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THE CYCLICITY OF THE LOWER MIOCENE DEPOSITS OF THE SW PART OF THE CARPATHIAN FOREDEEP AS THE DEPOSITIONAL RESPONSE TO SEDIMENT SUPPLY AND SEA-LEVEL CHANGES

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Abstract: The Lower Miocene deposits of the SW part of the Carpathian Foredeep show a recurrent cyclic arrangement. These cycles are typical transgressive/regressive cycles. Among many factors causing cycle stacking patterns two played a leading role: sea-level changes and the rate of sediment supply. The Eggenburgian and Ottnangian sedimentary record of the basin can be subdivided into several sequence stratigraphic units. Two sequences have been recognized within the studied area. Sequence I is formed by a succession of sediments forming segments A, B and C with their parasequence sets. Deposits of segment A are interpreted as lowstand/early transgressive deposits, segment B is formed by transgressive deposits and segment C by highstand deposits. Deposits of the falling stage were not described in the area under study but are traced more basinward. Within sequence II only one segment that is segment D (transgressive and highstand deposits) with its parasequence sets has been recognized. The morphology and different subsidence rate of various parts of the basin basement strongly influenced the thickness and development of recognized sequence stratigraphic units.

Key words: sequence stratigraphy, transgressive-regressive cycles, shoreline migration, sediment supply, basement morphology.

Introduction

The SW part of the Carpathian Foredeep (CF) is formed predominantly by Eggenburgian and Ottnangian (Lower Miocene) deposits. Various opinions exist about their detailed stratigraphy (Cícha 1995; Čtyroký 1991; Jiříček 1995 and other authors). The substantial differences among them are contingent on the lack of biostratigraphical data for the correlation of various lithofacies in different parts of the basin. This fact, together with the preservation of a relic of the Lower Miocene coastal depositional systems, leads to the absence of an accepted lithostratigraphic subdivision of the infill of the CF in the area of the Czech Republic.

The aim of this article was to contribute to the solution of the regional stratigraphic problems by attempts to reconstruct the depositional environments and by a general model of their development. The area under study is presented in Fig. 1. The structural pattern and general geological situation are presented in Fig. 2.

Regional framework

The formation of the CF was the result of flexural downbuckling of the passive North European Plate margin in the foreland of the Alpine-Carpathian orogene belt due to the load exerted by the accretionary wedge thrust stack (Kováč et al. 1993). The passive North European Plate margin is represented by the Bohemian Massif (BM) in the area under study. The CF, as the sedimentary basin lying between the front of a mountain chain and the adjacent stable block, is a type of foreland basin (Allen et al. 1986). The palinspastic reconstruction of the broader area under study is presented in Fig. 3.

The behaviour of the basin was above all influenced by the reaction of the BM to the collision with overthrusted Alpine-Carpathian blocks. This reaction was not uniform in all parts of the newly formed basin. The rate and extent of formation of accommodation space was locally different because of the varied behaviour of basement blocks bordered by fault zones in mainly NW-SE, NE-SW or N-S directions (Dudek & Špička 1975). The importance of such blocks having varied subsidence activity, is confirmed by the highly different preservation of Neogene deposits. The Variscan consolidate block (crystalline rocks and Paleozoic deposits) are locally deeply buried under extensive deposits of Mesozoic or Paleogene age. The differences in subsidence activity are connected with various factors — the actual thickness of deposits, the location of the investigated site during the evolution of the basin, its distance from the fold-and-thrust belt and from the hinge line, the orientation of thrust progradation, various affects on the basement by Mesozoic rifting activity (Cloetingh et al. 1997; Cogan et al. 1993; De Celles & Giles 1986; Einsele 1993; Allen et al. 1986; Kominz & Bond 1986). The highest sediment accommodation potential is presumed to have been formed in the area of the Vranovice and Nesvačilka troughs. The importance of these bedrock tectonic structures was recognized even in the thrusted flysch belt (Krejčí & Stráník 1992). Marine deposits of Egerian age were recognized in the Vranovice Trough (Čtyroký 1993).

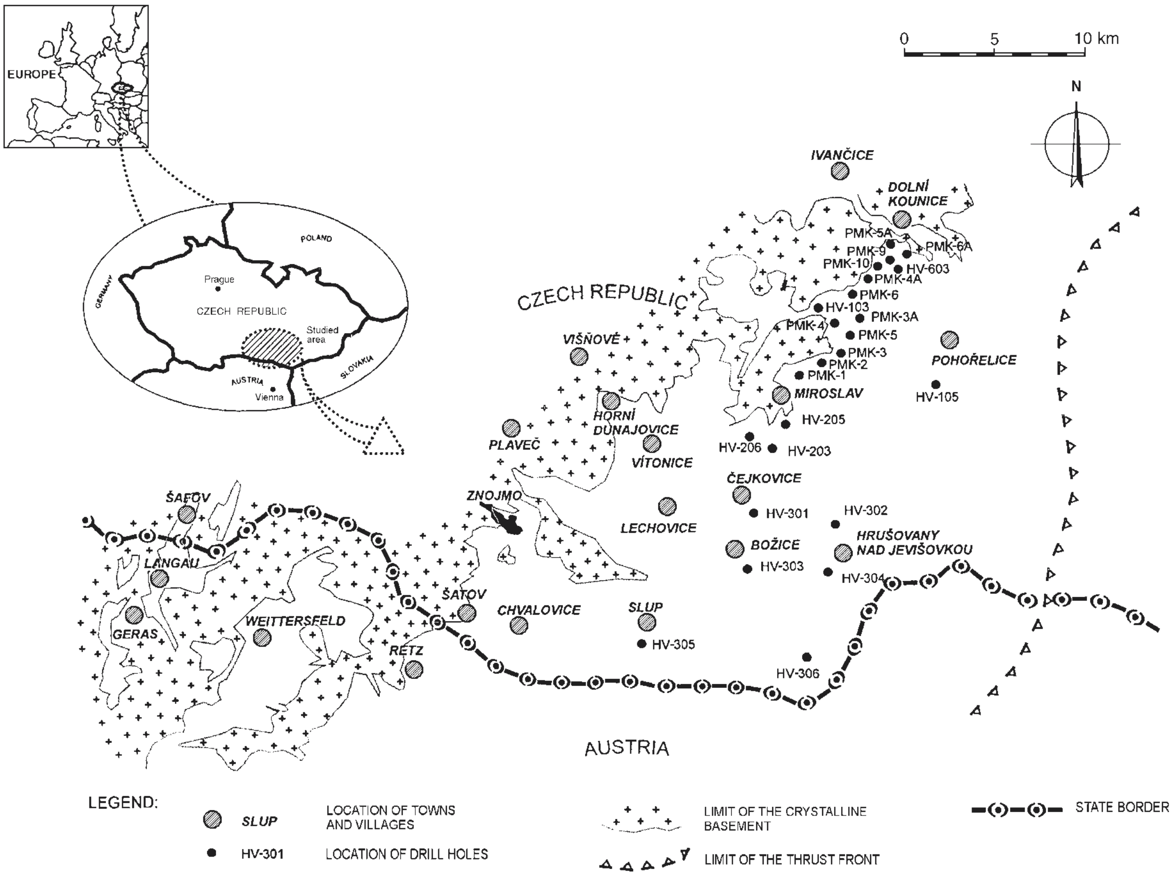

Fig. 1. Location map of the SW part of the Carpathian Foredeep showing the location of important drill holes.

Methods of study and terminology

A standard sedimentological study, detailed recognition of lithofacies and correlational and architectural studies are rather complicated in the CF because of the absence of extensive outcrops and the lack of samples from drill holes. Sedimentological studies of outcrops and drill cores were only possible in the part of the basin close to the crystalline rocks of the BM. This area represents the most landward part of the preserved basin fill. Coastal, deltaic and fluvial environments of deposition were recognized within this area. The results of sedimentological field study and observation were published in Nehyba et al. (1994, 1995) and Nehyba & Leichmann (1997).

The sedimentological studies were supported by the results of tephrostratigraphy, paleontology and palynology (Nehyba et al. 1994, 1995). The recognition of two tephra horizons within the Lower Miocene sedimentary succession (Nehyba 1995, 1997; Nehyba & Roetzel 1999) gave us a new way to correlate the CF deposits with deposits of the Molasse Zone in Lower Austria. The following published results: Batík et al. (1977), Cícha et al. (1957), Čtyroký (1991), Hladilová (1985), Kalabis (1970), Krystek & Tejkal (1968), Molčíková (1968, 1976), Tejkal (1958) etc. were further sources of information about former outcrops and drill holes.

An attempt was made to subdivide the Lower Miocene (Eggenburgian, Ottnangian) rocks into genetic packages based on bounding unconformities and discontinuities. The sedimentary succession was interpreted according to the concept of sequence stratigraphy (Helland-Hansen & Gjelberg 1994; Helland-Hansen & Martinsen 1994; Posamentier & James 1993; Van Wagoner et al. 1988).

As a consequence of confusion over terms existing in recent sequence stratigraphy literature, the terms which are used should be defined. Parasequence is a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces or their correlative conformities (Van Wagoner et al. 1988). Posamentier & James (1993) use the term parasequence as a descriptive term, unrelated to the scale of the depositional unit or the frequency of sea-level change. The parasequence is similar in scale and concept to the facies (sequence) succession (Walker 1990). The systems tract is defined by its position within the sequence and by the stacking patterns of the parasequences or parasequence sets. Often the term cycle-segment is similarly used. A systems tract/segment is a unit/body of deposits defined only by its position within a depositional cycle resulting from changes in relative sea-level and sediment supply (Helland-Hansen & Gjelberg 1994; Helland-Hansen & Martinsen 1994). Relative sea level-change is defined as the change in water depth at a certain location in the basin and is controlled by the rates of subsidence, sediment accumulation, and the rise or the fall of sea level. Systems tracts form the sequence, which is bounded by unconformities and

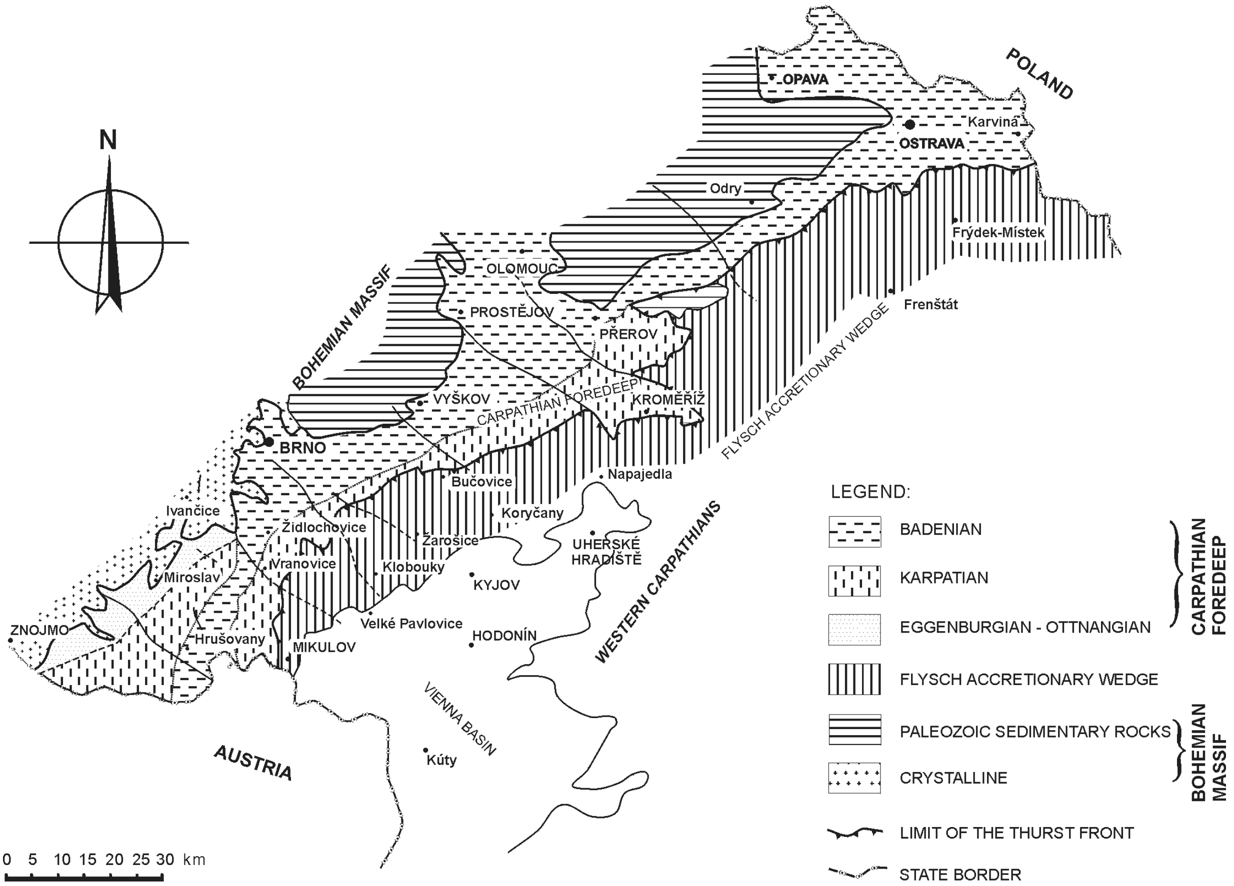

Fig. 2. Schematic general geological situation of the broader surroundings of the area under study.

their correlative conformities. The varying space available between sea level and the subsiding basin floor is called the sediment accommodation potential (Einsele 1993).

The recognition of parasequences, systems tracts or sequences is connected with the definition of bounding surfaces (key surfaces). These correlable surfaces can be important in reconstructing the depositional history of the basin and for mapping and correlational studies. They allow us to bracket the sedimentary successions into packages of genetic and stratigraphic importance. Recognition of these surfaces is both a practical (outcrops, seismic, core samples) and a theoretical problem and a subject of discussions. These surfaces reflect processes connected with relative sea-level changes or the interaction of sea-level changes with sediment supply (Helland-Hansen & Martinsen 1994).

The area under study represents a marginal part of the basin, that is the coastal depositional system. For that reason the study of shoreline behaviour (Helland-Hansen & Gjelberg 1994) can be effectively used for the recognition of sea-level changes. As the shoreline migrates in various directions through time, various surfaces of erosion or non-deposition have been produced. This premise is complicated in the studied area by the repeated migration of the shoreline on the crystalline basement and so the key surfaces in many places follow almost the same depositional plane. For that reason any intercalation or traces of terrestrial deposits within the sediment succession are very important.

The shoreline migration patterns consist of recurring motifs and are therefore cyclic. This cyclicity is produced by alternating regressions and transgressions. The shoreline migration could be a product of either allocyclic changes or autocyclic changes. In the studied area both changes played their role, so that a different hierarchy of cycles could be traced. Sedimentary cycles connected with sea-level changes and tectonic activity on the active margin of the studied basin (foreland basin) form the higher level of cycles with a greater areal extent. Cycles connected mainly with changes in sediment input usually have more local importance and could be recognized within the higher level of cycles. For that reason the local shoreline migration must be combined to give the composite stacking patterns with the average and long term migration of the shoreline. This reflects the temporary and repeated changes between the available accommodation space and sediment supply rates but still maintains an overall long term directional trend. The recognized progradational, aggradational and retrogradational parasequence sets (Van Wagoner et al. 1988) are examples of such stacked shoreline patterns.

Because the presented model of the basin development is based on the study of its proximal parts, it needs correlation with more distal parts of the basin. But only restricted data from distal parts of the CF are available. The number of cycles which can be identified in vertical profiles generally differs along the cross-section of the basin and the true number of cycles cannot be found at the very edge of the basin (U-

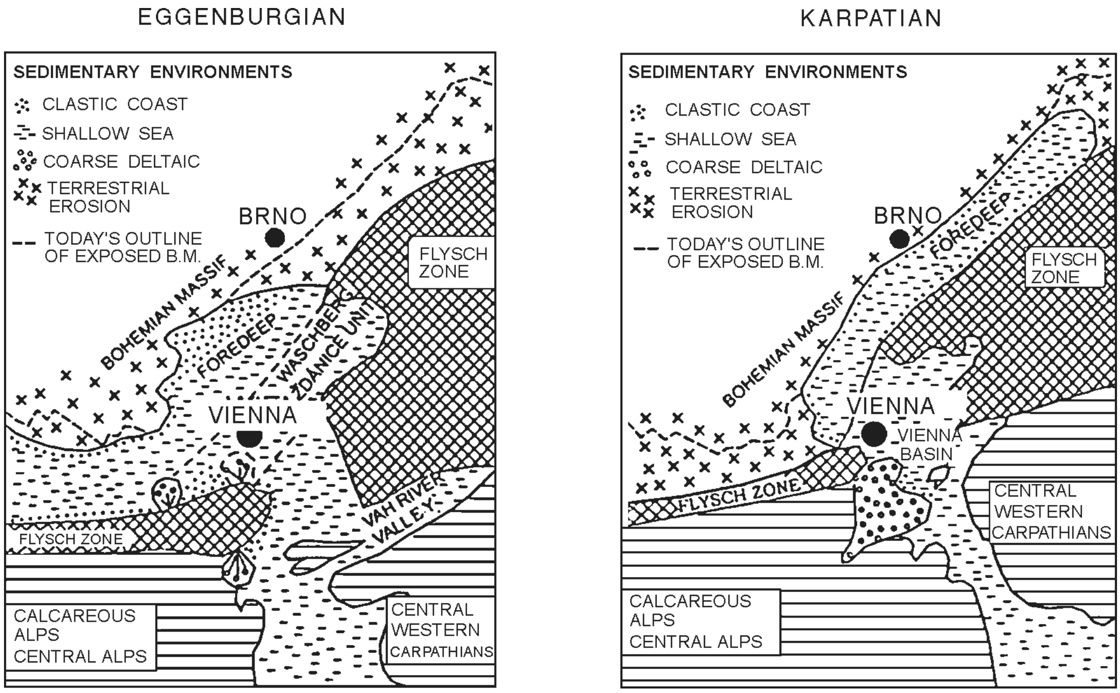

Fig. 3. Palinspastic reconstruction of the Alpine-Carpathian junction and of depositional environments in adjacent molasse basins (according to Seifert 1992).

ličný & Špičáková 1996). For that reason the presented model may reflect mainly local conditions and development which could be, at least partly, different from the development of the whole basin.

The recognized parasequences are limited by bounding discontinuities, and hence can be formally named in an allostratigraphic scheme (Walker 1990). Such an allostratigraphy could be a substitute for the lacking lithostratigraphy of the CF in the studied area or could at least be a subject for such a discussion.

The development of the depositional environment of the SW part of the Carpathian Foredeep in the Eggenburgian and Ottnangian

The Eggenburgian and Ottnangian sedimentary record of the CF can be subdivided into several sequence stratigraphic units. Some of them are preserved as erosional remnants and were actually recognized only in a restricted part of the basin. The recognized units very probably have a more complex internal organization. Their further subdivision or change of presented unit scheme depends on the quality and abundance of reliable data. The proposed sequence stratigraphic schema of the Lower Miocene deposits of the CF is presented in Fig. 4.

Cycles recognized in the studied part of the basin are typical transgressive/regressive cycles. Among many factors causing cycle stacking patterns two played a leading role, that is sea-level changes and the rate of sediment supply. The recognized cycles belong to the third-order and fourth-order cycles (Einsele 1993). The transgressive and regressive cycles, tectonic activity and climatic changes within the Neogene basins of the Alpine-Carpathian realm are presented in Fig. 5. Eustatically and tectonically controlled regional changes of sea level were in addition strongly influenced by the morphology of the flooded area and by both the quality and rate of sediment supply into the basin (Schlager 1993). Local morphology played a significant role for both the development and preservation of sequence stratigraphic units.

Sequence I

This sequence is assigned as sequence I according to the position within the sedimentary record of the CF. It consists of a succession of sediments forming segments A, B and C with their parasequence sets (see Fig. 4). These sediments were deposited during one cycle of relative sea-level rise and fall and so form one depositional sequence (Vail et al. 1991).

The combination of the Savian orogenic phase together with sea-level rise led to the Eggenburgian marine transgression (see Figs. 4 and 5) which inundated the studied area through the Alpine Molasse Zone mainly from the S or SE (Brzobohatý & Cícha 1994). Prior to the transgression, the crystalline basement was deeply weathered and modelled into depressions and ridges. The highly varied morphology led to the complicated depositional condition. The complex shape of the transgressive trajectory is still visible in geological maps as the highly complicated contact between the BM and the Miocene deposits. The relics of Eggenburgian deposits are preserved on the BM many kilometers away from the continuous extent of the CF deposits.

Segments A and B are mutually connected because their formation is predominantly or absolutely connected with marine transgression. The recognition of these segments is considered predominantly in terms of the main environmental settings — fluvial channels and floodplains vs. coastal plain.

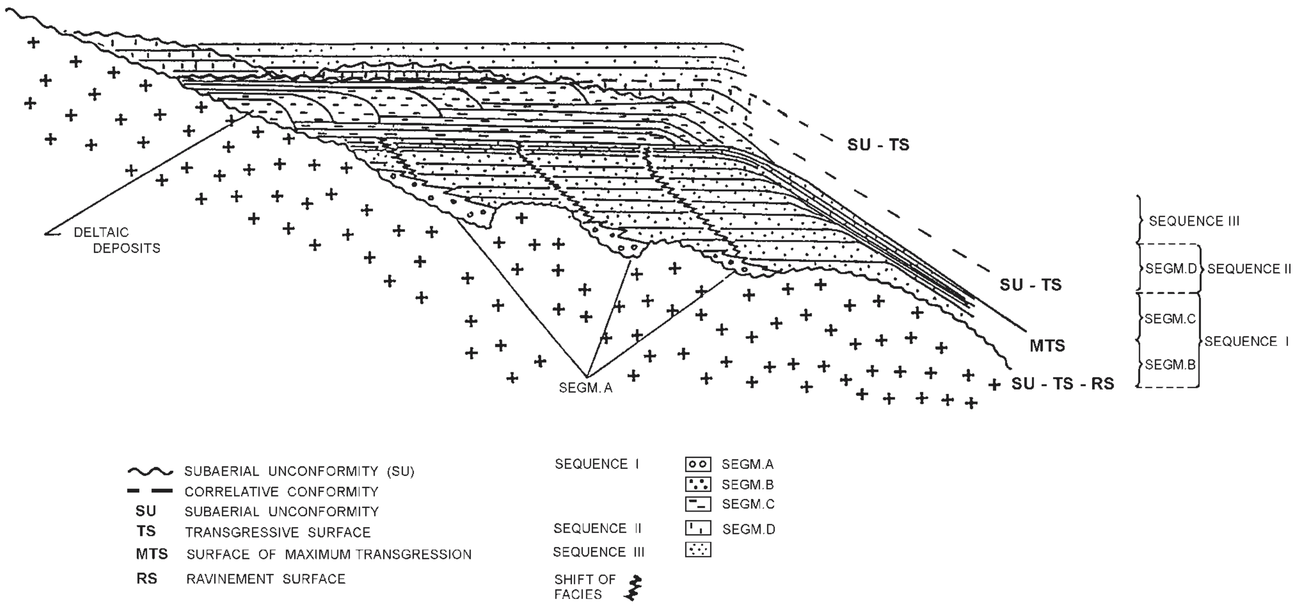

Fig. 4. Schematic sequence stratigraphic schema of the Lower Miocene deposits of the Carpathian Foredeep.

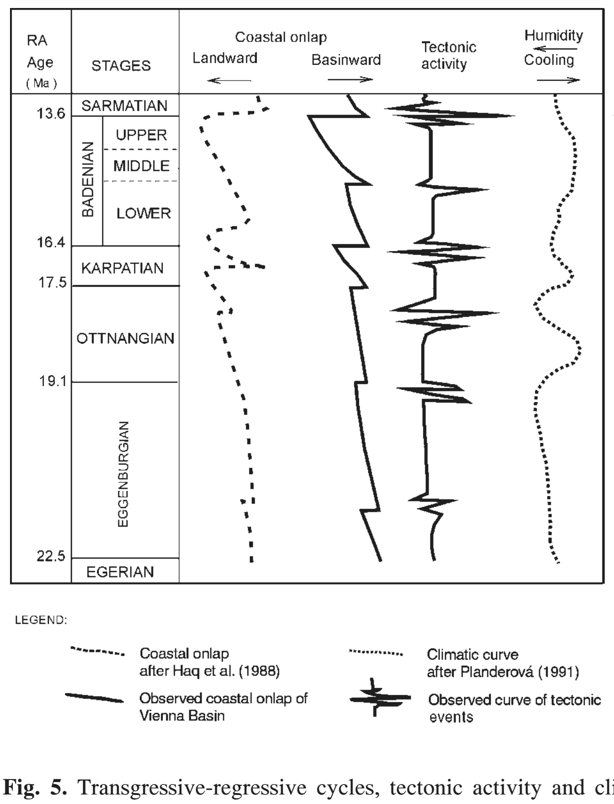

Fig. 5. Transgressive-regressive cycles, tectonic activity and climatic changes of West-Carpathian basins (according to Hudáčková et al. 1996).

Segment A — lowstand/early transgressive deposits

The terrestrial red bed deposits form the basal segment (segment A) of the Lower Miocene sedimentary succession (see Fig. 4) and rest unconformable on pre-Neogene bedrock. They are generally assigned as „Žerotice Beds" (ŽB) and can be defined according to their terrestrial depositional environment, more precisely as alluvial, fluvial or even lake/lagoonal deposits (Čtyroký 1991; Dlabač 1969, 1976; Krystková & Krystek 1981; Prachař 1970). Their occurrence, thickness and deposition were strongly influenced by the morphology of the basement and by the character, amount and the rate of sediment supply. Very variable petrographical content and grain size is typical.

Segment A may be absent in some parts of the studied area, especially in the places where topographical highs originally existed. The existence of valleys (incised valleys ?) with fluvial deposition and some interfluve „paleohighs" without preserved deposits can be supposed. The valley fill systems generally developed in response to a relative fall in baselevel (Dalrymple et al. 1994; Zaitlin et al. 1994). The valley was cut by fluvial processes and so the segment A basal surface is erosional and irregular and can be classified as a subaerial unconformity surface. The base of segment A marked a sequence boundary. Initial fluvial aggradation within the valleys started during a lowstand period, but the bulk accumulated during base level rise is connected with the early transgressive stage (Koss et al. 1994). The formation of segment A deposits is connected with the generation of the accommodation space genetically related to the transgression. Start of transgression can be reflected by the change in fluvial style (Shanley & McCabe 1994). Recognition of such a surface is very difficult in this case, because only restricted subsurface data are available. The upper bounding surface of segment A (the base of segment B) is connected with marine transgression and can be classified as a ravinement surface. This surface is produced as the shoreline migrates over a subaerial surface during relative sea-level rise. According to the subdivision of incised valley fills (Dalrymple et al. 1994; Zaitlin et al. 1994), the studied segment A belongs predominantly to the seaward reach, characterized by backstepping lowstand to transgressive fluvial deposits overlain by transgressive sands.

The ravinement surface is diachronous because it was formed progressively as the shoreline gradually moved landward (Nummedal et al. 1993) and is not a chronostratigraphic surface. A varied stratigraphical position of segment A sedimentary fill is known. In the wider surroundings of Miroslav it has Late Eggenburgian age (Nehyba 1997), because the volcaniclastic horizon 1 was recognized within them. The same tephra horizon was recognized within the biostratigraphically defined Upper Eggenburgian marine and shoreline deposits (segment B see further) in the surroundings of Znojmo. For this reason, the sediments of segment A are of Egerian/Eggenburgian age in this area. In the studied area, the isochronous tephra layer time line is cut by the diachronous upper bounding surface of segment A. The terrestrial deposits are also interfingered with biostratigraphically defined Eggenburgian deposits in some drill holes (HV-603 Jezeřany, HV-301 Čejkovice, HV-303 Božice, HV-305 Slup, etc.). A diochronous position of this surface is even obvious, when we look at the area of the Molasse Zone in Lower Austria. Here in the southern part of the crystalline margin of the BM the marine transgression started in the Lower Eggenburian (Steininger & Roetzel 1991). All these data show that the transgression continued generally from the S towards the N, NW and NE where stratigraphically younger deposits reflect this process.

Segment B — transgressive deposits

The deposits of segment B show transgressive onlap onto the lower segment boundary. They rest on the upper surface of segment A or sit directly on the pre-Neogene basement. The base of the sedimentary fill of segment B represents deposition on the coastal plain. This marine flooding connected with change of depositional environment enables us to recognize the base of this segment within the cores. An important landward shift of the facies belt was recognized within segment B (see Fig. 4). The backstepping geometry reflects an excess of accommodation over sediment supply.

The basal bounding surface of segment B can be classified as a ravinement surface, transgressive surface or erosional marine flooding surface according to the position within the basin. The slope of this surface (controlled by the rate of relative sea-level rise, sediment supply and local morphology of slope) played an important role for preservation and development of „back-barrier" deposits (Thorne & Swift 1991) and also for the type of transgression (Helland-Hansen & Martinsen 1994). The margins of the BM formed by highly various bedrocks provide the possibility for the study of variable development and preservation of aggradational coastal plain and valley fill deposits behind a transgressing shoreline, because of varied rates of sediment supply and subsidence. A wide range of deep or shallow valleys had been formed during the pre-transgression period of time. Various types of transgressive systems tract development (transgressive deposits) have been recognized in the area under study.

The situation in the wider surroundings of Znojmo (predominantly „marginal development" of Eggenburgian deposits according to Čtyroký 1991), where the transgressive deposits often rest directly on the pre-Neogene basement, could be explained by non-accretionary transgression (see Fig. 6). This type of transgression implies that the trajectory of the retreating shoreline was close to the subaerial surface, which existed landward of the shoreline at the onset of transgression. The overall angle of facies migration is determined by the slope of the transgressed surface. Accommodation is not generated at the landward side of the shoreline, but may be present during the initial stage of transgression (segment A). A low-gradient, high rates of relative sea-level rise and low sediment input rates are usually typical for these types of transgression (Helland-Hansen & Martinsen 1994). In the area under study these deposits are characterized by the important role of the redeposition of older pre-transgressive deposits often with Cretaceous microfauna.

But in some other areas (NE, E of Znojmo, surroundings of Miroslav, etc.) the transgression can be documented as accretionary (see Fig. 6). Accretionary transgression implies that the transgressing shoreline position climbs stratigraphically upwards and landwards. Accommodation is continuously generated and filled behind the retreating shoreline (Helland-Hansen & Martinsen 1994). Further evidence for the accretionary transgression is the frequently documented repetition of cycles of the alternation of marine and brachyhaline facies (Čtyroký 1991, 1993). The abundant oscillations and instability of depositional environment conditions (depth, water dynamics, salinity, etc.) were recognized. Palynological studies (Zdražílková 1992; Doláková-Zdražílková 1996; Nehyba et al. 1995) documented both a saline and a coal swamp environment in the backshore.

A highly varied thickness of the aggradational coastal plain (thick and thin back-barrier wedge see Thorne & Swift 1991) has been recognized within the studied area. More condensed facies successions were documented generally in the SW part of the studied area and closer to the edges of the BM. At a greater distance from the crystalline basement the development of a thick back-barrier wedge was recognized. These deposits are represented especially by the sedimentary successions studied in parts of the cores HV-301 Čejkovice, HV-302 Pravice, HV-303 Božice and HV-304 Hrušovany nad Jevišovkou as so called „pelitic complex" (Čtyroký 1991). The succession from open marine to shallow marine conditions, then repeated isolation of the basin with higher evaporation and finally again shallow marine conditions were documented (Čtyroký 1991; Hladilová 1985, 1988; Zdražílková 1992). The thicker back-barrier wedge was recognized also in the surroundings of Miroslav within PMK cores. These deposits could be interpreted as lagoonal deposits, that is coming from an environment periodically protected from the action of waves and storms. Periodical changes of depositional environment confirm the important role of mainly sea-level changes, but several thin intercalations of red beds also document the important role of sediment supply.

The principal role in the development and thickness of segment B deposits was played by varied rates of sediment supply and subsidence. The areal distribution of recognized

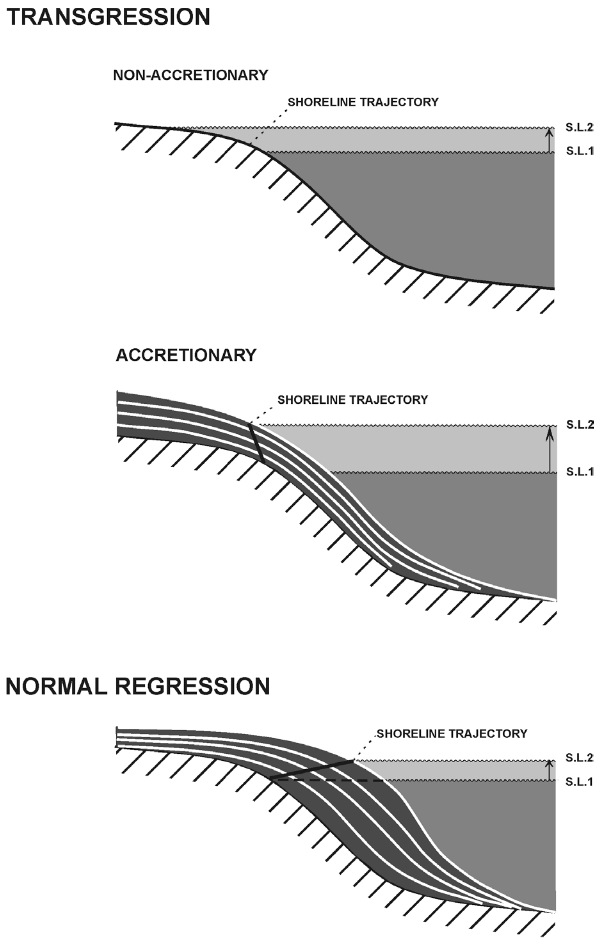

Fig. 6. Different shoreline trajectory classes according to Helland-Hansen & Gjelberg (1994). Arrangement of segment B can be explained by processes connected with both non-accretionary and accretionary transgression. The actual type of transgression was different in various part of the basin and depended mainly on the slope of the transgressive surface and sediment supply. Arrangement of segment C can be connected with normal regression. S.L. — indicates sea level and its change.

types of transgressive systems tract development reflects the higher sediment supply and subsidence generally in the NE and E part of studied area. It shows on locally restricted source to the N and also important role of bedrock tectonic structures. The physical relation of marine systems tract to coeval coastal plain deposits (McCarthy et al. 1999; Plint et al. 1999) is areally restricted in this case. It reflects the fact that only part of sedimentary fill of segment A can be connected with the early transgressional stage.

The upper bounding surface of segment B forms the maximum transgressive surface. This surface marks the change from landward migration and upbuilding of the sedimentary unit into a basinward-prograding wedge.

The upper part of segment B has varied sedimentary content according to the depositional environment (open marine vs. coastal plain). The first scenario can be traced in the surroundings of Znojmo. Here the bed of rhyolite volcaniclastics of horizon 1 (Nehyba 1997) described above the paleontologically proved Upper Eggenburgian marine deposits (segment B) was thought to be the highest member of Eggenburgian (Čtyroký 1991). Above this tephra horizon mainly sandy deposits without marine fauna have been found, occasionally with boring traces. S and SW of Znojmo sterile pelitic lithofacies or quartz sands have been described as Eggenburgian-Ottnangian deposits. These deposits can be interpreted as condensed section facies reflecting the time of maximum regional transgression of the shoreline. Such facies are deposited within the marine environment (Loutit et al. 1988).

The impact of maximum flooding on the coastal plain can be traced in the broader surroundings of Miroslav. Here a molluscan fauna has been found in the PMK drill holes above the volcaniclastic horizon 1. Study of the fauna (Čtyroký & Čtyroká 1989; Nehyba et al. 1994, 1995) proved the slow transition from marine to brachyhaline conditions or their alternation within the core profile.

Segment B reflects a generally gradual transgression with local progradational and retrogradational phases (relative sea-level changes). Within segment B a lower retrograding parasequence set and an upper aggrading-retrograding parasequence set can be recognized. The repeated occurrence of lagoonal deposits above foreshore sediments, horizontal and vertical interfingering of alluvial-fluvial, shallow marine and deltaic deposits confirm this situation which generally leads to the aggrading stacking patterns. Individual cycles within the segment were affected mainly by the rate and character of material transported into the basin. The role of sediment supply became more and more important throughout the sediment profile. The distance of the studied area from the margins of the basin, the local basement morphology (slope gradient) and character of the basement played also important roles.

Segment C — highstand deposits

Highstand deposits represent the late part of eustatic sea-level rise, its stillstand and the early part of its fall. Usually a lower aggradational unit is succeeded by a seaward progradational unit with downlap onto the top of the transgressive deposits (Einsele 1993). The deposits of this segment have been recognized up to now predominantly in the surroundings of Miroslav and are products of delta deposition. They are arranged in an aggradational to predominantly progradational pattern.

Facial succession shows the continuous development of the depositional environment from marine/prodeltaic conditions towards the delta front and finally to the delta plain (Nehyba 1995). The delta plain deposits make up the main part of the studied sediment succession with the final delta abandonment facies development (Reading 1995). This facies succession shows the progradation of the delta into the basin. Prograding clinoform downlaps onto the maximum flooding surface, which is the basal bounding surface of segment C. Delta deposition produced an almost flat surface gradient (Nehyba et al. 1994). The preservation of the delta deposits and the position of the delta body is very probably connected with the subsidence activity of the Vranovice Trough because these deposits were only recognized on the western margins of this structure.

The areal position of the delta deposits and the Vranovice Trough is presented on Fig. 7.

The point of reversion in the development of the basin from transgressive (higher role of accommodation) to regessive condition (higher role of sediment supply) is placed close to the base of segment C. It corresponds to the time of turnover of the shoreline in a maximum landward position. Whereas the position of this surface is clearly defined beneath the delta deposits, in the southern part of the basin the situation is more complicated. But even in these parts of CF the increasingly important role of sediment supply can be recognized up to the top of segments B and C.

Čejkovice Sands (ČS) could also be preliminarily connected with segment C. But whereas the deltaic deposits show clear evidence for progradation, ČS are more probably connected with aggradation. They have been recognized further to the SE of Miroslav (more basinward), where they lie directly above the marine to brachyhaline pelitic complex (Krystek 1983). They are of Late Eggenburgian (Brzobohatý & Cícha 1993) or Eggenburgian age (Čtyroký 1993) and have formerly been interpreted as beach sands (Krystek 1983). ČS are formed by almost monotone deposits of fine-grained quartz sands, with rare coarse layers. The thickness of ČS (in the core HV-301 Čejkovice more than 90 m), and the thin intercalations of red beds within them, indicate a more complicated depositional history. They can be preliminary classified as an aggradational parasequence set. The Čejkovice Sands reflect both the shoreline position and the high rate of sediment supply. They could be connected with deposition processes within the wave-dominated delta.

The upper horizon of volcaniclastics (horizon 2) has often been recognized within the basal part of deltaic deposits. These volcaniclastics were correlated with the bentonite and smectite clay beds in the surroundings of Ivančice, Višňové, Plaveč and Horní Dunajovice, with some terrestrial red beds on the most NW margins of the foredeep (Nehyba 1997) and with volcaniclastics recognized in the Zellerndorf and Langau formations within the Lower Austrian Molasse Zone (Nehyba & Roetzel 1999). The deposits of the Zellerndorf Formation are open marine pelites and are interpreted as the deep water deposits. The Langau Formation is formed by brackisch facies with lignite deposits (Steininger & Roetzel 1991). Both these formations reflect the greatest extent of the transgression to the west in the area of the Molasse Zone (Roetzel et al. 1999). The correlation with Zellerndorf Formation implies that segment C could be at least partly of Ottnangian age. The study also shows that the migration of the shoreline during the deposition of segment C was probably different in various parts of the basin. Because of the restricted areas with a higher input of sediment (deltas) the shoreline migration was, at least locally, basinward, whereas in the rest of the basin landward and upward migration continued. Continuous sea-level rise was a uniform factor for the whole basin.

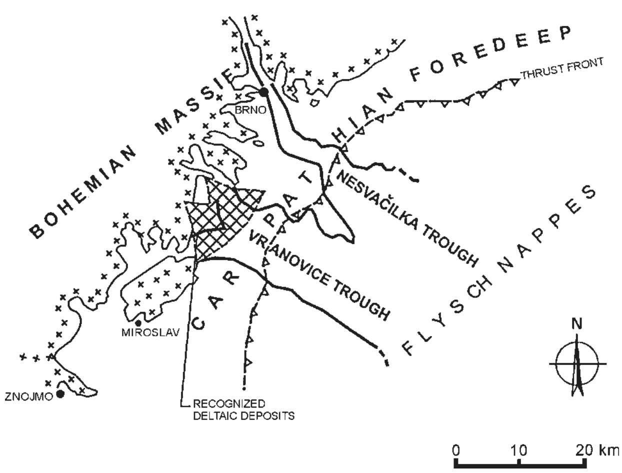

Fig. 7. The areal position of deltaic deposits (segment C) and the location of the Vranovice Trough.

The deposits of segment C are connected with normal regression (see Fig. 6) according to the presented data. This type of regression is connected with conditions of a steady or rising sea level and with a greater rate of sediment supply than is the accommodation space generated at the shoreline. Consequently in this case, the shoreline will be built up seawards (Helland-Hansen & Martinsen 1994). Regression during rising sea level also generates accommodation space behind the shoreline, giving space for the net aggradation of non-marine deposits. If the sea level is rising, water depths will increase in front of the advancing shoreline, the steep profile of shoreline migration develops and the effect of deepening is more evidently seaward (see Zellerndorf vs. Langau Formation).

The base of segment C is formed by the surface of the maximum transgression. The upper surface is connected with subaerial nonconformity because of the presence of delta abandonment facies (subaerial part of delta) and a coeval terrestrial depositional environment. This surface also forms upper sequence boundary in the studied area.

Highstand deposits are generally very widespread in the marginal areas of the shallow basins and have high preservation potential (Einsele 1993). The relic preservation of such deposits in the studied part of the CF confirm the high degree of erosion and redeposition during the following sea-level falls and rises.

Sequence II

This sequence is assigned as sequence II according to the position within the sedimentary record of the CF. This succession of sediments and parasequence sets was deposited during one cycle of relative sea-level rise and fall and so it can be classified as one depositional sequence (Vail et al. 1991).

Segment D — transgressive and highstand deposits

Shallow-marine deposits forming segment D have been found in the superposition of highstand deposits (segment C) of sequence I. The occurrence of transgressive deposits above subaerial unconformity is explained as the beginning of a new sedimentary transgressive-regressive cycle i.e. a new depositional sequence (see Fig. 4).

The subaerial unconformity is explained by a seaward shift of facies which resulted from the deposition processes of the highstand systems tract. Sediments deposited during the succeeding relative sea-level fall (forced regressive systems tract — see Helland-Hansen & Gjelberg 1994 or falling stage systems tract — see Plint 1988) have not been recognized in the area under study. These deposits have a high preservation potential basinwards (offshore deposits). Deposits of this falling stage systems tract could include the highly micaceous sandstones of the Křepice Formation (Pouzdřany Unit). An erosive nonconformity separates the Křepice Formation from the underlying Boudky Formation (Krhovský et al. 1995; Stráník et al. 1981). In the Vienna Basin the sea-level fall could have led to the deposition of the Hodonín and Lednice Sands between the Eggenburgian and Ottnangian part of the Lužice Formation. The sea-level fall also influenced the communication with the open sea as is evidenced by the dramatic changes in fauna content. This has been described from the beginning of the Ottnangian by many authors (Čtyroký 1991).

The Rzehakia Beds (RB) were recognized within segment D (Nehyba 1995). The occurrence of the RB (Ottnangian) is connected with the invasion of cooler waters (Čtyroký 1991). This marine ingression is explained and correlated with the early Miocene global sea-level rise (Haq et al. 1988 in Kováč et al. 1993; Krhovský et al. 1995). The fluctuation in salinity and the highly variable sedimentary content of the RB and their correlative deposits in the Pouzdřany and Ždánice units have been explained by climatic oscillations (Krhovský et al. 1995).

The start of the deposition of segment D is connected with transgression (non-accretionary transgression see Fig. 6). The delta abandonment facies at the top of segment C were inundated by shallow marine deposits at the base of segment D. The basal bounding surface of segment D was affected by erosion and redeposition during both sea-level fall and rise. The presence of beds of pebbly sandstones, conglomerates and pebbly mudstones on the base of segment D was often recognized (Čtyroký 1991; Nehyba 1995). This surface reflects redeposition and erosion during transgression (ravinement surface) because of the occurrence of shoreface deposits above. Facies succession allows us to subdivide segment D into two units (parasequence sets ?). The lower unit — preliminarily denominated as the retrograding parasequence set — often shows repeated FU cycles several meters thick. The upper unit — preliminarily denominated as the aggrading/prograding parasequence set — is formed by an almost uniform sandstone deposition. These sets are separated by a bed with a higher accumulation of coarse clasts and debris of macrofauna. The necessity of subdividing of segment D into several units is also indicated by its thickness (60 m in some drill holes). The setting patterns through the sedimentary succession can mainly be explained by sediment supply. The upper part of segment D could be a product of highstand (Ainsworth & Pattison 1994). Further data from drill holes are necessary to solve this problem.

The transgressive deposits (base of segment D) rest on the upper surface of segment C and begin with the transgressive surface (ravinement surface). The upper bounding surface forms the subaerial nonconformity described by Čtyroký (1991). This nonconformity is followed by the transgressive surface of younger Karpatian deposits. The locally restricted preservation of segments C and D in the area with the highest rate of formation of accommodation space in the studied area supports the idea that they are preserved only as erosional relics. The erosion could mainly be connected with the sea-level falls. The importance and variety of intensity of the erosion is supported by the fact that Karpatian deposits rest locally on various segments and sequences. Karpatian deposits form the next sequence — sequence III.

The extent of transgressions

Comparison of the areal extent of shoreline deposits during two succeeding transgressions (segment B versus basal part of segment D) shows, that the former progression of the shoreline onto the BM during the Ottnangian (segment D) can be documented at least locally. The coastal onlap of the transgressive phase varies with the changing amplitude of sea-level oscillations. If the time period of the transgressive-regressive cycles is long enough, a considerable part of the coastal onlap sediments is removed on the landward side by mechanical and chemical denudation during the subsequent regressive phase, unless it is protected by overlying continental sediments. Some part of the segment is eroded by the storm wave base during the next transgressive phase. Vertical sections from this region often show sharply based shoreface deposits within coastal plain deposits (lagoonal, deltaic, fluvial deposits).

Conclusions

The Eggenburgian and Ottnangian sedimentary record of the SW part of the Carpathian Foredeep can be subdivided into several sequence stratigraphic units. Some of them are preserved as erosional remnants and were actually recognized only in a restricted part of the basin.

Two sequences have been recognized within the studied area. Sequence I was deposited during one cycle of relative sea-level rise and fall and is formed by a succession of sediments forming segments A, B and C with their parasequence sets. Segment A represents lowstand/early transgressive deposits, segment B represents transgressive deposits and segment C represents highstand deposits. Deposits of the falling stage were not described in the area under study but are traced more basinward. Within the transgressive deposits a lower retrograding parasequence and an upper aggrading-retrograding parasequence sets can be recognized. Various types of transgressive systems tract development (transgressive deposits) have been recognized in different parts of the area under study. The accommodation space was not generated at the landward side of the shoreline during non-accretionary transgression, but may have been present at the initial stage of transgression. Whereas during accretionary transgression the accommodation space was continuously generated and filled behind the retreating shoreline (thick and thin back-barrier wedge). Within the highstand deposits a progradational parasequence set and an aggradational parasequence set can be described. The highstand deposits are connected with normal regression. This type of regression is connected with conditions of a steady or rising sea level and with a greater rate of sediment supply than is the accommodation space generated at the shoreline. Regression during rising sea level also generates accommodation space behind the shoreline, giving space for the net aggradation of non-marine deposits.

Within sequence II only one segment (segment D) with its parasequence sets has been recognized. This segment can be subdivided into two parasequence sets. The lower one is denominated as the retrograding parasequence set and represents transgressive deposits and the upper unit is denominated as the aggrading/prograding parasequence set and preliminary represents highstand deposits.

The deposition of Lower Miocene deposits was strongly influenced by the rate and character of sediment input, subsidence characteristics, sea-level changes and by the bedrock morphology especially by its slope angle. Local variations in sediment supply and the location of the sections investigated within the basin play a significant role in the recognition and dating of the sedimentary cycles. The increasing role of sediment input within the sequence sedimentary infill has been recognized.

In the studied area the most complete succession of Lower Miocene can be found within the Vranovice Trough. This is where the next research activity for solving the stratigraphic problems of the region should be placed.

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