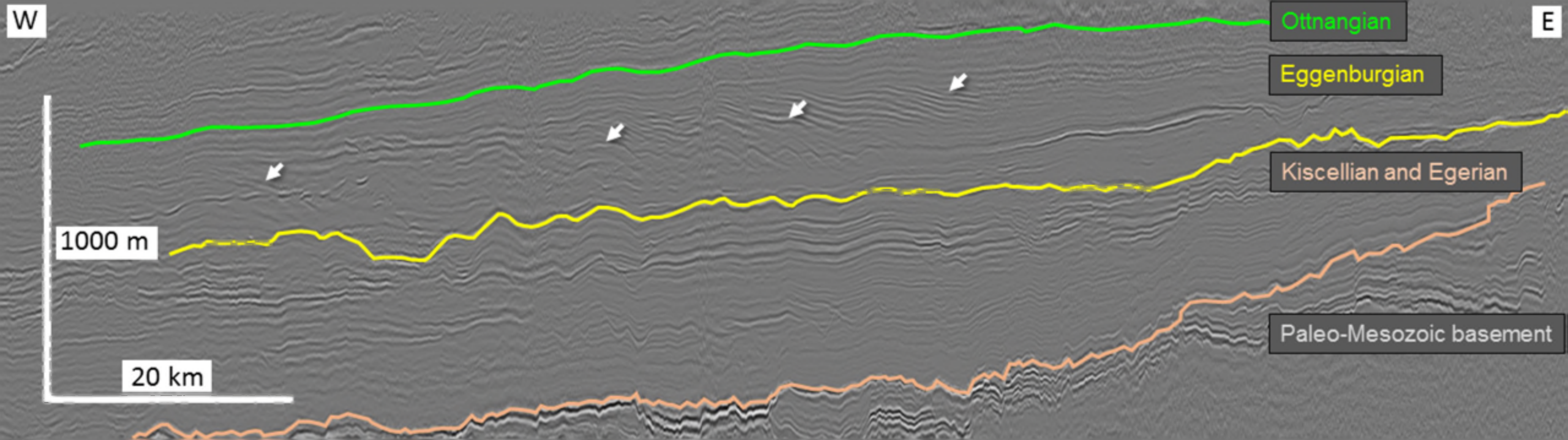
A cartoon displaying the gradual disappearance of the deep Paratethyan basins through lateral shelf edge accretion and the subsequent development of the modern Danube catchment (black arrows) during the Neogene. The cross sections represent the almost 3000 km long course of the present-day Danube. A: Late Eggenburgian (Burdigalian); B: Late Badenian (Serravallian); C: Pannonian/Bessarabian (Tortonian); D: Pannonian/Pontian (Messinian); E: Recent. For simplicity, the significant tectonic changes of the area are neglected here, except for the middle to late Miocene paleogeographic re-arrangements which resulted in the opening of the Central Pannonian and Dacian Basins in the Tisza and Moesia microplates, respectively. NAFB: North Alpine Foreland Basin, VB: Vienna Basin, DKB: Danube (Kisalföld) Basin, CPB: Central Pannonian Basin, CB: Carpathian Basin (early to middle Miocene only), DB: Dacian Basin, EB: Euxinian Basin. Not to scale.

Basin	sub-basin	Clinoform height (undecompacted; m)	Clinoform height (decompacted; m)	Progradational distance (km)	Age of progradation (Ma)	Forward growth rate (km/My)
North Alpine Foreland Basin	eastern part	200-250	300-500	80 (W to E)	19-18*	80*
Vienna Basin	central part	up to 400	600-800	40 (NW to SE)	14-13	40
Danube (Kisalföld) Basin	central and southern part	200-300	300-600	60 (NW to SE)	10-9	60
Central Pannonian Basin (Alföld)		250-450	370-900	250 (NW to SE)	8.6-4	54
Dacian Basin	western part (Getic Depression)	up to 400	500-800	70 (W to E)	7.5-5	28
				120 (E to W)	8-5	40
	eastern part	100-120	150-240	200 (N to S)	9-6*	67*
Euxinian Basin (Black Sea)	northwestern shelf	500-800	750-1600	>100 (NW to SE)	5.5-0	18

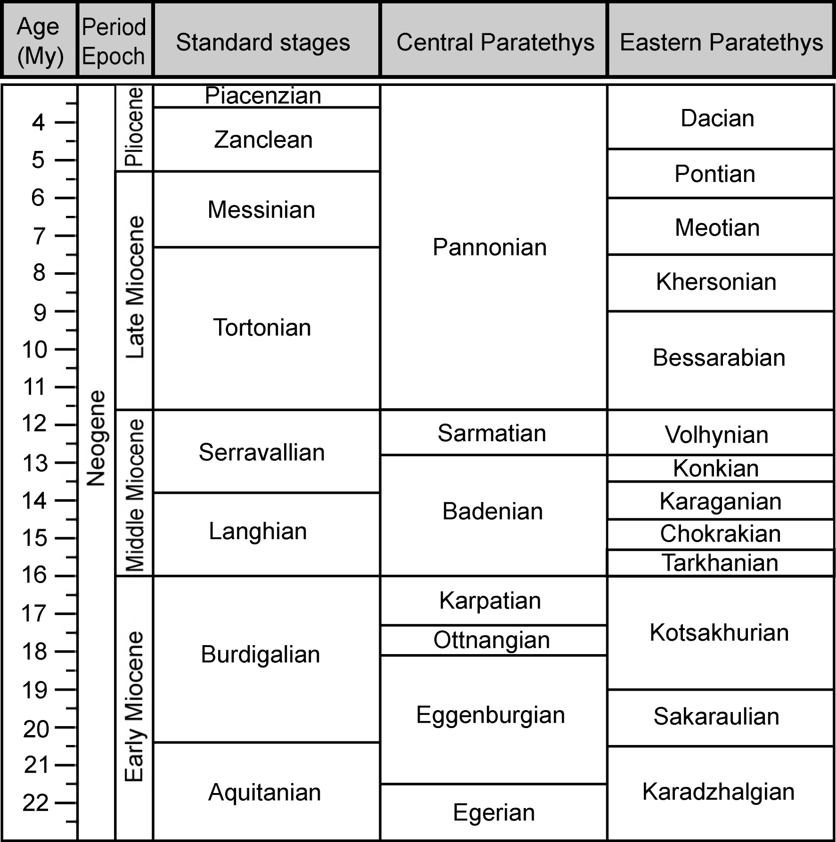
Table 1.

The major characteristics of clinoform sets from various Paratethyan basins. *: very rough estimate, indicating the possible maximum rather than a real value.

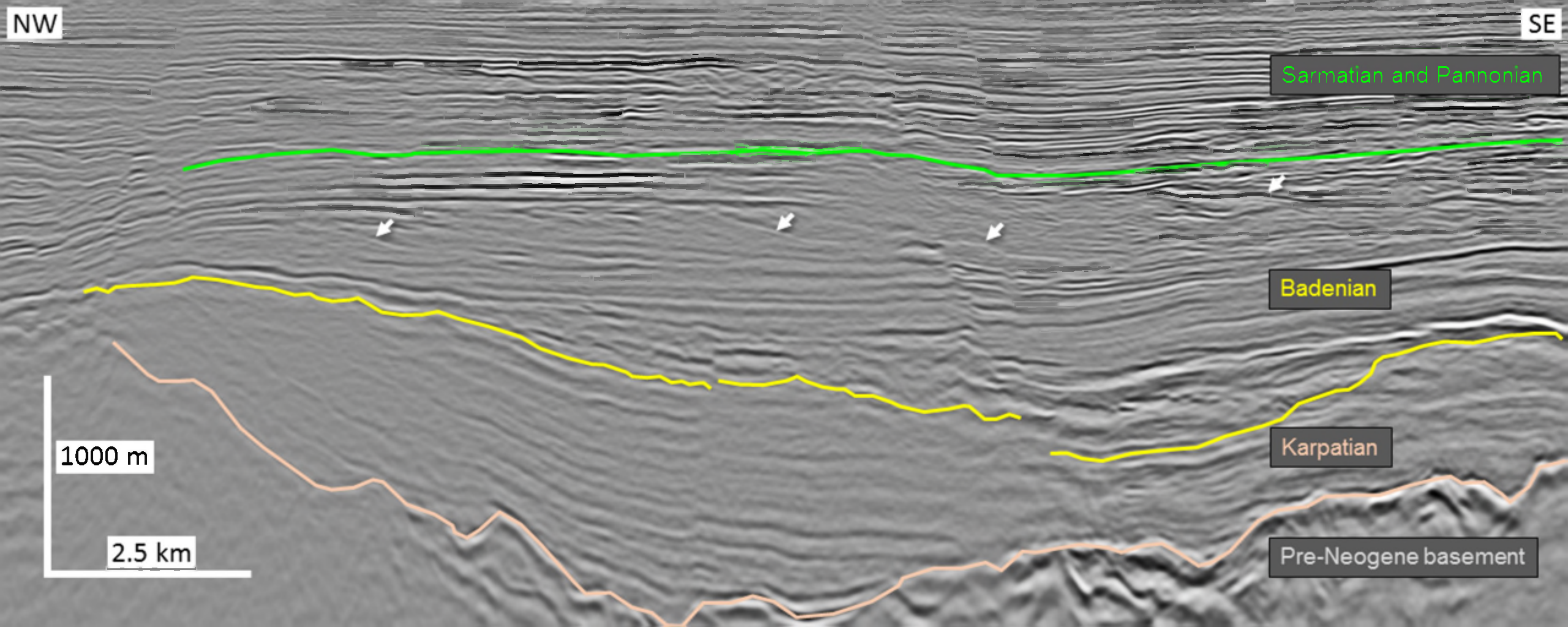

10°E
15°E
20°E
25°E
30°E
50°N
45°N
BOHEMIAN MASSIVE
W CARPATHIANS
E CARPATHIANS
Danube
NAFB
19-18 Ma
Fig.2
14-13 Ma
Fig.4
VB
DKB
Fig.5
10-9 Ma
TR
ALPS
8.6-4 Ma
Fig.6
APUSENI MTS
Fig.9
9-6 Ma
FD
S CARPATHIANS
CPB
Fig.10
6-0 Ma
DB
Fig.8
8-5 Ma
GD
Fig.7
7.5-5 Ma
Danube
EB
DINARIDES
500 km

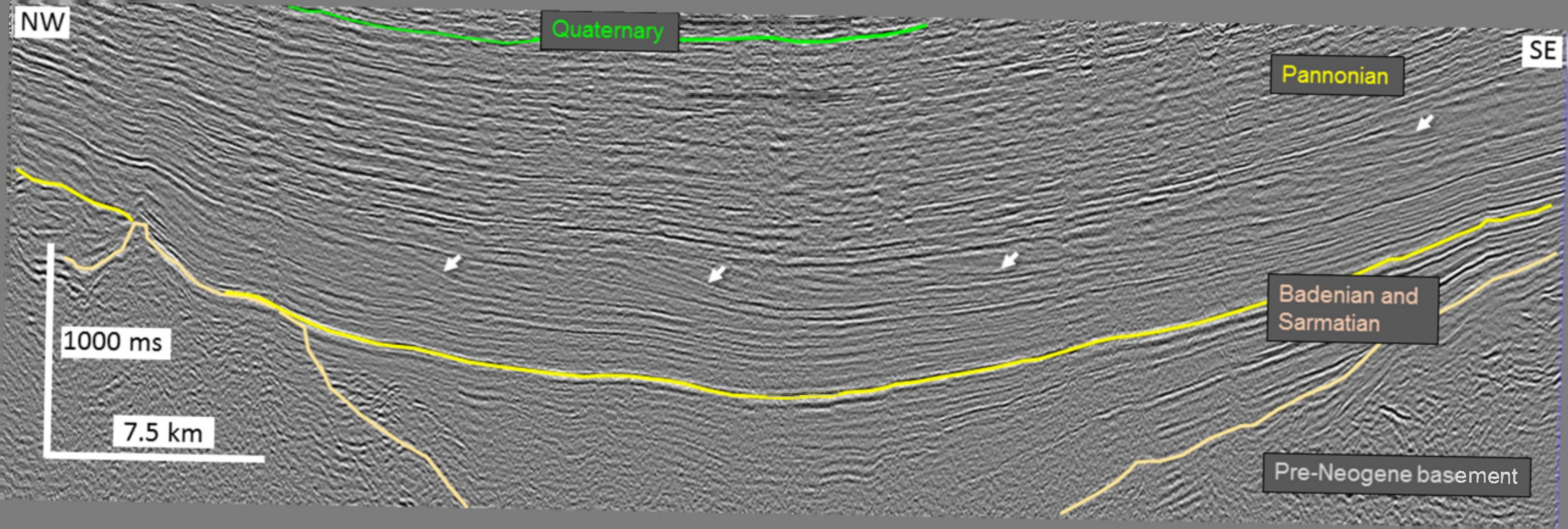


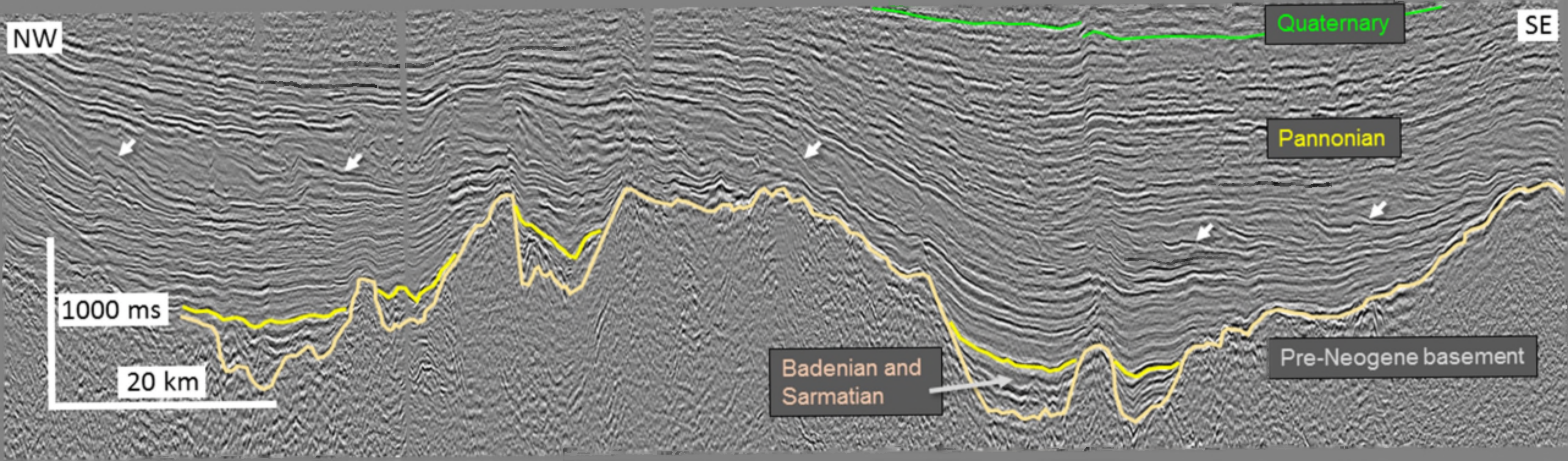
W
E
Ottnangian
Eggenburgian
Kiscellian and Egerian
Paleo-Mesozoic basement
1000 m
20 km

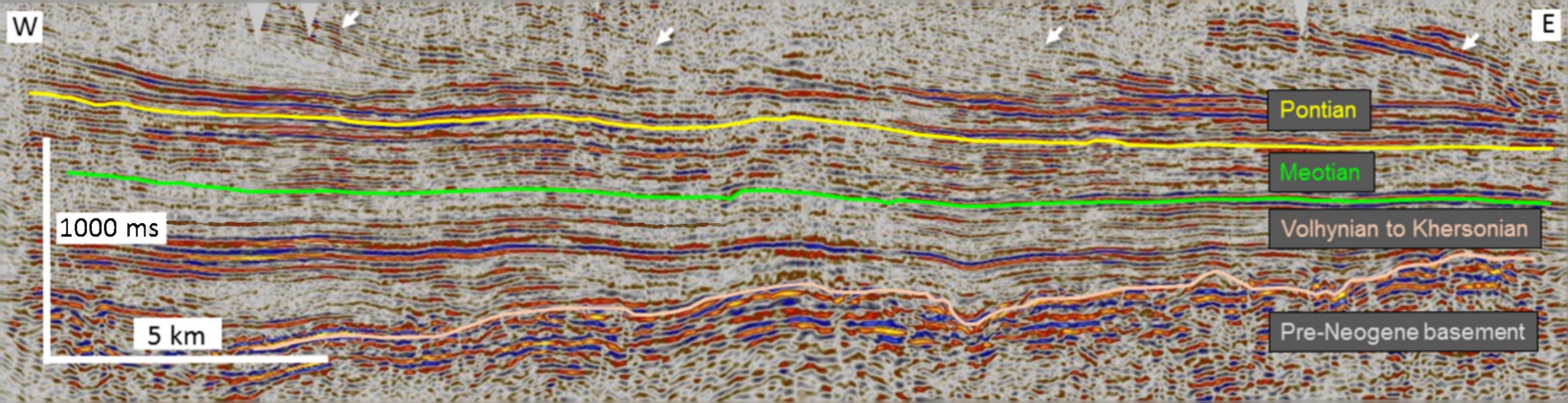


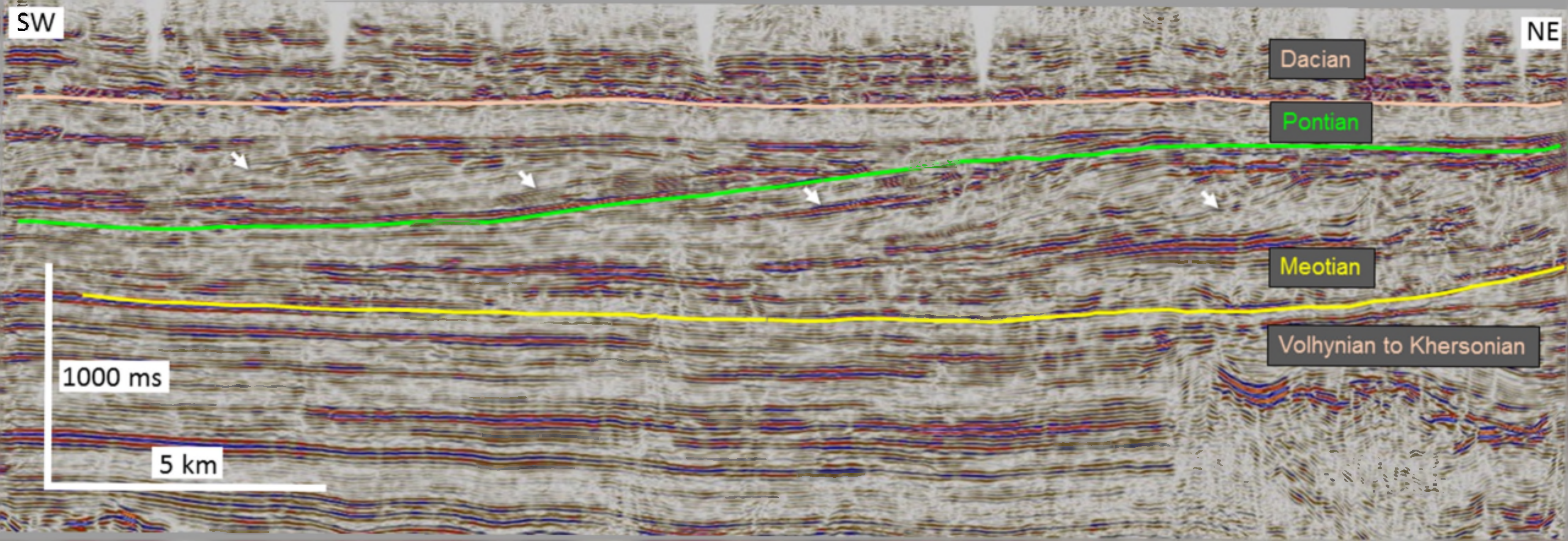
Age (My)
Period Epoch
Standard stages
Central Paratethys
Eastern Paratethys
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
Neogene
Pliocene
Late Miocene
Middle Miocene
Early Miocene
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Pannonian
Sarmatian
Badenian
Karpatian
Ottnangian
Eggenburgian
Egerian
Dacian
Pontian
Meotian
Khersonian
Bessarabian
Volhynian
Konkian
Karaganian
Chokrakian
Tarkhanian
Kotsakhurian
Sakaraulian
Karadzhalgian

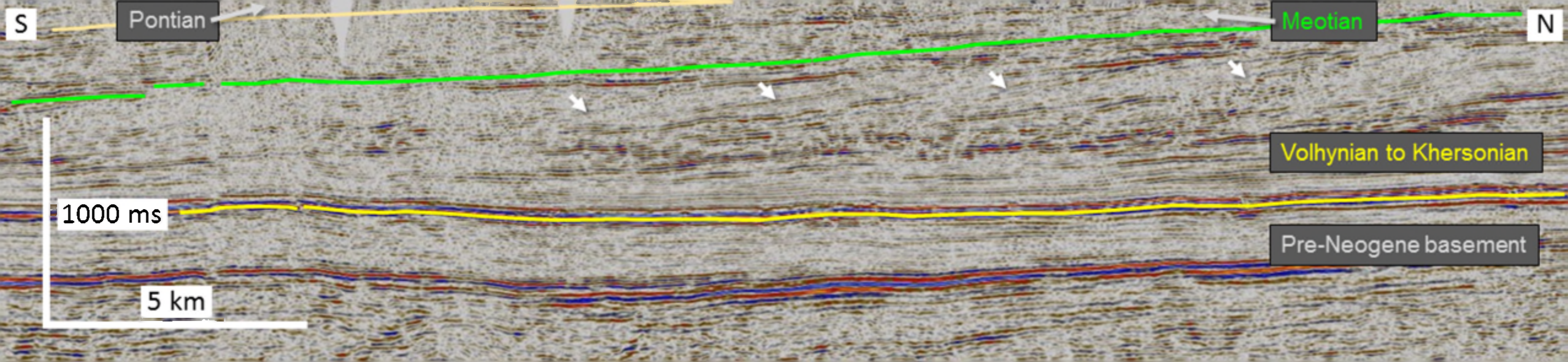

NW
SE
Sarmatian and Pannonian
Badenian
Karpatian
Pre-Neogene basement
1000 m
2.5 km

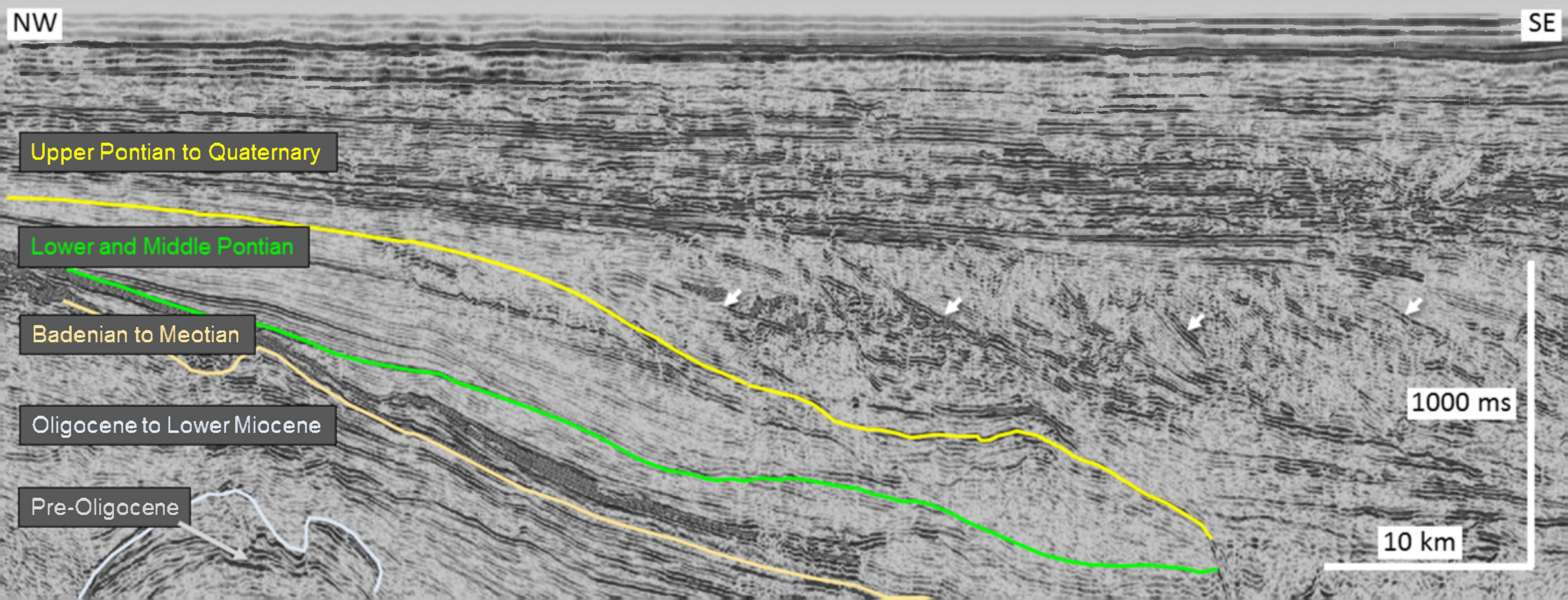

NW
Quaternary
SE
Pannonian
1000 ms
7.5 km
Badenian and Sarmatian
Pre-Neogene basement


NW
SE
Quaternary
Pannonian
1000 ms
20 km
Badenian and
Sarmatian
Pre-Neogene basement

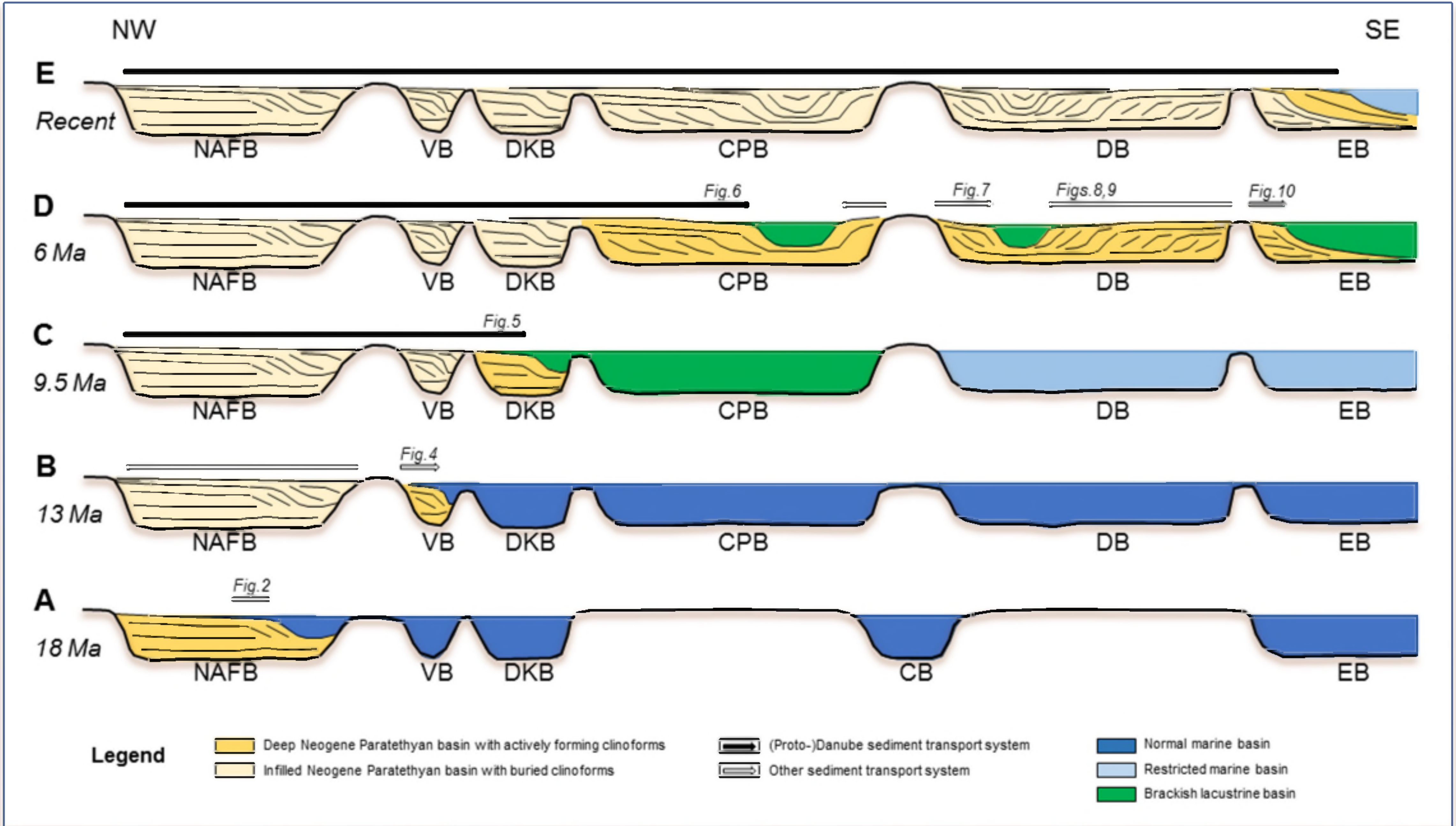

W
E
Pontian
Meotian
Volhynian to Khersonian
Pre-Neogene basement
1000 ms
5 km


SW
NE
Dacian
Pontian
Meotian
Volhynian to Khersonian
1000 ms
5 km


S
Pontian
Meotian
N
Volhynian to Khersonian
1000 ms
Pre-Neogene basement
5 km



NW
SE
Upper Pontian to Quaternary
Lower and Middle Pontian
Badenian to Meotian
Oligocene to Lower Miocene
Pre-Oligocene
1000 ms
10 km


NW
SE
E
Recent
NAFB
VB
DKB
CPB
DB
EB
D
6 Ma
Fig.6
Fig.7
Figs.8,9
Fig.10
NAFB
VB
DKB
CPB
DB
EB
C
9.5 Ma
Fig.5
NAFB
VB
DKB
CPB
DB
EB
B
13 Ma
Fig.4
NAFB
VB
DKB
CPB
DB
EB
A
18 Ma
Fig.2
NAFB
VB
DKB
CB
EB
Legend
Deep Neogene Paratethyan basin with actively forming clinoforms
Infilled Neogene Paratethyan basin with buried clinoforms
(Proto-)Danube sediment transport system
Other sediment transport system
Normal marine basin
Restricted marine basin
Brackish lacustrine basin