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Depositional architecture, sequence stratigraphy and geodynamic development of the Carpathian Foredeep (Czech Republic)

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Abstract: Five 3rd-order depositional sequences were recognized within Neogene infill of the Carpathian Foredeep. Individual sequences are characterized by the diverse shape and extent of the basin, by characteristic depositional architecture and lithofacies. Their deposition was controled by the principal ruling factors, namely eustasy, tectonics, sediment supply, and basement morphology. 4th-order depositional sequences (transgressive-regressive cycles) are also identified within the 3rd-order depositional sequences. Depositional sequences are related to three distinct stages of the geodynamic history of the basin. The pre- ("main") collisional stage (Egerian/Eggenburgian) is represented by sequence I and was ruled by eustasy, sediment-supply rate and basement relief. The collisional stage (Eggenburgian–Late Karpatian) is represented by three sequences. Sequence II (Eggenburgian–Early Karpatian) reflects the initiation of thrusting due to loading of the West Carpathian accretionary wedge. This process was mainly responsible for creation of accommodation space, while the other factors were supplementary. Sequence III (Karpatian) was ruled mainly by interactions between tectonic/flexural subsidence and isostatic rebound associated with the forebulge migration toward the foreland and thrust front. Sequence IV (Late Karpatian) is the upper part of the clastic wedge and reflects the main collision and rapid subsidence in the foreland basin. The depositional architecture was dominantly driven by tectonic processes. The post- ("main") collisional stage (Early Badenian) is identical with sequence V, which was ruled both by eustasy and tectonics. Accommodation space (incised valley?) developed in the internal parts of the basin.

Key words: Neogene, Carpathian Foredeep, peripheral foreland basin, depositional sequences, transgressive-regressive cycles.

Introduction

The evolution of peripheral foreland basins is very complex. Their development is controlled by flexural rigidity of both the foreland plate and accretionary wedge, geometry, density and migration rate of thrust load, structures of the active and passive basin margins, intra-plate stress, eustasy, climate, volume and density of sediment infill, reactivation of plate structures, and along-strike variations (e.g. Stevens & Moore 1985; Allen et al. 1986; Fleming & Jordan 1989; Bradley & Kidd 1991; Posamentier & Allen 1993; Peper et al. 1995; Sinclair 1997; Cloetingh et al. 1998; Castle 2001, etc.). Foreland basin fill sequences are typically asymmetric in cross-section perpendicular to their active margin, with the thickest part located adjacent to, or partially beneath the associated thrust front. This asymmetry results from the location of tectonic activity, maximum subsidence, sedimentation along the active margin, and post-depositional processes (Blair & Bilodeau 1988; Burbank et al. 1988; Heller et al. 1988; Sinclair et al. 1991). The tectonic history of subsidence and infilling is commonly expressed in terms of isostatic adjustment to emplacement of a thrust load, which also provides erosional detritus to a synorogenic clastic wedge (Flemings & Jordan 1989). The dominant ruling factors of the depositional architecture are eustasy and tectonic subsidence connected with thrust loading. Their complex interaction affects basin infill on different temporal and spatial scales, playing more regional or local roles during various periods of basin evolution (Flemings & Jordan 1989; Sinclair et al. 1991; Schlager 1993; Posamentier & Allen 1993; Busby & Ingersoll 1995; Emery & Myers 1996; Sinclair 1997; Gupta & Allen 1999; Einsele 2000; Castle 2001). Long-term cycles (2–10 Ma) are generally thought to be controlled by accretionary wedge loading and long-term erosion rates within the orogen. Short-term fluctuations (0.01–0.5 Ma) are attributed to high-frequency eustasy, thrust events or changes in intraplate stress levels (Peper 1993). Recognizing individual controlling factors is also complicated by the development of basin depozones (wedge-top, foredeep, forebulge and back-bulge), lateral shifting of them through time (DeCelles & Gilles 1996), and the contrasting stacking patterns between proximal and distal settings (Catuneanu et al. 1997).

Several models relate depositional sequence geometry of foreland basin and tectonic processes (Blair & Bilodeau 1988; Heller et al. 1988; Burbanck & Beck 1991; Plint et al. 1993; Catuneanu et al. 1999; etc.). However, the mutual interplay of processes of continental deformation and eustasy challenges sequence stratigraphic studies adapting classical concepts to processes of tectonic/flexural subsidence (Flemings & Jordan 1989; Sinclair 1997).

Carpathian Foredeep — geological setting

The Carpathian Foredeep (CF) is a peripheral foreland basin that developed on the European plate margin due to the Carpathian accretionary wedge overthrust and deep subsurface load. The CF exhibits striking lateral changes in basin width, depth, stratigraphy of sedimentary infill, along with variations in pre-Neogene basement composition and tectonic subsidence (Kováč et al. 1995; Krzywiec & Jochym 1999; Zoetemeijer et al. 1999; Krzywiec 2001).

The rheologic anisotropy of the European plate was an important controlling factor on the development of the basin. The western part of the CF is located on the eastern margin of the Bohemian Massif, a complex terrane of rigid lithosphere with estimated effective elastic thickness (EET) values of ~10 km (Lankreijer et al. 1999) that governed the bending of the Alpine-Carpathian transition zone. The Cadomian crystalline basement (Dyje and Brno batholiths) was strongly reworked and sutured to the eastern flank of the Bohemian Massif during the Variscan orogeny (Kalvoda et al. 2007). Paleozoic sediments (Cambrian to Permian) with complex histories overlay the basement along with local Jurassic to Cretaceous platform and basinal deposits. Mesozoic extension produced normal faulting in the eastern part of the Bohemian Massif (Ziegler 1980).

The study area (Fig. 1) in the western part of the CF is filled by Neogene clastic deposits (Fig. 2). The sedimentary record started in the Eggerian/Eggenburgian (22.5 Ma) and ended by the Early Badenian (15.5 Ma). Isolated outcrops of marine deposits indicate that the CF extended much further to the west and that its present-day western boundary is related to erosional processes occurring mainly after the Miocene. The CF continues south into the North Alpine Foredeep Basin (Alpine Molasse). Visible widening of Neogene depositional space in the contact area is a result of the generation and interaction of two peripheral foreland basins in the foreland of both Eastern Alps and Western Carpathians. Varying intensity and orientation of flexural loading along with a polyphase nature of the active basin margin and gradual change of its position influenced the basin architecture and infill.

The dominance of basinal deposits and relative insignificance of terrestrial and carbonate sediments categorize the basin as a filled to underfilled molasse type (e.g. Flemings & Jordan 1989; Sinclair 1997). Cogan et al. (1993) developed a conceptual model for the structural evolution of the CF's basement that proposed the formation of a series of down-faulted and flexed blocks and an elastic response to thrust and sediment loading. Numerous references to prior studies of the basin can be found in Brzobohatý & Cicha (1993).

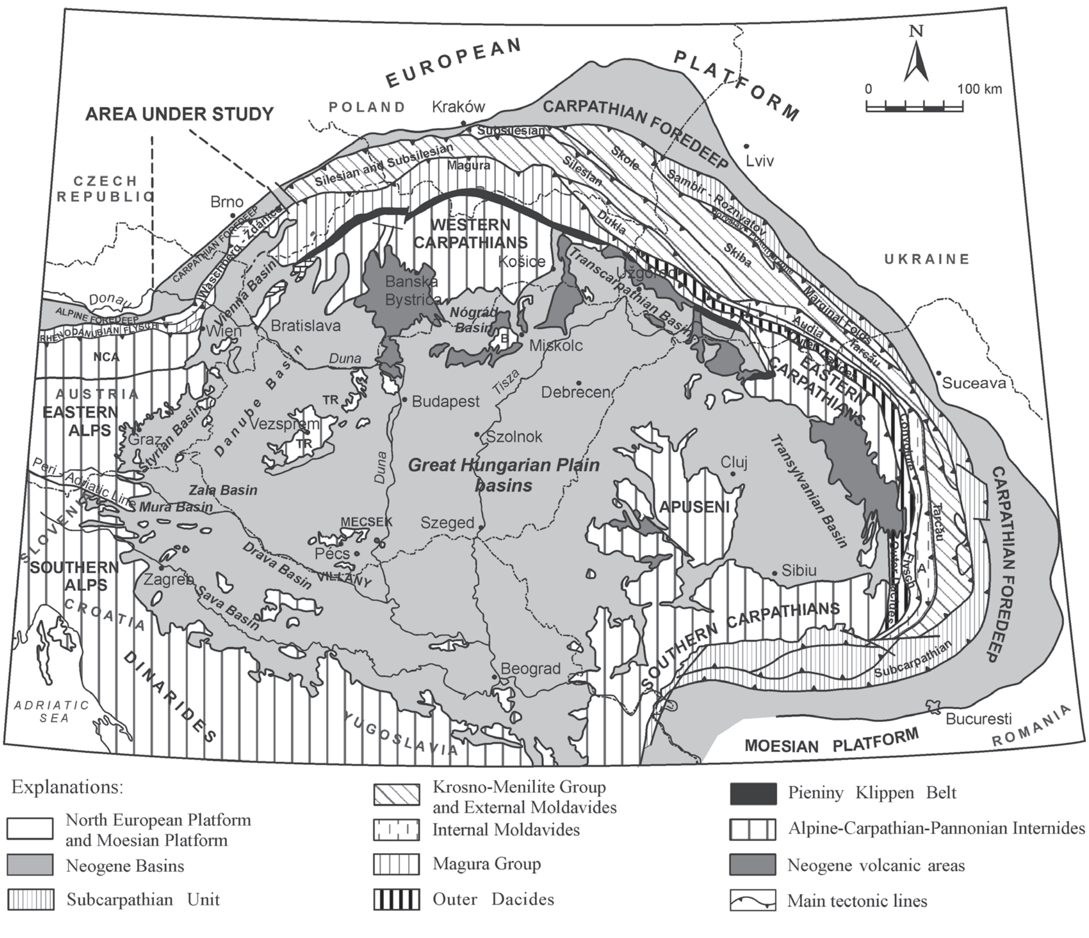


Fig. 1. Schematic map of the area under study and its position within the Carpatho-Pannonian region (modified after Kováč 2000).

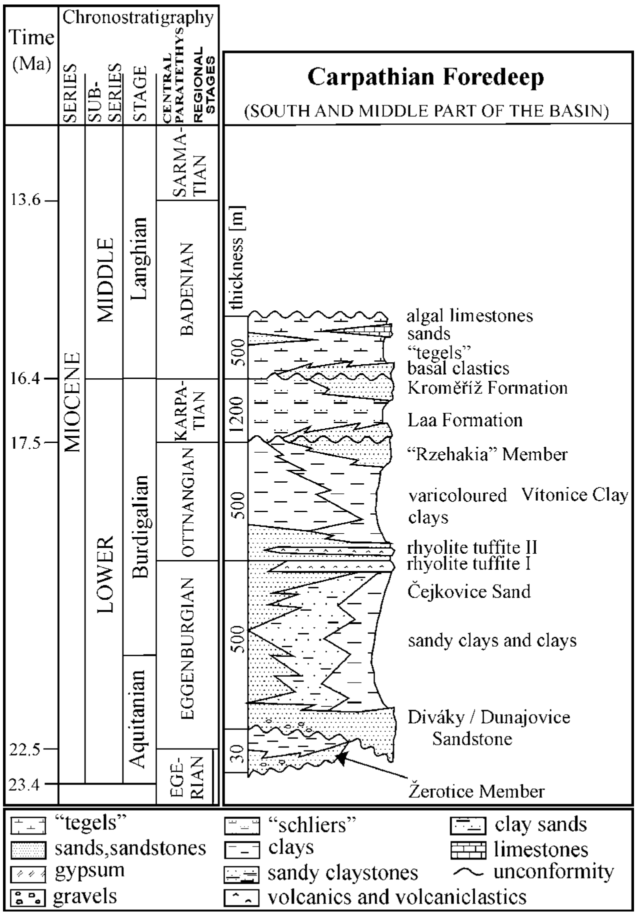


Fig. 2. Stratigraphic scheme of the Miocene of the studied part of the Carpathian Foredeep (modified after Brzobohatý in Chlupáč et al. 2002; Adámek et al. 2003; Adámek 2003 and Mandic et al. 2004). ("tegel" — olive green calcareous clay; "schlier" — calcareous grey silstone to silty claystone with fine horizontal lamination.)

Methods

This study and results are based mainly upon subsurface data because of the limited extent and small number of outcrops (Fig. 3). Sedimentologic and sequence stratigraphic interpretations of well logs calibrated by well cores represent the primary source of data (similarly Van Wagoner et al. 1988; Gorin et al. 1993; Posamentier & James 1993; Cant 1996; Emery & Myers 1996; Heller et al. 1998; Martín-Martín et al. 2001). Wells with well logs are located dominantly along the eastern (proximal) part of the basin. Surface outcrops (Nehyba 2000) and shallow drill holes (Nehyba & Petrová 2000) provide information about the western, marginal parts of the basin.

The quality of available well logs varied and predominantly only results of the "standard" well log techniques of spontaneous potential (SP) and resistivity (Rag 2.12) can be studied (Nehyba et al. 2003; Šikula & Nehyba 2004). Seismic reflection profiles calibrated by well logs show the basic structure of the Carpatian Foredeep (Nehyba et al. 2000, 2003). Sedimentological studies (sedimentary structures and textures, facies analyses) provided insight into the changing depositional environment during the basin evolution (e.g. Reineck & Singh 1984; Walker 1990; Reading 1996). Sedimentary petrography (i.e. pebble analyses, thin sections, non-opaque heavy mineral content, garnet and tourmaline compositions) allows us to recognize the source area. Tephrostratigraphy as an alternative stratigraphic method also helps to correlate strata of the same age in the basin (Nehyba 1997; Nehyba & Roetzel 1999; Nehyba et al. 1999).

Sequence stratigraphy

The CF's sedimentary fill records a number of sea-level fluctuations of different frequency and magnitude. The dominant seismic response of the sedimentary fill of the CF is in the form of topsets (see Fig. 17). Aggradation of thick topset deposits is the result of higher tectonic subsidence along the active basin margin, which led to more rapid deposition in its proximal parts compared to distal ones situated at the passive basin margin (e.g. Posamentier & Allen 1993). The dominance of lateral transport from the active

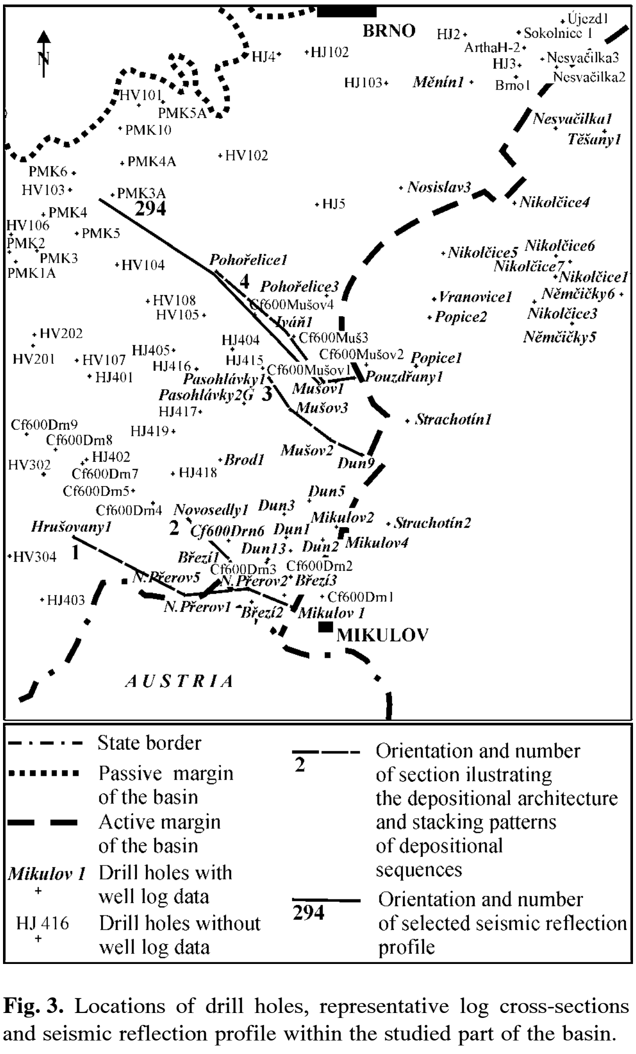


Fig. 3. Locations of drill holes, representative log cross-sections and seismic reflection profile within the studied part of the basin.

basin margin is assumed. Changes in the creation of accommodation space reflected in the depositional architecture (progradation, aggradation or retrogradation) are influenced by the balance of the rate of sea-level change and sediment supply and the areal extent of topsets (Milton & Bertram 1996).

Depositional cycles within the CF of relative sea-level rise and fall are similar to the transgressive-regressive cycles of Johnson et al. (1985), and transgressive and highstand systems tracts (TST and HST, respectively) can be identified. A sequence boundary is connected with the change from progradational to retrogradational depositional architecture. This surface can be identified as the surface of maximum progradation (MPS). Evidence of subaerial erosion in marginal parts of basins or by facies dislocation supports an interpretation of a sequence boundary. Near the active basin margin where higher subsidence rates occur, subaerial unconformities do not extend onto marine shelves, and conformable successions of beds occur with no evidence of subaerial exposure (type 2 sequence boundary). They pass into subaerial unconformities in areas of lower subsidence, cutting across marine shelves. These type 1 unconformities amalgamate in areas with the lowest subsidence rates, forming composite erosional surfaces with larger stratigraphic gaps towards the foreland (Emery & Myers 1996). These broadly planar surfaces can coincide with later flooding surfaces and with the occurrence of lag deposits. A TST results when the sediment supply is lower than the formation of accommodation space. Facies belts shift toward the basin margin and a retrogradational depositional architecture can be followed. An HST results when sediment supply exceeds accommodation space, leading to a progradational depositional architecture following the aggradational one. A maximum flooding surface (MFS) is located between the TST and HST. A TST and HST (i.e. one T–R cycle) form a 4th-order ("high-frequency") depositional sequence that represents a time period of 0.1 to 0.5 Ma. The thickness of a sequence varies generally reaching about 90 m. Parasequences and parasequence sets (Posamentier et al. 1988; Van Wagoner et al. 1988; Emery & Myers 1996; Uličný 1999) are recognized within the systems tracts.

The problem with the application of sequence stratigraphy to the studied deposits is the clear identification of individual key surfaces. Syn- and post-depositional processes affected the sedimentary record especially in the marginal parts of the basin (Nehyba 2000). Sequence boundaries can sometimes be evaluated as suspect because the change in geometry may be connected with a different process than relative sea-level change.

The multiple amalgamations of sequence boundaries and MFS's along one surface, together with varying (progradational vs. retrogradational) framework indicate a record of

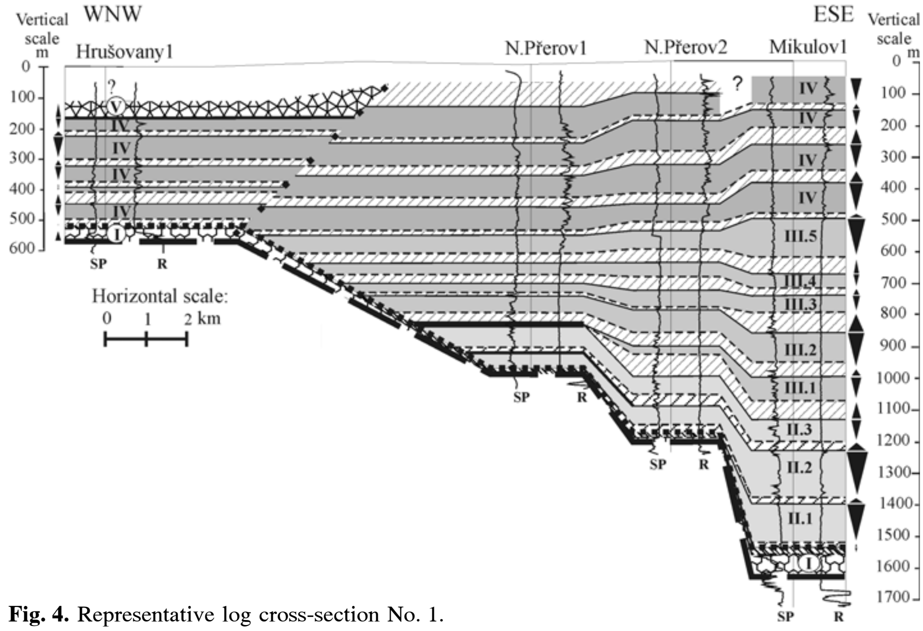
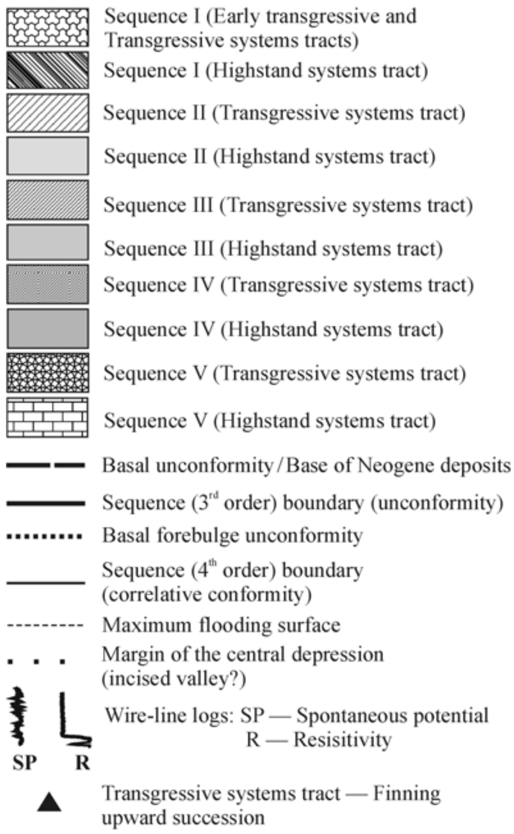


Fig. 4. Representative log cross-section No. 1.

Explanations to the Figures 4 – 7



cycles of several orders. Different temporal and spatial scales of cyclicity record different scales and periodicities of relative sea-level change. Parasequences and parasequence sets, 4th-order and five 3rd-order depositional sequences represent the shortest, middle and longest cycles, respectively. Five 3rd-order depositional sequences characterized by different basin shape, extent, depositional architecture and lithofacies were recognized within the Neogene infill of the CF. They reflect the unique combination of the principal ruling factors (eustasy, tectonics, sediment supply, and basement morphology) and record the dynamic evolution of the collisional margin. Depositional geometry of recognized 4th-order and 3rd-order depositional sequences together with their key surfaces can be followed in Figs. 4, 5, 6 and 7. Kováč et al. (2004) similarly recognized five in Eggenburgian to Early Badenian deposits of the Vienna Basin.

The recognized 3rd-order sequences can be connected into 3 stages of geodynamic development of the basin according the relation to the "main" collision along the active margin of the basin. The role of thrust loading represents the principal feature of peripheral foreland basins in general.

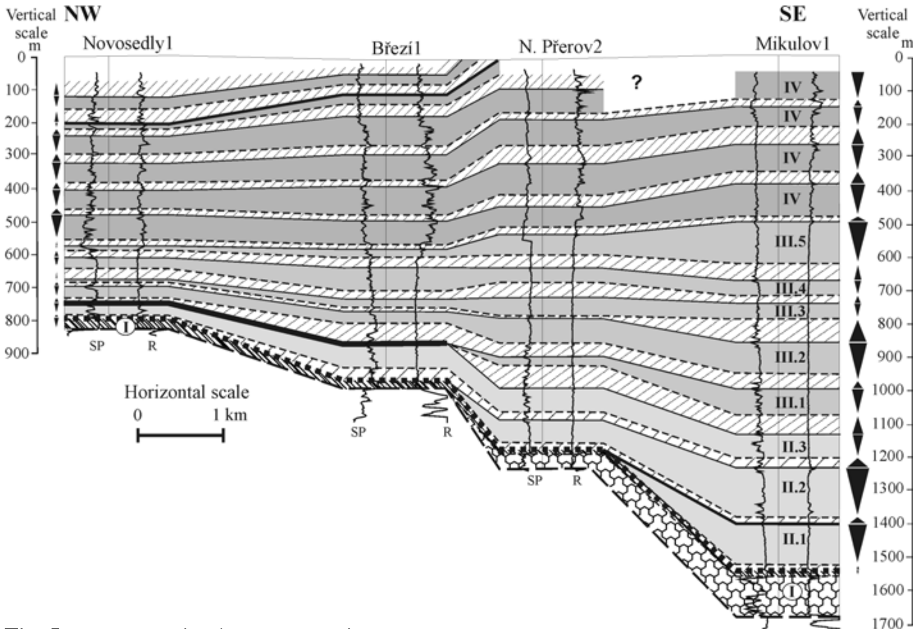


Fig. 5. Representative log cross-section No. 2.

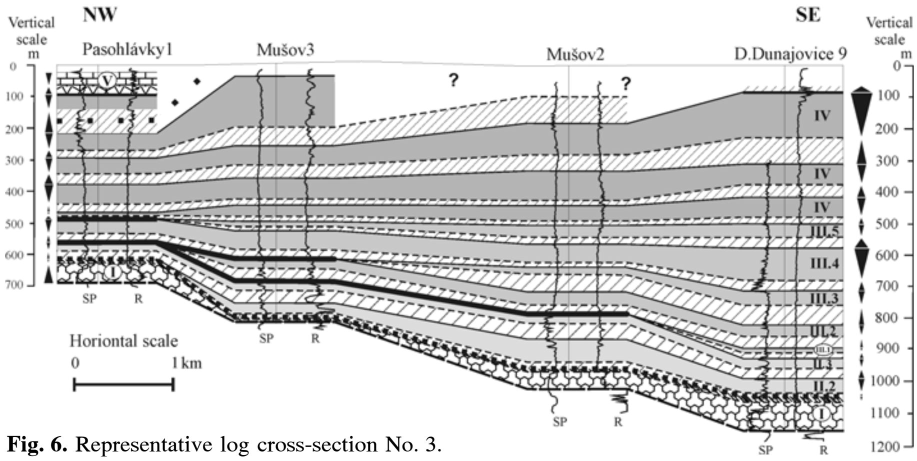


Fig. 6. Representative log cross-section No. 3.

Pre- ("main") collisional stage

The pre- ("main") collisional stage is represented by depositional sequence I. Deposition in the CF began during the Egerian–Early Eggenburgian. A detailed isopach map (Fig. 8) shows that accommodation space developed in a large part of the study area with respect to morphology of the pre-Neogene basement. Areas with deposits of maximum thickness are located close to both active and passive basin margins, and the typical wedge geometry of foredeep depozones did not develop.

Several lithofacies and depositional environments are distinguished (Fig. 9 and Table 1). Fluvial and deltaic deposits occur locally on the base of the succession predominantly along the western margin of the basin. Coastal (i.e. shoreface, foreshore) and shallow marine deposits form the dominant proportion of the succession especially towards the E. The association of non-opaque heavy minerals is highly variable, high contents of stable minerals (i.e. zircon, tourmaline, rutile), staurolite, apatite and generally low garnet content are typical.

Nehyba (2000) proposed a sequence stratigraphic model for this sequence in the western distal parts of the CF. This model is assumed valid for the entire basin. The lower sequence boundary is a very irregularly shaped basal unconformity caused by longlasting subaerial erosion. Dominantly non-marine sediments of an early transgressive systems tract found immediately above it were deposited locally within paleovalleys. These terrestrial deposits progressively grade upward at different rates in different areas into coastal-shallow marine deposits as a consequence of a marine flooding from the S, SE and E, forming the TST with a highly variable lithology that terminates in an MFS. Relief and different rates of sediment supply strongly influenced the shoreline trajectory during this time. Deposition

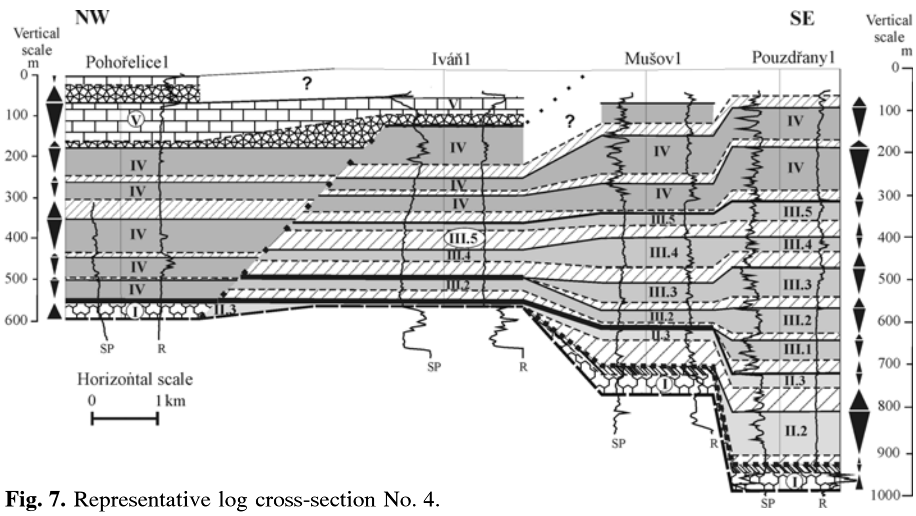


Fig. 7. Representative log cross-section No. 4.

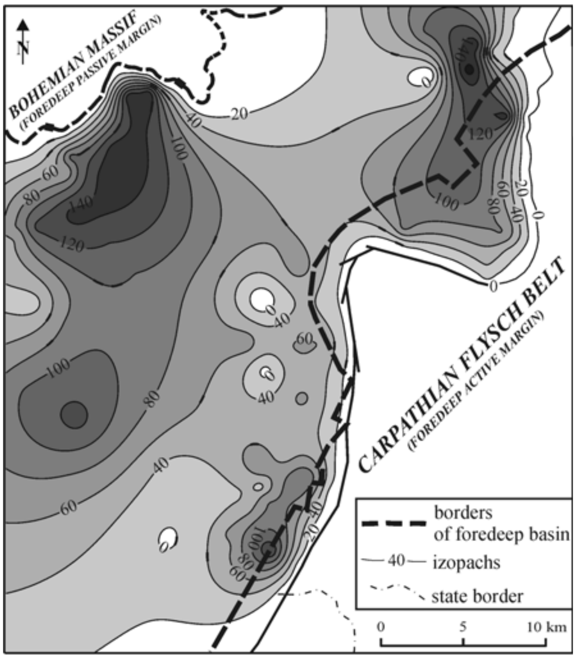


Fig. 8. Thickness map of the deposits of stage I (Late Egerian/Early Eggenburgian-Eggenburgian/Ottnangian).

of an HST above the MFS was strongly influenced by position within the basin and the rate of sediment supply, ending in an unconformity related to a complete reorganization of the basin.

Basement relief, sediment supply and eustasy were the principal ruling factors of this sequence. The role of tectonic subsidence was possibly connected with the "early Savian phase" of thrusting recorded in the Eastern Alps. The initial stage of basin development typically has a lower subsidence and increase in accommodation space compared to later stages. Accommodation space was formed mostly through eustasy (cycle CPC 1 of Kováč 2000; cycle TB 2.1. Haq 1991). The study area can be correlated with the development in the marginal parts of the Alpine Foredeep Basin. Material was shed from the deeply weathered margins of the Bohemian Massif and does not mark the initiation of West Carpathian accretionary wedge thrusting.

Collisional stage — development of synorogenic clastic wedge

A synorogenic clastic wedge with a generally westward prograding, eastward thickening framework dominates the whole basin fill. During this stage, accommodation space was created foremost through flexural subsidence. Three depositional sequences (sequences II, III and IV) overlying the initial sequence were recognized within this stage. Sequence II represent the lower, sequence III, the middle and sequence IV, the upper part of the clastic wedge.

Fifteen lithofacies have been identified (Fig. 10 and Table 2). They were deposited in coastal (foreshore, shoreface), shallow marine and deeper marine (bathyal) environments. Shallow marine sediments strongly predominate. Tectonic subsidence in response to thrust loading provided a mechanism for their accommodation space, while fluctuations in relative sea level provided means for transporting sand to depositional sites and produced a repetition of lithological patterns. Typically higher content of plant detritus shows that the rate of organic carbon productivity was high relative to the rate of siliciclastic sediment input, probably enhanced by a warm climate, with preservation from anaerobic bottom conditions through thermohaline water stratification preventing vertical circulation. Facies of condensed sections are characterized by higher contents of authigenic glauconite, phosphates and pyrite (e.g. Loutit et al. 1988; Amorosi 1995; Tucker 2001). Non-opaque heavy minerals within are characterized by a monotonous garnet association and low stable mineral content. Nehyba & Buriánek (2004) showed that this transition is also connected with a distinct change in garnet chemistry. These observations indicate a dramatic shift in provenance from a passive to active margin of the basin.

The cyclic deposits of the clastic wedge can be subdivided into temporally discrete packages representing mainly variations in tectonic activity; therefore, the temporal resolution of these cycles improves the resolution of the tectonic history of the active basin margin/thrust front (Mars & Thomas 1999). Cyclicity of filling of the peripheral foreland basin is schematized in Fig. 11. Thick fine-grained deposits reflecting retrogradation and deepening of the basin are connected with tectonic activity and thrust loading. Increased rates of subsidence trapped coarser-grained material in proximal parts of the

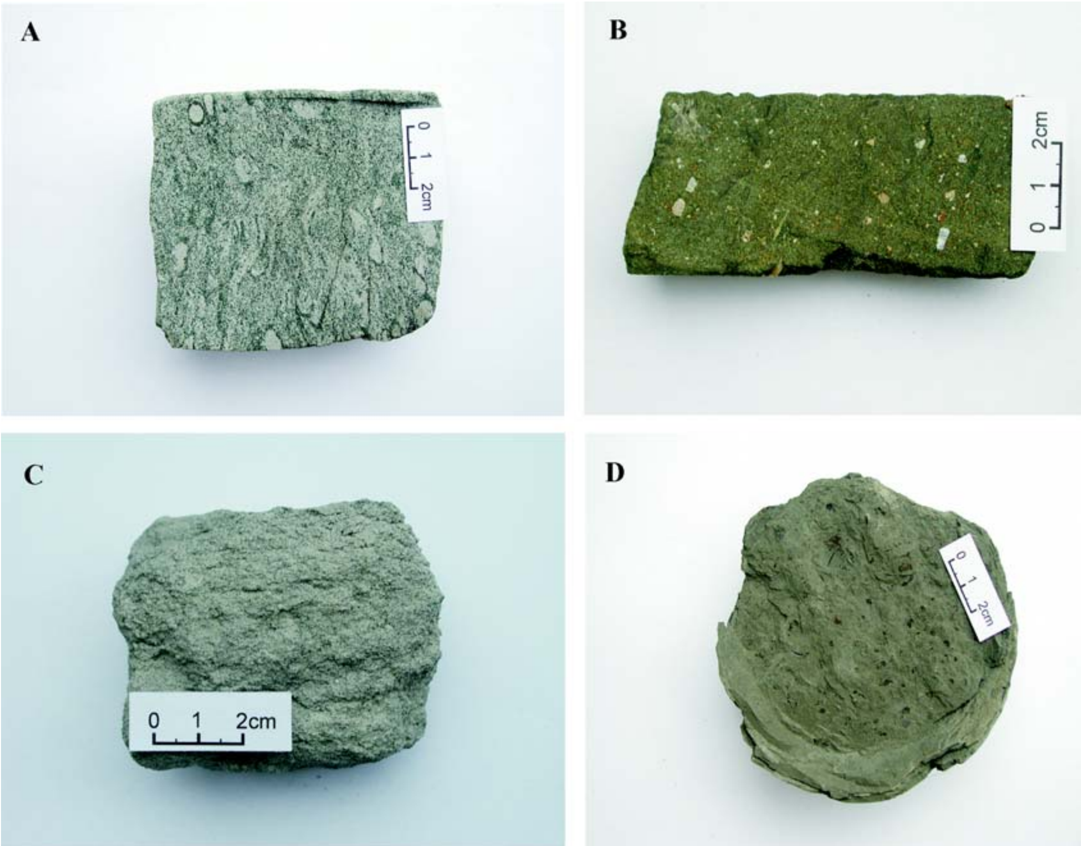


Fig. 9. Selected examples of lithofacies of pre- ("main") collisional stage. **A** — facies Sb, **B** — facies Sg, **C** — facies Sp, **D** — facies M2.

Table 1: Description and interpetation of lithofacies of pre-collisional stage.

	Description	**Interpretation**
Sp	Fine to coarse micaceous sandstone, cross-bedded, noncalcareous. Abundant plant remnants, rarely shell debris. Poor sorting.	Coastal deposits — upper shoreface.
Sg	Coarse to very coarse micaceous sandstone to fine conglomerate with sandy matrix support. Crude cross-bedding or massive. Content of plant debris, glauconite and bioturbation vary. Poor sorting.	Coastal deposits — upper shoreface.
Sb	Fine to medium rarely coarse micaceous sandstones, noncalcareous. Bioturbation, cross-bedding and horizontal lamination. Abundant plant remnants. Rare mud flasers, scattered subangular quartz granules and shell debris. Poor sorting.	Coastal deposits — middle to lower shoreface, transitional zone to offshore (Driese et al. 1991).
Sm	Noncalcareous, medium to coarse micaceous sandstone, massive. Abundant plant remnants. Content of glauconite varies.	Coastal deposits (shoreface).
Sl	Fine to medium micaceous sandstone, horizontal lamination or flaser bedding, rarely rippled. Dark grey claystone flasers with abundant plant remnants. Abundant deformation (loading structures). Content of glauconite is variable.	Coastal environment — channels, lagoonal deposits.
M1	Dark grey, brown or green grey silty claystone to clayey siltstone, both calcerous and noncalcareous. Horizontally laminated or massive. High content of plant debris. Scattered angular to subangular quartz clasts. Content of pyrite, glauconite, phosphates and shells is generally low.	Shallow marine environment (inner shelf to transitional zone), inconvenient (anoxic?) condition for colonisation.
M2	Dark grey, brownish, green claystone, silty claystone and siltstone, noncalcareous. Abundant plant remnants. Massive and horizontal bedding. Rarely scattered angular quartz granules. Poor sorting. Higher content of phosphates, fish remnants, pyrite and glauconite.	Shallow marine deposits, condensed deposition (Loutit et al. 1988; Amorosi 1995; Tucker 2001).

basin, forming wedges that thicken toward the thrust belt. Thrust cessation led to the filling of proximal part, which in turn permitted the progradation of coarse-grained material into the distal part of the basin. The shoreline propagated over the shallow-water deposits, and the general trend of shallowing can be followed. Relatively thin but extensive sandstone beds record rapid progradation during the slow subsidence. The com-

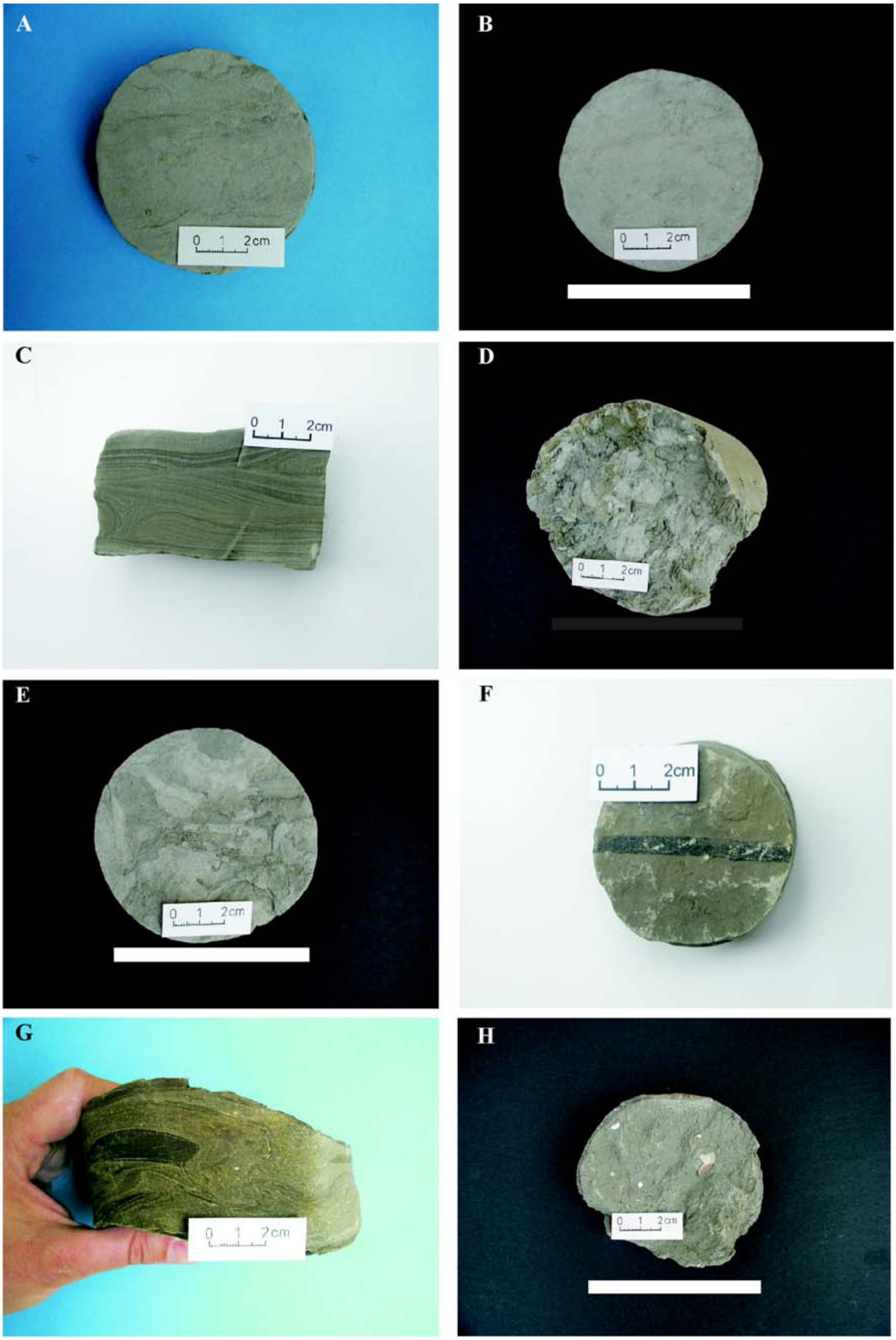


Fig. 10. Selected examples of lithofacies of synorogenic clastic wedge (sequences II, III and IV). **A** — facies F1, **B** — facies F3, **C** — facies F7, **D** —facies F14, **E** — facies F5, **F** — facies F2, **G** — facies F8, **H** — facies F13.

Table 2: Description and interpretation of lithofacies of synorogenic clastic wedge.

	Description	Interpretation
F1	Grey to dark grey, greenish or greyish silty or fine sandy claystone, calcareous and noncalcareous. Massive, rarely slightly bioturbated. High differences in content of pyrite, glauconite, phosphates, fish remnants and plant debris.	Varied condition — anoxic, low rate of deposition vs. rapid deposition, high rate of sediment supply. Deposition below the storm wave base — distal shelf or deep water environment.
F2	"Schliers" — grey siltstone to silty claystone, calcareous. Fine horizontal lamination sometimes slightly undulated (HCS?). Laminas of silt or very fine sand. Content of glauconite, pyrite, phosphates and plant remnants varies.	Deposits of currents (distal storm or gravity ones?), distal parts of shelf or deep-water environment.
F3	Grey silty or fine sandy claystone with interbeds of light grey micaceous fine sand or sandstone. Lenticular or wavy bedding. Locally bioturbated. Content of glauconite, pyrite, phosphates and plant debris highly varies.	Outer to middle storm dominated shelf or transitional zone (McCave 1970, 1971; Allen 1982). Infuence of storms of density currents.
F4	Grey sometime green-grey micaceous siltstone with abundant plant debris. Horizontal lamination.	Distal current deposits (density flows or storm flows?). Outer and middle storm dominated shelf.
F5	Grey, fine to medium micaceous sandstone, horizontal or undulatory lamination, parting lineation (HCS? — Harms et al. 1975; Dott & Bourgeois 1982) or flaser bedding. Laminas of darker mudstone with abundant plant remnants. Presence of glauconite is rare.	Shallow marine (middle to inner storm dominated shelf) to transitional zone between coastal and shelf environments (Hamblin & Walker 1979; Hunter & Clifton 1982; Walker & Plint 1992; Driese et al. 1992; Hill et al. 2003).
F6	Light grey, fine- to medium-grained micaceous sandstone, good sorted, positive grading. Sandstone beds thicker than 0.5 m.	Transitional zone between coastal and shelf environments (Walker & Plint 1992; Hill et al. 2003).
F7	Light greym fine- to medium-grained micaceous sandstone. Horizontal lamination or massive. High differences in the content of plant debris.	Transitional zone between coastal and shelf environments (Walker & Plint 1992) or outer storm dominated shelf (Reineck & Singh 1984; Driese et al. 1992).
F8	Grey to brown grey, fine- to medium-grained sandstone, horizontal lamination. Abundant plant debris. Clay and coal intraclasts. Rarely shell debris, fish remnants and granules.	Coastal and proximal shallow marine environment. Reworking of cohesive deposits — important sea level change.
F9	Pebbly mudstones — angular to subangular sandstone intraclasts (Ø several cm) within grey claystones.	Coastal and proximal shallow marine environment — role of storms or sea level fall (Kelling & Mullin 1975).
F10	Pebble to matrix supported fine-grained conglomerates forming thin laminas (residual deposits).	Coastal and proximal shallow marine environments — role of storms or sea level fall (Walker 1985).
F11	Dark grey, brownish or greenish silty to fine sandy claystone, calcerous and noncalcareous. Highly bioturbated.	Distal shallow marine deposits — below storm wave base (Keith 1992).
F12	Light grey very fine to fine micaceous sand to sandstone, intensively bioturbated.	Coastal environment (Reading 1996; Hill et al. 2003).
F13	Light grey, medium- to coarse-grained micaceous sandstone. Horizontal lamination with scattered rounded granules to small pebbles. Very rare plant and shell debris.	Coastal environment (Snedden & Nummendal 1991) to storm dominated outer shelf (Driese et al. 1992).
F14	Micaceous medium to coarse sandstones with abundant dark clayey intraclasts. Chaotic fabric — intraformational breccia. Occurrence of pyrite and plant detritus. Rare angular to subangular small pebbles.	Coastal and proximal shallow marine environment. Erosion of cohesive intrabasinal deposits due to action of large storms or sea-level fall.

mencement of fine-grained sedimentation above coarse-grained deposits indicates renewed tectonic activity. However, the model may be complicated by episodic or non-episodic thrusting, differences in the distribution of loading due to variations in thick- and thin-skinned thrusting, the size of the catchment area, and erosion of the wedge-top depozone (Blair & Bilodeau 1988; Heller et al. 1988; Plint 1988, 1991; Burbank & Beck 1991; Keith 1992; Plint et al. 1993; Mellere & Steel 1995; DeCelles & Gilles 1996).

The typical features of the peripheral foreland basin including: (1) displacement of the zone of maximum subsidence toward the foreland of the migrating thrust belt, (2) uplift, migration and erosion of the flexural forebulge, and (3) consecutive onlapping of the foreland basement by foredeep sediments can be followed within the basin infill of the CF only during this stage.

The position of the flexural hinge line (margin of the forebulge) in Figs. 12–14 is highly approximate and was located according to the map of the regional Bouguer anomalies — reduction density 2.67 g/cm^3 (Sedlák 2000).

Initial tectonic/flexural subsidence — lower clastic wedge

Sequence II records the initiation of thrusting as the ruling factor in providing sediments accommodation space, leading to the development of a characteristic peripheral foreland basin (e.g. Busby & Ingersoll 1995). Orogenward tilting of the basement through forebulge migration preceded the onset of flexural subsidence and clastic wedge deposition. Initial thrust loading produced a typical unconformity at the base of the succession, termed a basal forebulge unconformity (Crampton & Allen 1995), reflecting the beginning of a complete reconstruction of the basin shape and a shift in provenance. Toward the passive margin, the unconformity is overlain by progressively onlapping sediments above an increasing stratigraphic gap. Progressive truncation geometry, extent of hiatus, and polarity of sediment supply are the main differences between a basal forebulge unconformity and an unconformity driven by eustasy (e.g. Flemings & Jordan 1989; Sinclair et al. 1991).

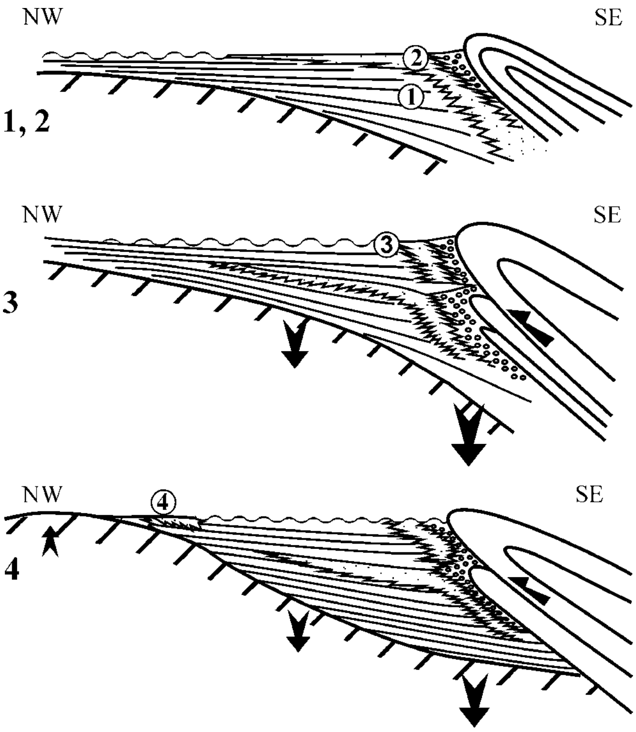


Fig. 11. Cyclicity of filling of the peripheral foreland basin (according to Plint et al. 1993): **1** — Increase pf tectonic activity along the active margin, rapid subsidence, deposition of fine-grained clastics in the dominant part of the basin, deposition of coarse clastics only in proximal parts of the basin. **2** — Cessation of tectonic activity along the active margin, reduction of subsidence rate, progradation of the coarse deposits into the basin. **3** — Rejuvenation of the tectonic activity, rapid subsidence, coarse-grained material trapped in proximal parts of the basin, fine-grained deposition in the dominant part of the basin. **4** — Continuing activity of the thrust front, steepening of the flexure profile, erosion of the peripheral forebulge, deposition of coarse clastics also in the distal parts of the basin (different provenance).

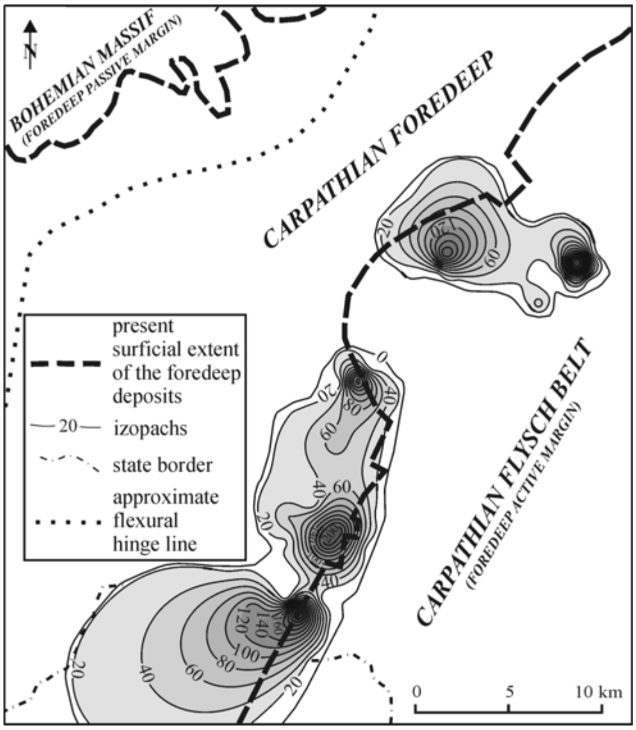


Fig. 12. Thickness map of the deposits of sequence II (sequences II.1 and II.2 — Late Eggenburgian–Ottnangian/Early Karpatian).

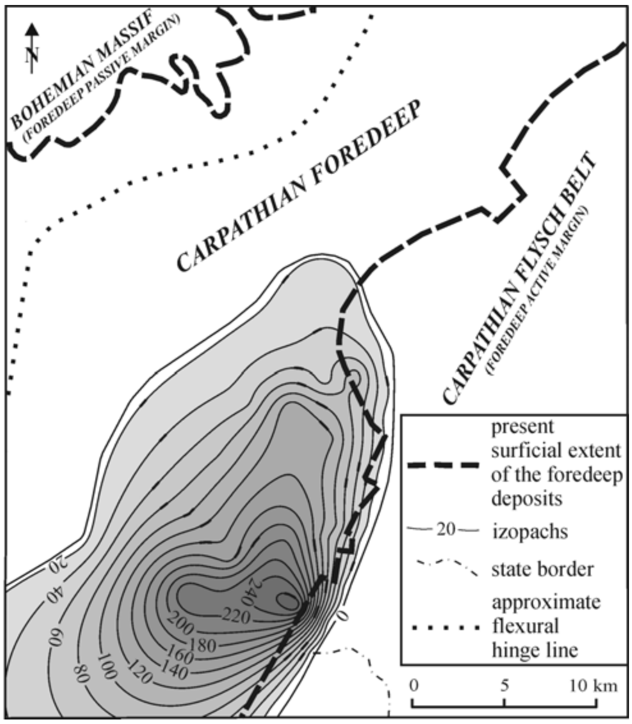


Fig. 13. Thickness map of the deposits of sequence II (sequence II.3 — Ottnangian/Early Karpatian).

Sequence II began in the Late Eggenburgian (Savian phase of thrusting) and ended in the Ottnangian or Early Karpatian (early Styrian phase of thrusting). Minor differences in the stratigraphy are found between more proximal and distal parts of the basin. Seismic lines and deep boreholes show a progressive deepening of the basement/basin-fill contact toward the orogene. Sequence II deposits are observed only close to the basin's present-day eastern margin (Figs. 12 and 13). They reveal a typical synorogenic clastic-wedge shape and thicken toward the active margin. They are typically composed of fine-grained siliciclastic sediments and represent the lower part of the clastic wedge. The basin revealed different lithofacies, architecture, extent, and position of its active and passive margins during sequence II than during sequence I.

Three 4th-order depositional sequences (II.1., II.2., II.3.) were documented that show progressive onlap of the successive sequences toward the passive margin and thickening of each sequence toward the active margin (see Figs. 4, 5, 6, 7, 12 and 13). Correlative conformities in the area of greater subsidence grade into amalgamated unconformities in more distal parts of the basin. The shingled framework of these generally westward prograding sequences suggests a history of a progressively increasing subsidence rate as a response to an advancing thrust front and in-

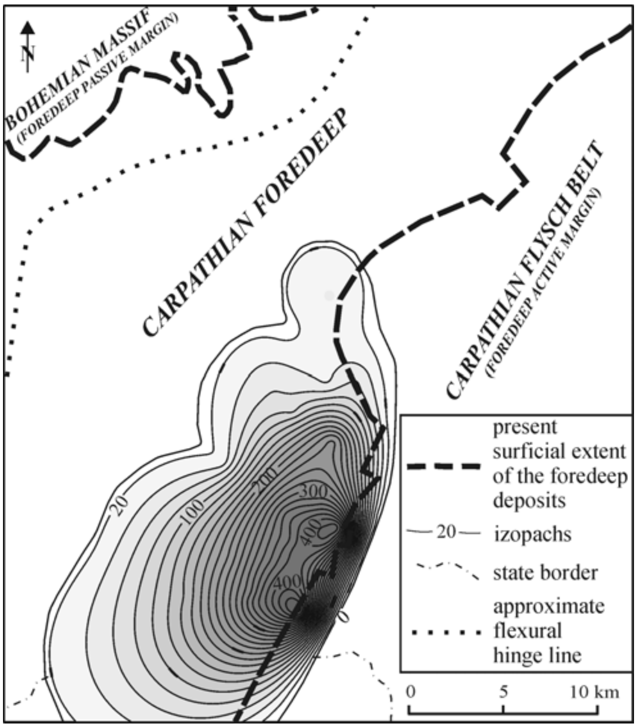


Fig. 14. Thickness map of the deposits of sequence III (Karpatian).

creasing thrust load and sediment supply (Mars & Thomas 1999). The lateral persistence of parasequences and systems tracts indicates no perceptible erosion prior to deposition of the next sequence. The consistent geometry of the succession and transgressive shale onlap suggest continuous loading (Plint et al. 1993).

A high subsidence and sediment underfilling characterize sequence II deposition. Pre-flexural basement relief influenced smaller scale depositional patterns especially in marginal areas (e.g. Gupta & Allen 1999). Both 4th-order sequences II.1. and II.2. reveal a limited lateral extent, whereas sequence II.3. has a much greater range and TST thickness (see Figs. 12 and 13). Therefore, tectonics (early Styrian phase) and eustasy (cycle CPC 2 of Kováč 2000) both played a vital role throughout deposition of the sequence II.3.

Relaxation — middle clastic wedge

The depositional architecture of sequence III was ruled mainly by an interaction between tectonic/flexural subsidence and migration of the forebulge toward the foreland, and isostatic rebound connected with migration of the forebulge toward the thrust front (e.g. Flemings & Jordan 1989; Sinclair et al. 1991; Schlunegger et al. 1997). The isopach map of deposits of sequence III (Fig. 14) shows its location as being close to the basin's active margin, the shape of the synorogenic clastic wedge, and the considerable thickness of these Karpatian deposits. They can be divided into five 4th -order sequences (III.1., III.2., III.3., III.4. and III.5.). The bases of these sequences are relative conformities in the proximal (internal) parts of the basin, whereas toward the distal parts they are unconformities and often amalgamated (see Figs. 4, 5, 6 and 7). The basal forebulge discontinuity forms the base of prograding sequences only in the most distal parts of the basin, revealing the progressive onlap by the overlying sediments. The erosive zone and facies belts overlying the basal forebulge unconformity are parallel to the Western Carpathian thrust front and migrated into the foreland over time, ahead of the advancing orogenic accretionary wedge. The erosional gap along the unconformity is wider in the direction of migration. The occurrence of sandy facies is significantly higher in the sequence III compared to sequence II. It may reflect a closer distance to the active margin or a significant redistribution of deposits. Typical is a rhythmic framework of successive sequences with alternating progradation with onlap advance generally toward the NW and retrogradation with relative retreat generally toward the SE. The whole succession reveals an overall progradational framework, that is retreat of the forebulge toward the foreland to the NW. The consistent geometry of stratal truncation suggests a connection with episodic uplift and migration of the forebulge (e.g. Plint et al. 1993).

Thrusting in the Eastern Alps toward the N ended during the Karpatian but continued in the Western Carpathians (Kováč 2000). Changes in the stress field of the Alpine-Carpathian Foreland led to the modification of the basin's flexural amplitude and profile, and possibly a reactivation of basement faults, etc. An acceleration of subsidence in response to thrust loading led to moderate to high production rates of accommodation space in proximal parts of the basin. The role of sediment redistribution and local forebulge erosion may also have influenced the depositional architecture. An increase in sediment supply redistributes the loading and reduces the amount of accommodation space (Fleming & Jordan 1989). The shape of the basin and position of its active and passive margins differ significantly from the present. Sequence III probably represents the time between the early and late Styrian phases of thrusting.

Main collision — upper clastic wedge

Sequence IV represents the Late Karpatian upper part of the synorogenic clastic wedge and records the main collision along the active margin coinciding with a high subsidence in the foreland basin. The high rates of sediment supply and increase in accommodation space led to the deposition of thick successions during tectonic processes that also directly affected the basin fill. The isopach map (Fig. 15) shows a widely distributed wedge-shaped body of deposits that thickens toward the active margin. The area with maximum deposition is located more to the W and NW compared to previous stages and is aligned with the active margin.

Seven transgressive-regressive (T-R) cycles were recognized within sequence IV deposits (see Figs. 4, 5, 6 and 7). Their consideration as sequences however is suspect because of missing data from the marginal parts of the basin. The architecture of individual cycles differs significantly from that of 4th-order depositional sequences (T-R cycles) of sequences II and III. They have a wedge shape with the lower boundary inclined toward the active basin margin and an almost horizontal upper boundary (onlap) during sequences II and III. T-R cycles of sequence IV reveal, on the contrary, a subhorizontal or even slightly inclined base toward the distal parts of the basin to the W or NW. The number of T-R cycles also rises in this direction because of the occurrence of upper cycles. Successive T-R cycles upward through the succession reveal gradual advance of their maximal thickness towards the basin (generally to W). Lower T-R cycles are generally thicker in proximal parts of the basin, whereas upper T-R cycles are thicker in central parts. All of these features reflect a migration of the zone of maximum deposition toward the W (compared to the sequences II and III), which can be attributed to acceleration of thrusting along the active margin. The presence of sandy facies within these cycles in proximal and distal parts of the basin reflects both the relative proximity to the active margin and sediment redistribution.

During sequence IV deposition, the basin underwent a complete reorganization that affected its shape and lateral extent during assumed extensive flooding of the foreland. The position of the basin's active margin was generally similar to its present-day location. Karpatian (late Styrian phase) NW-SE compression observed as final thrusting of the Flysch Belt characterizes the collisional zone along the eastern margin of the Bohemian Massif in the study area.

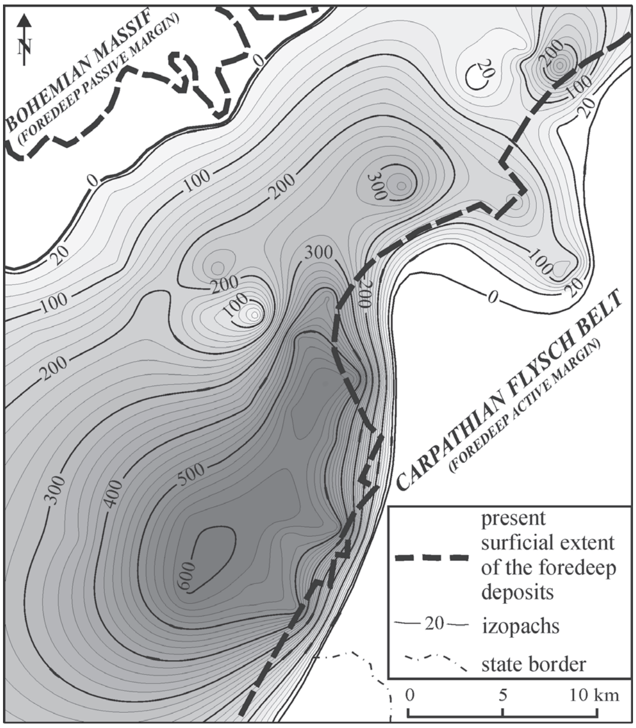


Fig. 15. Thickness map of the deposits of sequence IV (Late Karpatian).

Post- ("main") collisional stage

All major architectonic elements of foreland basins are conventionally considered to accumulate due to flexural subsidence of the foreland plate with typically regional orogen-ward thickening on a basinal scale (Beaumont 1981). The distinctive geometry of deposits of the basin's final stage suggests that flexural subsidence was not the major generator of accommodation space.

Sequence V (Early Badenian) deposits are located in the central parts of the basin where a significant oblique seismic termination surface cutting the Neogene basin fill is seen in seismic reflection profiles. This surface forms a broad depression throughout middle parts of the basin elongated along the generally SW-NE trend of the basin axis. Sequence IV deposits mostly fill the lower part of depression, whereas sequence V deposits fill the upper part. Sequence V (Early Badenian) is dominated by two lithofacies with areas of maximum thickness forming an almost symmetrical depression (Figs. 16, 17). The first lithofacies are basal or marginal coarse clastics deposited in coarse-grained Gilbert deltas (Nehyba 2001) and contain an abundance of intraclasts indicating cannibalization of older basin fill. These clastics are located along both W and E margins of the depression and have a maximum thickness of 175 m. The second lithofacies are basinal pelites ("tegel") with maximum thickness of ~600 m that were deposited in deep-water. Pelites are almost uniformly distributed in the whole depositional area.

The depression's origin is obscured by limited data on deposits close to the termination surface. Tomek (1999) suggests a pre-Early Badenian compressional origin (pop-up structure). On the contrary, Jiříček (1995) interpreted the depression as the slope of outer molasse. We preliminarily proposed the formation of the depression as an incised valley formed within the basin along the active margin. Its origin was probably tectonically induced. Compression of the Carpathian orogenic wedge oriented towards NNW and NW

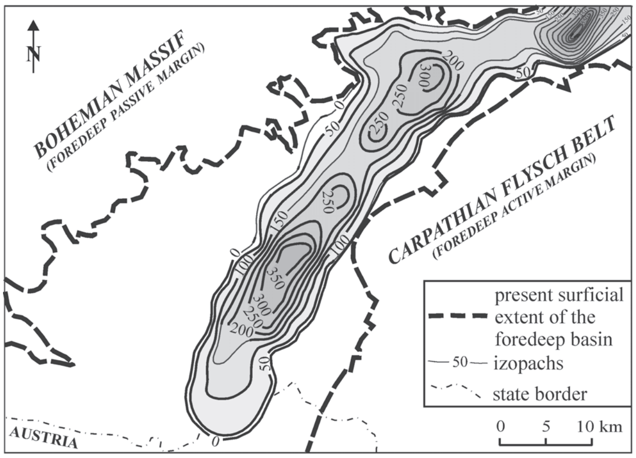


Fig. 16. Thickness map of the deposits of sequence V (Early Badenian).

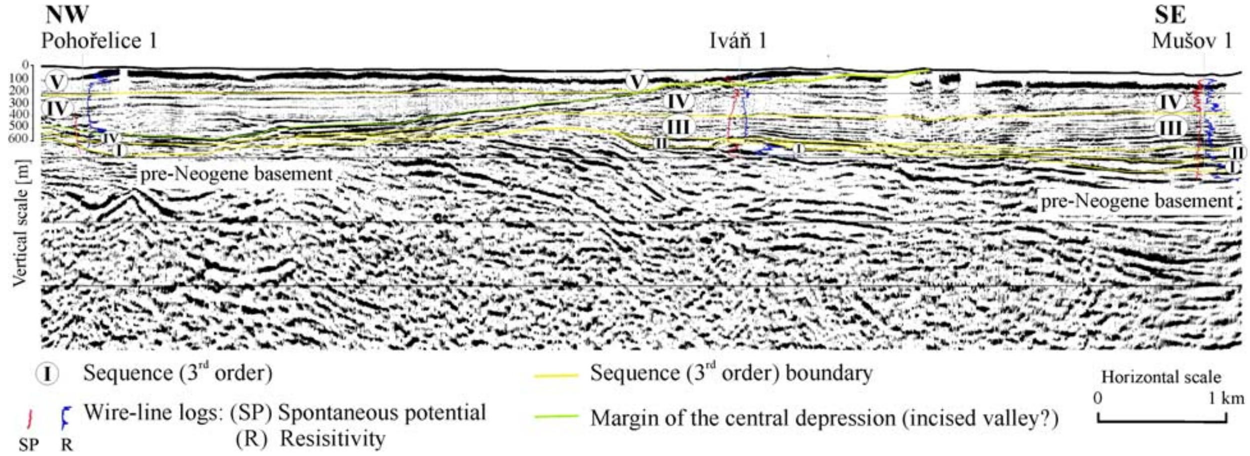


Fig. 17. Regional reflection seismic profile 294 calibrated by wells crossing the Carpathian Foredeep from the proximal to the distal/marginal parts of the basin. See Fig. 3 for location of the profile.

changed its orientation towards NNE and NE during Late Karpatian and Early Badenian (Kováč 2000). This shift led to the dominant formation of accommodation space (flexural subsidence) in the northern part of the CF whereas its south-western part (studied here) was affected by relative uplift. Older basin infill (predominantly Karpatian in age) were eroded and deformed. Longitudinal depression along the basin axes (i.e. SW-NE direction) was formed (incised valley). These processes led to the formation of Gilbert deltas along the basin margin with basinward transport direction and sources from both opposite NW and SE margins. Final flooding of the "entire" basin was dominated by deposition of basinal pelites (Nehyba 2001). This process was combined with eustatic sea-level change (TB 2.3 of Haq 1991, CPC 3 of Kováč 2000). Two Early Badenian transgressive phases of sea-level rise are supposed in the CF (Brzobohatý & Cicha 1993) with the last probably the most extensive. This preliminary model could be further complicated with speculative allochthonous position of sequence IV, by the role of NW-SE oriented extension/transtension within the formed stress field (Kováč 2000) or by possible reactivation of basement faults (especially NW-SE and NE-SW oriented) and tectonic origin of the valley. Some similar patterns were described by Janbu et al. (in print). The proposed schematic evolution of the CF during the Early Badenian is presented in Fig. 18. Tectonic activity combined with eustatic sea-level change were the dominant ruling factor of basin formation and deposition during the Late Karpatian and Early Badenian.

Discussion

A generally westward (towards passive basin margin) propagation of the synorogenic clastic wedge, recorded in sequences II, III and IV (see Figs. 4, 5, 6 and 7), generally illustrates successive basin filling in response to foreland subsidence. The sequence II occurred in the eastern part of the basin where greater subsidence is reflected in greater thicknesses with limited westward extent. Subsequent sequences prograded further westward, where less subsidence provided less accommodation space, resulting in a thinner but wider extent of them. Progressively increasing subsidence in response to an advancing thrust front, increasing thrust load, isostatic adjustment to the load, and infilling of the basin with a synorogenic clastic wedge, demonstrating diachronous differential subsidence in different parts of the basin are the explanation for these observations. Along-strike variations in stratigraphic thickness and systems tract and parasequence distributions reflect the influence of structural irregularities along the collisional margin superimposed on a described long-term pattern. The short time taken for forebulge migration reveals rapid orogenic advance rates increasing the likelihood of underfilling (e.g. Sinclair et al. 1991).

The progression of main tectonic subsidence from the Late Egerian in the S part to the Middle Miocene in the NE part of the CF reflects an evolution in orientation of the main convergence between the Alpine/Carpathian nappe stack and its foreland along the eastern margin of the Bohemian Massif. If we accept significant strike variations in tectonic processes (diachronous collision between margins inclined at an angle) then we may presume that the position of basin depozones and axes changed dramatically through the time. The combination of lateral and longitudinal transport led to repeated redistribution of deposits and complicated the recognition of source areas.

These results may provide insight into the discussion about the occurrence of Ottnangian deposits in the CF (Jiříček 1983; Čtyroký 1991, etc.). They are generally restricted within the basin only to the NW marginal area (Rzehakia Beds) but with a very limited occurrence in their internal parts. They are highly probably related to sequences I, II, and reveals an aggradational depositional architecture. These deposits represent an erosional relic and may be connected to deposition in the forebulge or back-bulge depozone. Because of the generally low rate of tectonic subsidence particularly in the distal area, eustatic influence upon sedimentation may have been greater than a tectonic one. The forebulge became a barrier for sediment distribu-

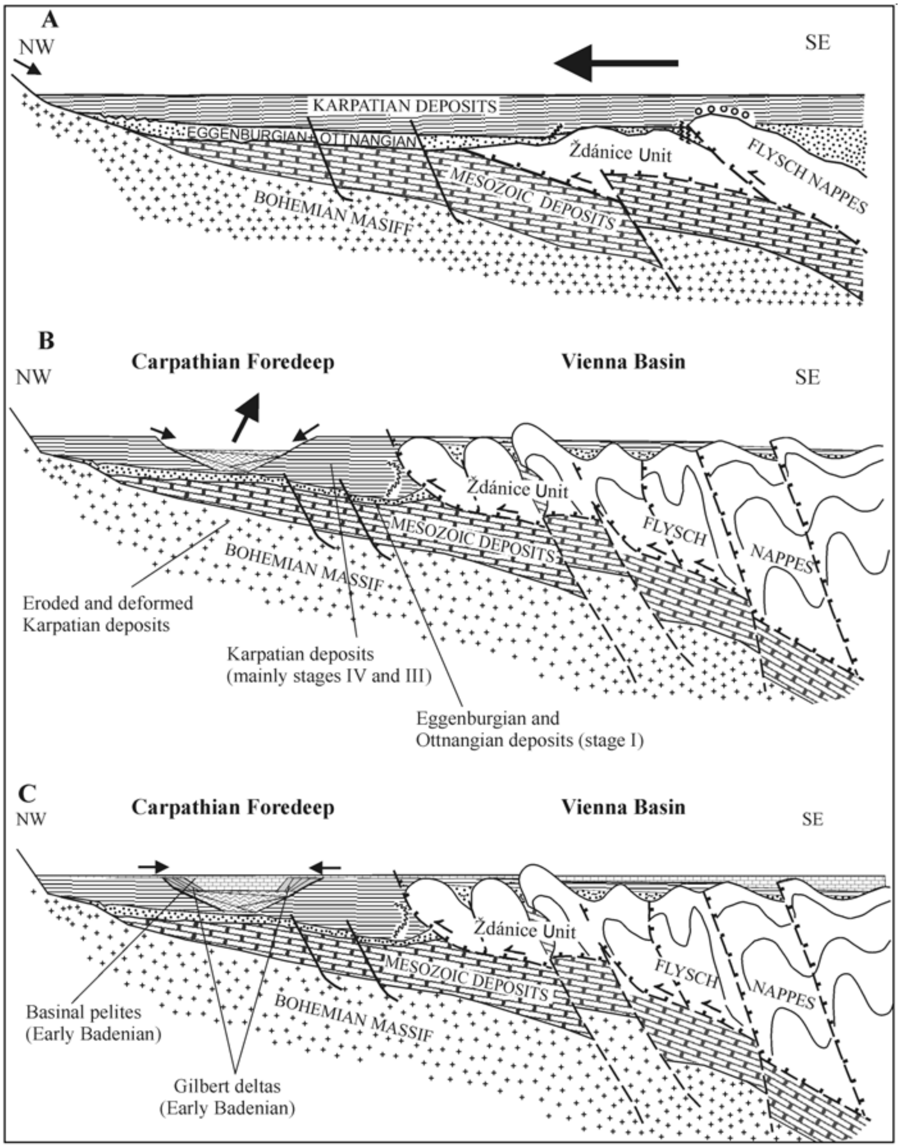


Fig. 18. Schematic evolution of the Carpathian Foredeep. **A** — Deposition during sequences III and IV, **B** — Formation of central depression (incised valley), **C** — Deposition of sequence V. ⟵ — Transport direction.

tion so that different provenances in opposite parts of the basin can be traced. The transgressive onlap of Karpatian deposits (sequences III and IV) upon deposits of various sequences and stages (i.e. different extents of hiatus) indicates erosion of Ottnangian deposits in more proximal parts of the basin. The position of the basin's different depozones and their successive migration (reciprocal stratigraphy) also played an important role. During a single thrusting event, flexural uplift of the forebulge and subsidence of the foredeep and back-bulge occur simultaneously. As a result, opposing relative trends in accommodation space or relative sea-level change are produced in laterally equivalent strata. In areas undergoing flexural subsidence (foredeep, back-bulge) accommodation space increases and deposits reflect relative sea-level rise. In contrast, accommodation space decreases in areas undergoing uplift (wedge-top, forebulge) and deposits reveal shoaling-upward progradational trends ending in unconformity surfaces (Giles & Dickinson 1995; Catuneanu et al. 1999).

A possible explanation for the limited width of the basin is an overall post-flexural uplift. Because of the basin's asymmetrical shape, this process may have accordingly narrowed the basin and accentuated the bulge area.

Conclusions

Five 3rd-order depositional sequences of the Carpathian Foredeep Basin were recognized within its Neogene infill. Individual sequences are characterized by typical basin shape, extent, depositional architecture and lithofacies, that is by the various roles of the principal ruling factors (eustasy, tectonics, sediment supply, and basement morphology). 4th-order depositional sequences (transgressive-regressive cycles and their systems tracts were identified within these five stages. Recognized 3rd-order sequences can be connected into 3 stages of geodynamic development of the basin according the relation to the "main" collision within the West Carpathian accretionary wedge. Pre- ("main") collisional stage (Eggerian/Eggenburgian) is represented by sequence I. The most important ruling factors were eustasy, rate of sediment supply and basement relief. Deposition in the basin can be compared with deposits in the marginal parts of the Alpine Foredeep Basin. The collisional stage is reflected in three sequences. Sequence II (Eggenburgian–Early Karpatian) reflects the initiation of thrusting as the primary ruling factor creating accommodation space, while the role of other factors (i.e. eustasy, sediment supply and relief) was supplementary. A peripheral foreland basin with all the typical characteristics was formed. Three 4th-order sequences were recognized that are related to deposition of the lower part of the synorogenic clastic wedge. Sequence III (Karpatian) was ruled mainly by interactions between tectonic/flexural subsidence and isostatic rebound associated with the forebulge migrating toward the foreland and thrust front, respectively. Five 4th-order sequences were identified belonging to the middle part of the clastic wedge. Sequence IV (Late Karpatian) comprises the upper part of the synorogenic clastic wedge that represents the main collisional event and high subsidence in the foreland basin. Tectonic processes dominated the depositional architecture, directly affecting the basin fill. During this time, the basin underwent a complete reconstruction, affecting its shape and lateral extent while extension was causing flooding of the foreland. Seven T-R cycles are recognized; however, their placement into 4th-order sequences is unclear. Post- ("main") collisional stage (Early Badenian) is reflected in sequence V. Deposition was ruled by tectonics and eustasy. Accommodation space developed dominantly in the internal parts of the basin (incised valley?).

The sequence stratigraphic study of the western part of the Carpathian Foredeep suggests a complicated evolution of the foreland basin that developed in the collisional zone located between the Bohemian Massif and both Eastern Alps and Western Carpathians. The depositional architecture's response to various intensities and orientations of flexural loading and the active margin's polyphase nature can provide a significant addition to the general evolutionary model of peripheral foreland basins.

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