

Alluvial Architecture and Fluvial Cycles in Quaternary Deposits in a Continental Interior Basin, E Hungary

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Key words: Fluvial sedimentology, Depositional cycles, Sequence stratigraphy, Quaternary, Körös Basin, Pannonian Basin System, Hungary.

Abstract

The thickness of the studied Quaternary alluvial complex, located in the eastern part of the Pannonian Basin System, can exceed 500 m. Based on subsurface facies analysis the following large-scale depositional elements were identified: channel-fill deposits, point bar deposits, alluvial fan (sandy sheet-flood) deposits, floodplain and floodbasin deposits, and thinner sandy-silty beds. They are classified into four types of facies associations, showing a characteristic stacking pattern on the logs. Facies zonation and basin-scale facies mapping of the overall Quaternary sedimentary succession shows that in several areas dominated by stacked, multistorey sandy channel fill sediments, pre-existing superimposed channel belts can be presumed. In the central and deepest part of the basin muddy floodbasin (distal floodplain and wetland) sediments dominate. Between these the largest area represents the floodplain where single channel fill sands are interbedded in the alluvial plain muds. In the eastern part of the basin the well-logs highlight the distal part of an alluvial fan where sandy sheet-flood deposits alternate with floodplain sediments.

The recognized facies associations show a vertical pattern, i.e. they form a 40–100 m thick fining-upward fluvial cycle. The most characteristic and even ideal cycle can be observed in the channel belts and in the proximal floodplain zone. Here the basal member of the cycle is made up of multistorey channel fill beds cut into the underlying floodplain deposits. This is overlain by an alternating sandy-muddy succession of channel fill and floodplain deposits forming the intermediate member. The upper member is composed of silty-clayey floodplain deposits with occasional very thin, discrete silty-sandy bodies.

These three members form a fining upward sedimentary cycle interpreted as representing low-, increasing- and high-accumulation space deposits, respectively. As the basal multistorey channel fill sandstone facies association generally proved to lie above an extensive erosional surface which can be correlated regionally in the basin, allocyclic controls can be assumed. In some parts of the basin the cycle is not complete as the incised channels can be single, so the low-accumulation space deposits can be missing and the high accumulation space deposits, i.e. the aggrading floodplain sediments, can be truncated.

On a regional scale, six regionally extensive cycles were differentiated above each other. Although these cycles were allocyclic the question of whether they were tectonically or climatically driven remains open. However, the fact that six of them have been identified, suggests that they represent the large-scale 400 ka Milankovitch cycles during the Quaternary. The tectonic overprint is apparent in the thickness and internal architecture of the individual cycles.

1. INTRODUCTION

In the investigations of Quaternary systems, terrestrial deposits generally represent only a selected set of climatic events and are discontinuous in time and space. Correlation of the different non-marine to the quasi-continuous deep-marine sequences and ice-cores, which provide superb tools for the global analysis of Pleistocene climatic events and cycles, is rather ambiguous.

A prerequisite to examine a continuous terrestrial sedimentary succession is to find a continuously subsiding basin where there is high potential for the deposition and preservation of a Quaternary sequence of considerable thickness. A promising site for this is the Pannonian Basin System having several sub-basins which fulfil this criterion. The potential role of the deepest sub-basins of the Pannonian Basin as key sites for continuous Quaternary terrestrial sequences was already recognized in the 1970's and an extended investigation was initiated including drillings with full core recovery and subsequent palaeomagnetic measurement (COOKE et al., 1979; RÓNAI, 1985).

The Körös basin can be recorded as a reference area having a continental Quaternary sedimentary succession averaging 400–500 m thick, comprising three wells with continuous cores and numerous lab tests. Several studies were undertaken here and cycles of different scales (called half-cycles) were recognized in various numbers (MOLNÁR, 1973; MIHÁLTZ-FARAGÓ, 1982; RÓNAI, 1985). Two of the cored wells with palaeomagnetic data were recently investigated and prove that sedimentation was continuous in the basin at least on the scale of 5th-order (40 ka as well as 100 ka) Milankovitch cycles (NÁDOR et al., 2000). Moreover, there are hundreds of wells in the area drilled for water prospecting and hydrocarbon exploration. Analysis of the well log response opened new possibilities for further progress and most of the sedimentological work for this study was therefore based on well-logs, but also utilised data of the cored wells.

After the concept of sequence stratigraphy was introduced for fluvial basins, most of the work was done on large coastal plains but increasingly an approach and synthesis was published for continental interior basins (POSAMENTIER & ALLEN, 1991; SHANLEY & McCABE, 1994, 1998; LEGARRETA & ULIANA,

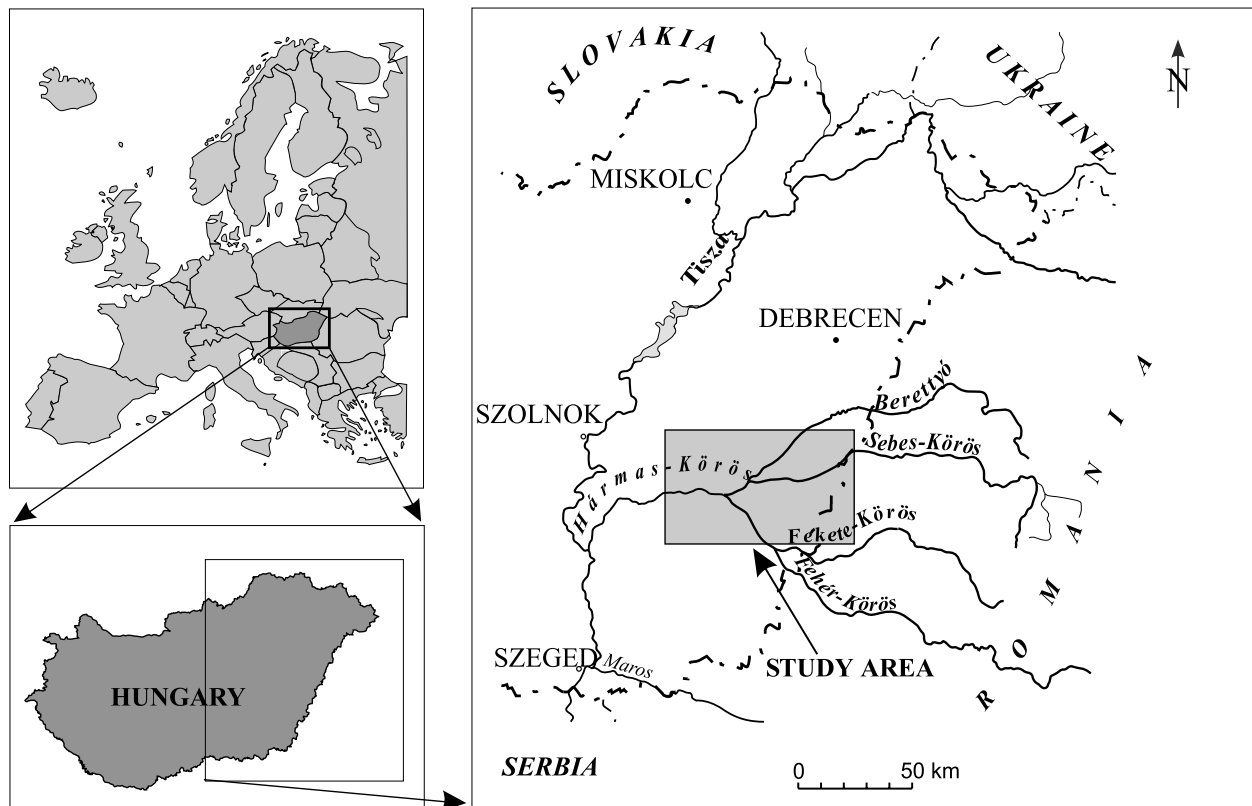


Fig. 1 Location of the study area.

1998; SCHUMM, 1993; ETHRIDGE et al., 1998; QUIRK, 1996; BLUM & TÖRNQVIST, 2000; MIALL, 2002). Terminology, however, has been rather diverse as the sequence stratigraphic terms were worked out for coastal and nearshore settings and these do not really fit into an alluvial complex. As our time range during the Quaternary refers to the Milankovitch frequency band deciding whether to speak in terms of cycles or sequences is also a problem (VAIL et al., 1991). Finally, cycles rather than sequences were chosen as sequences are better used for 3rd order cycles.

The aim of this study was to reveal the alluvial and stratigraphic architecture of the Quaternary sediments (sensu MIALL, 1996) based on the sedimentological and sequence stratigraphic interpretation of some 60 well-logs. The fluvial systems were reconstructed on a basin scale, as well as the areal distribution of the facies and facies associations. The whole succession was subdivided and correlated on the basis of stacking of the large-scale alluvial elements of the fluvial succession, using subsurface methods, wells, cores and wireline logs, due to the lack of any outcrops. This study is the first assessment of ongoing work.

2. GEOLOGICAL SETTING

The Körös Basin is a Quaternary continental interior basin lying in the eastern part of Hungary (Figs. 1 and 2). It is one of the sub-basins of the Pannonian Basin

with high subsidence rates, both preceding and during the Quaternary. It comprises the present-day floodplain of the river Körös and its tributaries; the Sebes-Körös, Fehér-Körös, Fekete-Körös and the Berettyó. These four small rivers drain the Apuseni Mountains in Romania, not far from the study area. The confluence of these transverse rivers clearly pinpoints the present-day depo-centre. The Körös river joins the Tisza, an axial river flowing to the south in the central part of the Pannonian Basin. The basin surface is remarkably flat and all geomorphological observations substantiate active subsidence of the basin (COOKE et al., 1979; RÓNAI, 1985). In spite of the fact that it is connected to the sea by axial rivers, there are several barriers on its way (e.g. in the western part of the Körös Basin, see Fig. 2), therefore it can be considered as a continental interior basin. The river Tisza serves as a local base level and its changes or avulsions can modify the whole fluvial system of the basin.

The formation of the Pannonian Basin System began during the Middle Miocene as a back-arc extensional basin connected to the uplift of the Carpathians, and the subsidence of the basin has been more or less continuous, interrupted by inversion several times (ROYDEN & HORVÁTH, 1988; HORVÁTH & CLOETINGH, 1996). Due to its complicated tectonic history, subsidence was differential in space and time, thus a series of sub-basins were formed. The huge Lake Pannon occupied the basin and was infilled by an enormous amount of terrigenous clastic sediments transported to

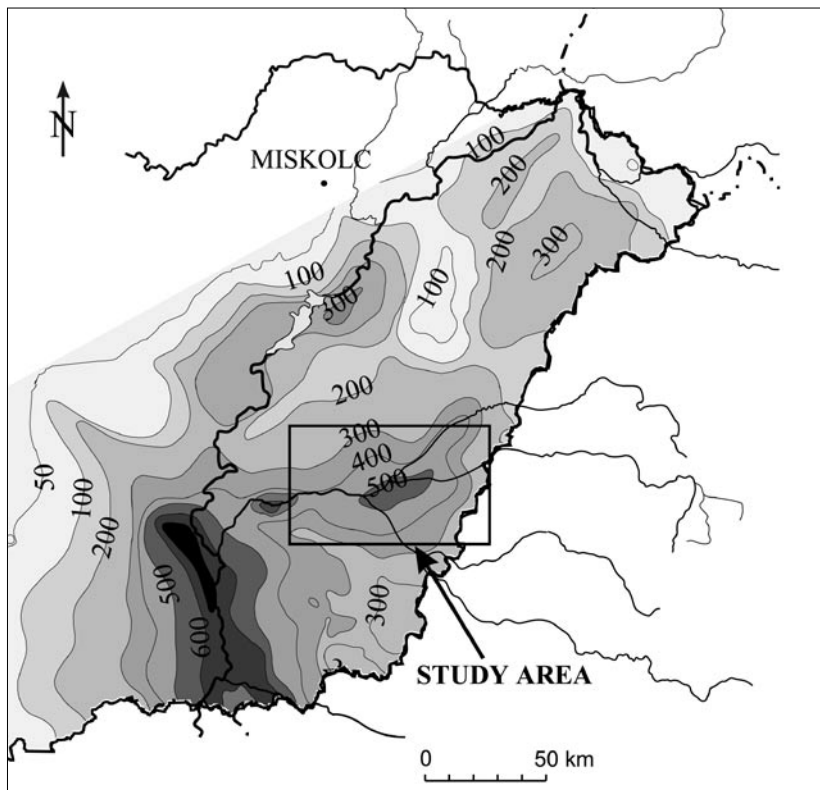


Fig. 2 Isopach map of the Quaternary complex in the Hungarian Plain indicating the study area, the Körös Basin (modified after Isopach map of the Quaternary sediments by RÓNAI & FRANYÓ in BORSY, 1992).

the basin by large rivers draining the emerging marginal mountains. By Pliocene times the lake was filled with an extremely thick lacustrine sedimentary sequence and fluvial sedimentation occurred (BÉRCZI & PHILLIPS, 1985; JUHÁSZ, 1991, 1994). Basin inversion during the Quaternary resulted in significant uplift of the marginal areas and local subsidence of the basin centre (ROYDEN & HORVÁTH, 1988; NAGYMAROSY & MÜLLER, 1988; HORVÁTH & CLOETINGH, 1996). The deepest parts of the basin, however, are still subsiding, although the depocentres migrated slightly after the compressional phase. The studied Körös Basin is one of these continuously subsiding areas where fluvial sedimentation occurred in an interior basin distant from the sea, and sediment thickness reached 400–500 m in the study area (Fig. 2).

3. METHODOLOGY AND DATASETS

The work has been carried out by subsurface facies analysis, correlating large-scale architectural components (sensu MIALL, 1996) and tracing unconformity bounded stratigraphic units on a basinal scale, using mostly wireline-log datasets. The terminology of the paper from a sedimentological and stratigraphical viewpoint refers to MIALL (1996). The sequence stratigraphic terminology is discussed in detail in Section 6.

Hundreds of wells have been drilled in the area, and the best available lithological data and logs were pro-

vided by the water prospecting wells. These wells do not have cores but they have fairly good quality well-logs, generally SP, resistivity and in some cases gamma ray. For this reason most of the sedimentological interpretation was based on the analysis of the well-log response. On seismic sections unfortunately only the lower boundary of the Quaternary succession was visible.

Some 65 water-prospecting wells along geological profiles were chosen for analysis and interpretation. The distance between the wells was generally 5 to 15 km. The results of the fully cored wells were also taken into consideration. On the basis of the well-log shapes and stacking of vertical profiles not only can lithological interpretation be made, but also subsurface facies analysis (“electrofacies”) as well as environmental and stratigraphic interpretation (PIRSON, 1970; SERRA, 1985). Log interpretation may provide larger scale (litho- and sequence-) stratigraphic and sedimentological interpretation than that of the fully cored boreholes. The overall tendencies and larger bedforms of a thick sedimentary succession (i.e. fining-upward cycles) can be identified more easily, therefore it is suitable for large-scale architectural and stratigraphic reconstruction. However, sedimentary structures and other important details remain hidden in this kind of interpretation. The main problems with vertical profile interpretation are that (1) in some cases allogenic and authogenic processes can lead to the same vertical succession, and (2) similar vertical profiles can be generated in rivers by different autogenic processes (MIALL, 1996).

As the distance between the individual wells were several (5–15) kilometres, correlation and interpretation could be carried out on a basin scale, and we interpreted thicker packages, or large-scale depositional units.

4. ALLUVIAL ARCHITECTURE

The lithostratigraphy and architecture of the studied Quaternary succession of the Körös basin is rather complex. Variations both in space and time, i.e. horizontal and vertical tendencies can be observed in the alluvial architecture of the basin. The smallest recognizable units on the studied well-logs were the “electrofacies” (e.g. sand bodies with characteristic log shapes), characterized in the previous section. The thickness of the identified facies units is between 3 and 30 m in the wells. The identified facies are stacked into a vertical pattern forming characteristic facies associations or facies assemblages in many of the wells.

4.1. Depositional facies

On the basis of the well-logs, these facies units were interpreted as the large-scale depositional elements *sensu* MIALL (1996). Logs obviously do not show the internal architecture of the individual channel fill deposits, hierarchy of bounding surfaces, internal and external geometry, etc. Nevertheless, the main depositional elements identified through log-shape characteristics, and their stacking pattern, provide a view on the overall architectural build-up. All the elements which were interpreted were on a scale of *several tens of metres*, with obvious trends. Little interpretation was possible on the thinner (1–2 m) sands and silts.

The main depositional elements distinguished on the basis of well-logs were channel, floodplain, and point bar deposits. The thinner sandy–silty beds comprise natural levee, crevasse splay and aeolian deposits in the thick Quaternary fluvial succession of the Körös Basin, as well as alluvial fan deposits in the E part of the basin (Fig. 3).

The floodplains of several rivers merge here even today forming a wide area comprising the whole Körös basin. Earlier, before regulation of the rivers it was a wetland, or small lakes could be found depending on the pre-existing groundwater-level. This is why the term flood-basin would be a better fit for this environment. Aeolian sediments could not be differentiated on the basis of well-logs but the proportion of loess is probably either negligible in the thick fluvial sequence or occurs in the form of reworked loess on the basis of fully-cored wells. They can be incorporated into the thinner sandy–silty facies or the flood-basin sediments.

Channel-fill deposits

The sandy channel-fill deposits have a very characteristic appearance on well logs. Their sharp bases indicate

down-cutting into clayey or silty floodplain sediments and the log motif can be either a cylinder or bell shaped, and smooth or slightly serrated. Therefore they show great variability in terms of thickness, stacking and overall character. Analysing the well-log response several completely different channel forms can be identified. Only the vertical continuity of the channel fill can be observed and almost nothing is known about their lateral dimensions and relationships. Nevertheless, the position of the alluvial ridges or channel belts (in this case) can be estimated. Examining the log shapes, several channel facies types have been differentiated.

The first channel facies type (*Ecsegsfalva*) can be seen in Fig. 3 I/a. The sedimentary sequence comprises multistorey, amalgamated or distinct channel fill deposits superimposed on each other, with a very small proportion of the fine-grained members like floodplain or oxbow lake deposits. The individual sandstone bodies are thick (10–20 m) with a sharp base and they have a cylindrical shape with a slight fining-upward tendency at the topmost part. They represent rather large rivers which were presumably possibly braided or slightly meandering in nature.

The second type (*Csabacsüd*) can be seen in Fig. 3 I/b. There are also stacked, multistorey channel fill deposits superimposed on each other with a small amount of fine-grained material in between. Thus the depositional conditions were very similar but the sediments show a different pattern. The individual sandstone bodies are thinner and the fining-upward tendency is much more characteristic. Above the channel fills – sometimes represented only by the coarser-grained channel lags – the proximal point bars appear, thus some of the sand bodies represent complete point bars. This indicates a meandering river style with 8–10 m deep channels.

The third type (Fig. 3/II – *Déaványa*) appears as either a thinner or thicker, isolated, discrete channel fill sand body within the thick floodplain sedimentary succession. This is the most common channel type in the Pleistocene sedimentary complex in the study area.

Although we can estimate the channel depth of the pre-existing rivers and also the fluvial style, the geometry of the channels (e.g. the width/thickness ratio) unfortunately cannot be determined on the basis of subsurface facies analysis. Correlation between wells is rather uncertain in a fluvial environment due to the rapid lateral change of facies, even if the distance between the wells is only 1–2 km. When the wells are located very close to each other, the width of the channel belt may be estimated.

Point bar deposits

Point bar deposits are connected to meandering channel fills and have a characteristic shape on well logs. There is a succession of fining-upward tendencies that appear on the logs in the shape of a pine tree, with “branches” becoming finer and thinner upward. This is quite com-

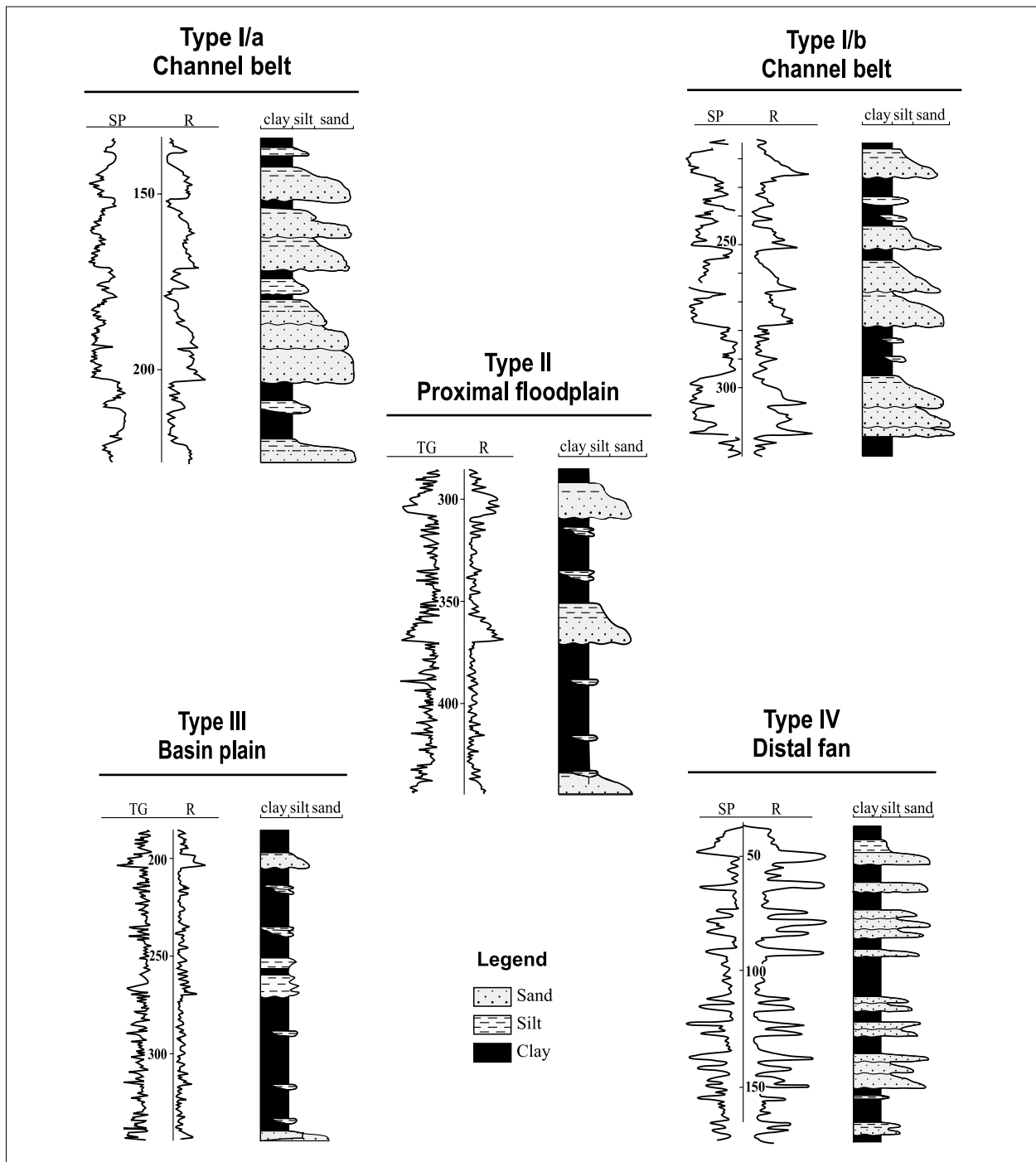


Fig. 3 Characteristic facies associations and large-scale depositional elements in the alluvial succession of the Körös basin. Type I: Different alluvial ridges or channel belts: (a) stacked, multistorey channel fills (braided river?), and (b) channel fill and point bar deposits (meandering river). High discharge, high sedimentation rates are common. Type II: Proximal floodplain: single channel fills interbedded in the alluvial plain muds. Thin sandy-silty beds as crevasse-splay, natural levee and flood-sheet deposits appear in the succession. Type III: Distal alluvial plain and wetland (basin plain). Type IV: Distal part of an alluvial fan, sandy sheet-flood deposits, possible poorly defined sheet-like channels.

mon in the sedimentary complex and generally overlies channel fill or channel lag deposits (Fig. 3 I/b, II). Their thickness can reach 10 m.

Alluvial fan deposits (sandy sheet-flood deposits)

Deposits of the distal zone of an alluvial fan appear in a discrete area, and frequently comprise thin (3–5 m), medium and fine-grained sandstone beds interbedded

with muddy deposits. The well-log looks extremely serrated without any characteristic tendency. This phenomenon can be observed in the eastern part of the study area, and represents sandy sheet-flood deposits and poorly defined sheet-like channel bodies interfingering with floodplain sediments. They were deposited in the far distal part of an alluvial fan formed in the foothills of the Apuseni mountains (Fig. 3/IV).

Floodplain and floodbasin deposits

Floodbasin deposits include the fine-grained overbank sediments of the floodplain and cover a wide flat basinal area. The Körös basin was probably a very flat area (as it is today), where several rivers flowed across the alluvial plain and their floodplains merged. Part of the floodplain was either inundated by water for long periods during the year, or the groundwater-table was very high, leading to the formation of wetlands and also lakes in some areas. The maps of the area from the last century before regulation of the Körös and Berettyó rivers show these characteristics of this area. The *floodbasin facies* comprise the fine-grained overbank deposits of this deep-lying wide, flat basinal area. It is clearly stratified, with alternating silt and mud in the sedimentary succession, causing an extremely serrated well-log shape.

In the proximal floodplain area, sandy channel fill deposits of variable thickness, crevasse splay and flood-sheet beds intercalate in the muddy succession. Approaching the channel belts, the sandy facies becomes more frequent due to river avulsions.

Thinner sandy-silty beds

The thinner (2–4 m thick) sandy-silty beds can be interpreted in a variety of ways in the absence of any evidence. Therefore we tried to avoid their precise interpretation. They can be considered as thinner channels, natural levee or crevasse-splay deposits. They may also represent some sheet flood events depositing reworked sediments. The crevasse splay deposits appear as coarsening upward or massive sequences on the well-logs but the limited thickness of these beds and the resolution of the logs does not facilitate differentiation between these facies.

4.2. Facies associations

In the sedimentary complex of the Körös Basin the identified facies, as mentioned above, are vertically stacked in different successions and the following characteristic facies associations were distinguished.

(1) Type I facies association

It is characterized by stacked, multistorey, amalgamated or distinct channel fills which either cut into each other or are incised into the underlying floodplain deposits (Fig. 3/I). This association can comprise several superimposed channel fill sandstone bodies with thin intercalations of fine-grained deposits. Thick, massive, clean sands with a sharp, erosive base can be identified from their log character. They represent superimposed major channel belts or alluvial ridges above each other either in a braided or meandering fluvial style, the latter with fining upward point bar deposits (Figs. 3/Ia and Ib, respectively). The number of channels varies in this facies association, sometimes there is only one thin sandy channel.

(2) Type II facies association

This association is characterized by the alternation of discrete sandy channel fill and muddy floodplain deposits. The thickness is very variable. Individual sandy facies (channel, point bar or crevasse splay deposits) can vary between 2–10 m in thickness. The facies association represents mainly the outer channel belt or the proximal floodplain area. This is the most common facies association in the Körös Basin.

(3) Type III facies association

The association is composed of silty-argillaceous floodplain and wetland deposits, sometimes with very thin isolated silt or sand bodies. These facies represent the aggrading sedimentary succession of the distal alluvial plain or the floodbasin. Type III muddy facies association or aggrading floodplain sediments may thin out or be completely absent in the channel belt while in other areas it can reach 80 m thickness.

(4) Type IV facies association

The type IV association is characterized by 3–5 m thick frequently interbedded sand and mud successions. It is interpreted as sheet-flood deposits interbedded with muddy floodplain deposits and represents the deposits of the distal zone of an alluvial fan. Thicker channel fills and thicker floodplain sediments in particular are missing. Channels are poorly defined, and some parts of the succession could be interpreted as representing a terminal fan, or channels were found outside the study area. The overall thickness of this facies association with interbedded sand and clay lithofacies, varies between 20–300 m (Fig. 3/IV).

In the area of the alluvial ridges and in the proximal floodplain facies associations types I–III overlie one another in succession in the studied Quaternary fluvial sedimentary succession indicating an evolutionary development from fluvial channels to floodplain deposits suggesting cyclic deposition. The thickness of the different facies associations is highly variable. Several cycles of this order can be recognized above each other in the observed Quaternary sedimentary succession.

5. LITHOFACIES DISTRIBUTION ON THE BASIN SCALE

In a large area like the Körös Basin the stratigraphic record of the complex fluvial system varies through space and time. Considering the general trends in the architecture of the Körös basin, rather complex spatial variations can be recognized in the Quaternary succession on the basin scale. Different tendencies can be traced both vertically and horizontally which help to reconstruct the stratigraphic architecture of the basin. Horizontally different lithofacies zones can be mapped where the Quaternary series is more muddy or more sandy (i.e. the sand/mud ratio is lower or higher) than

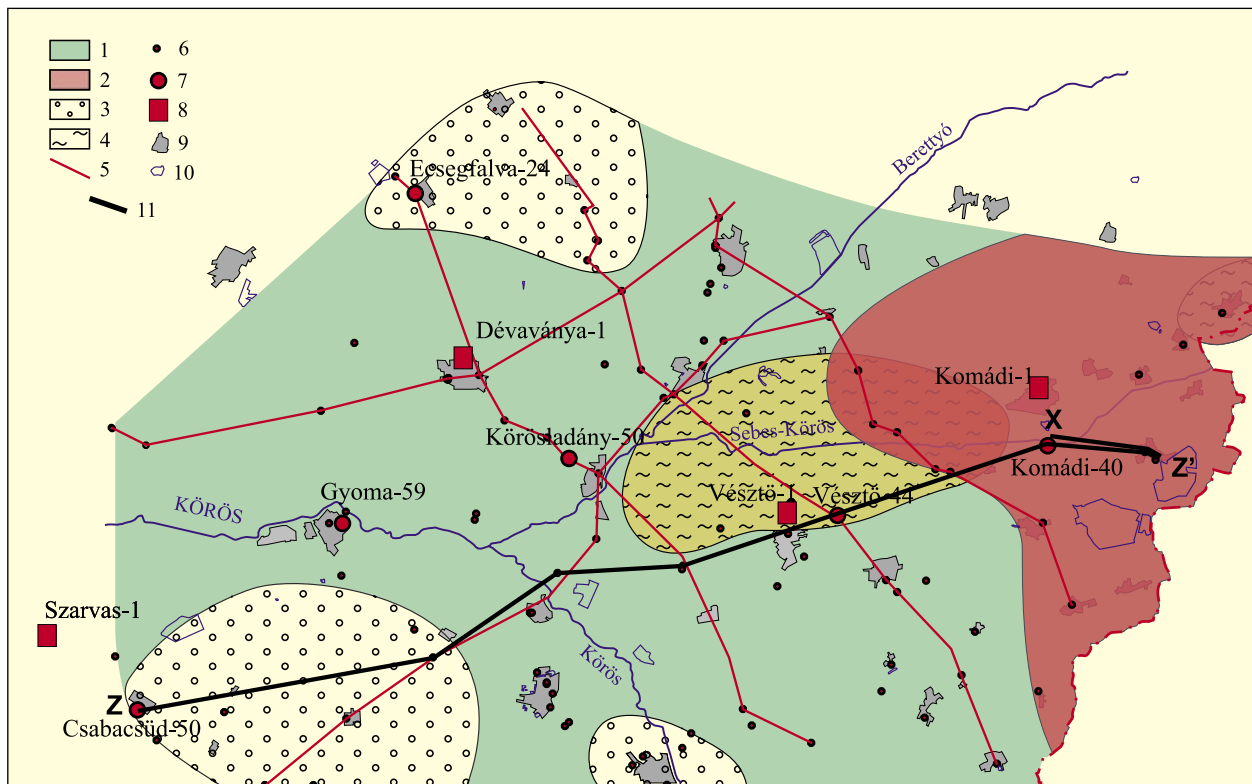


Fig. 4 Lithofacies distribution zones in the Körös basin. The boundaries are gradual, different zones interfinger with each other, and are variable vertically. Legend: 1) sandy–muddy zone: proximal floodplain; 2) frequent interbedded sand–mud zone: distal part of an alluvial fan, sandy flood-sheets; 3) sandy zone: main channel belts, alluvial ridges; 4) muddy zone: wetland, floodbasin; 5) studied profile; 6) well; 7) cited well; 8) cored well; 9) settlement; 10) pond; 11) cited profile.

the average for the basin. These variations are characterized on a basin scale and have major importance for the correlation of facies associations.

A lithofacies distribution map for the overall Quaternary succession in the study area is shown in Fig. 4. Four lithofacies zones were distinguished, a *sandy zone*, a *sandy–muddy zone*, a *muddy zone* and a *frequent sand–clay alternation zone*. There are also vertical trends in the succession therefore, e.g. the sandy lithofacies zone on the map does not necessarily mean that only the sediments of the channel belt can be found there. It means, however, that the sandy channel fill deposits are predominant. The boundaries of the lithofacies zones are gradual, they interfinger with one another.

The *sandy–muddy facies zone* characterizes the largest area where normal fluvial successions of the proximal floodplain and the marginal parts of the channel-belt are intercalated. This zone is characterized by a type II facies association, a typical sedimentary succession of which is shown in Fig. 5. Further away from the channel belt the number and thickness of the channel sands decreases.

There are several areas however where the succession is different. In the N, W and S margins of the basin the *sandy lithofacies zone* can be detected where type I facies associations with stacked, multistorey channel fill deposits are characteristic, i.e. superimposed channel

belts, with high net-to-gross ratio¹, or with rather small proportion of the fine-grained deposits throughout the whole Quaternary succession (Fig. 6). The three sandy zones presumably represent the *main channel belts* or *alluvial ridges*. Larger rivers just entered the study area and then left it. It is worth mentioning that larger rivers are not found along the axis of the basin in the deepest part where one would expect the course of the rivers to be, but they occur on higher areas surrounding the central parts which is the subject of ongoing investigations. Their continuity is not indicated due to a lack of data in the interconnecting areas.

In the central part of the area a *muddy facies zone* was distinguished where the sedimentary succession is composed of mainly fine-grained deposits (Fig. 7). It is largely characterized by type III facies associations of the *distal basin plain*. The area of this zone was a morphological low where subsidence was stronger than in the surroundings as indicated on the isopach map of the Quaternary sediments, which means also at the structural contour map at the base of the Pleistocene as the surface is almost totally flat now (Fig. 2). Therefore the preservation potential was higher and a thicker alluvial succession can be found here. This facies zone

¹Net-to-gross ratio: an oil-industry term referring to the ratio of net sands to the whole succession.

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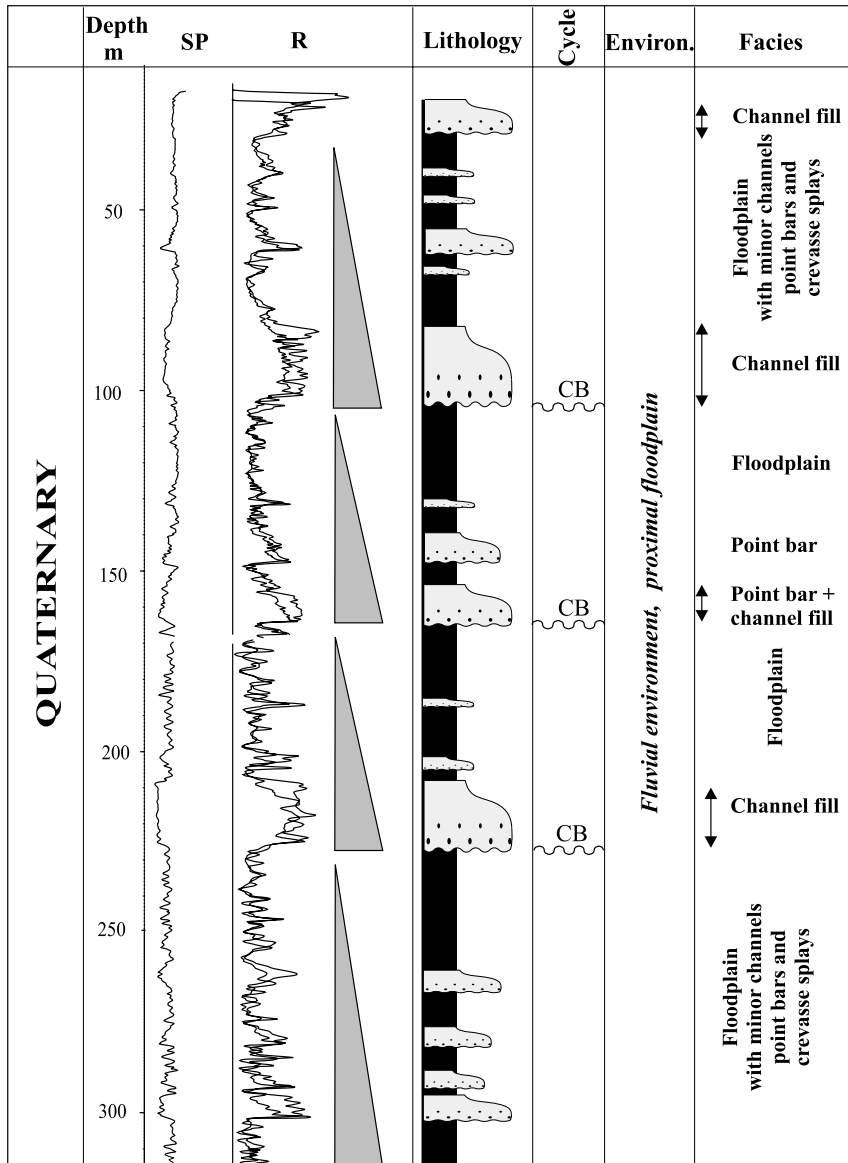


Fig. 5 Characteristic sedimentary succession in the sandy–muddy lithofacies zone, representing the proximal floodplain area (detail). From time to time smaller or larger channels cut through it.

is comprised of mostly clayey and silty floodplain and presumably wetland and occasional lacustrine deposits (Fig. 7). The water table may have been very high in this area and only a very few, thin sandy channel fill sandstone bodies can be found interbedded in the thick floodbasin succession. The base and the uppermost part of the succession, however, consist of some channel fill sands, the latter depicting the time when the Sebes–Körös arrived in the area where it flows even today.

In the eastern part of the Körös Basin this muddy facies zone intertongues with a sedimentary succession characterized by frequent, rather thin *sandstone bodies* intercalated with floodplain deposits (Figs. 4 and 8). It corresponds to sandy sheet floods of the distal zone of an alluvial fan (type IV facies association), occurring approximately along the course of the present day Sebes–Körös. The thickness of this type of facies is changeable within this zone. In some wells it can be

300 m thick, while in other wells it is only 50 m and sediments of the distal and proximal floodplain underlie it or intercalate with it. In the topmost part, channel fills appear indicating a proximal floodplain environment.

An overall vertical variation was also recognized in the basin, which is superimposed on the horizontal changes. Although the Pleistocene sedimentary succession starts with a laterally extensive sand bed (amalgamated channel sand or sand sheet) a few metres thick in all parts of the Körös basin, during Early Pleistocene times sediments were finer-grained on a basin scale. More floodplain sediments occur in the lowermost part of the sequence. In the middle parts of the sedimentary succession sandy facies become more prevalent in a few areas. In the uppermost 150–200 m, however, sediments become much more sandy, channel fill beds can be detected in all parts of the basin, even in the muddy facies zone.

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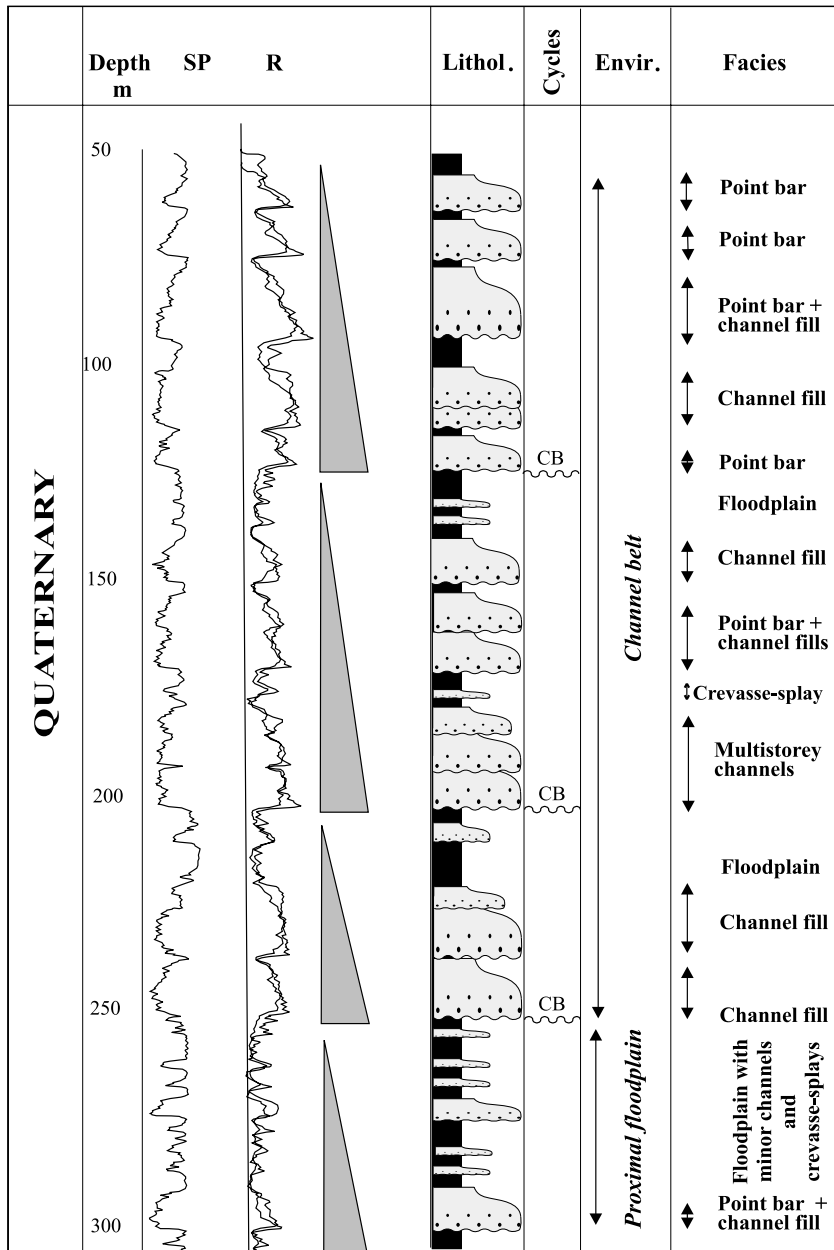


Fig. 6 Characteristic sedimentary succession in the sandy lithofacies zone, representing the area of a channel belt or alluvial ridge (detail).

On the basis of the facies map of the basin at least three separate fluvial systems can be identified. The sand zones pinpoint the depositional axes of the channel belts. The sandy facies zones in the N and S were probably parts of the main channel belts of two distinct river courses, probably the ancient Tisza in the N and W considering the large channel sizes, and the ancient Körös in the S. The sandy facies zone in the W may be a continuation of one of them or their confluence. An alluvial fan system can be recognized in the eastern area of the basin with the sandy sheet-flood characteristics of the distal zone which interfinger with the muddy wetland zone towards the centre of the basin.

6. SEQUENCE-STRATIGRAPHIC FRAMEWORK – A FIRST ASSESSMENT

The studied Quaternary sedimentary succession represents a maximum time range of 2.6 Ma. Any kind of subdivision results in tens of thousand to hundreds of thousand year cycles, i.e. fourth to fifth-order cycles. VAIL et al. (1991) restricted the term “depositional sequences” to the so-called third-order eustatic cycles of 0.5–3 Ma time scale. Later POSAMENTIER et al. (1992) pointed out that sequence stratigraphic concepts are time and scale independent. The terms cycles and sequences were often interchanged on the scale of the Milankovitch frequency band, as sea-level changes were also controlled by climatic cycles in this time-frame. The original sequence stratigraphic terminology used

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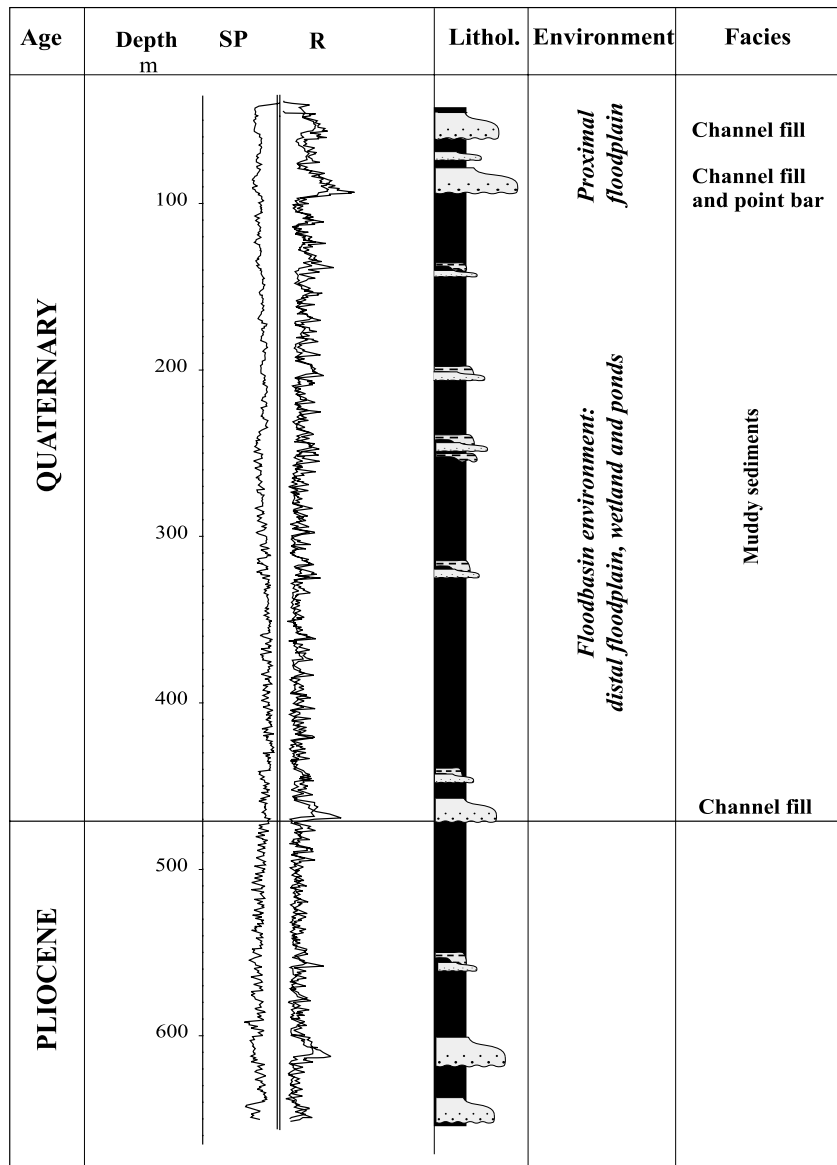


Fig. 7 Characteristic sedimentary succession in the muddy lithofacies zone, representing the floodbasin or wetland area. Channels can be observed at the base and the uppermost part of the Quaternary. Thinner or thicker muddy intercalations within the succession are common.

parasequences for the 4th to 5th order frequencies, during interpretation of carbonate and fluvial sedimentary successions the authors often use cycles.

As our time range during the Quaternary refers to the Milankovitch frequency band (short-term, 5th order, and long-term, 4th order cycles) we prefer the term cycles here to sequences, and cycle boundary (CB) to sequence boundary, though the identified cycles could well have been sequences.

As for the subdivision of individual cycles, the sequence stratigraphic terminology is not really relevant to fluvial sequences and different terms seem to be very artificial in usage. In this interpretation we refer to the terminology introduced by WEISSMANN et al. (2002) on the basis of BLUM & TÖRNQVIST (2000). Therefore we use the terms *low-*, *increasing-* and *high-accumulation space deposits* for systems tract terminology

which can correspond to lowstand, transgressive and highstand systems tracts respectively.

6.1. A brief review of various concepts and terminology on the fluvial response to climate change in continental basins

The basic concepts of sequence stratigraphy were established and applied mainly for coastal and marine sequences (VAIL et al., 1977; POSAMENTIER et al., 1988; VAN WAGONER et al., 1988, 1990; POSAMENTIER & ALLEN, 1991). Most of the examples for terrestrial sequence stratigraphy were taken from large coastal plains where sequence boundaries could be correlated from the shallow marine area, and base-level control through eustatic control was emphasised. Only very few attempts were made to apply the basic concepts to terrestrial strata. The application of sequence

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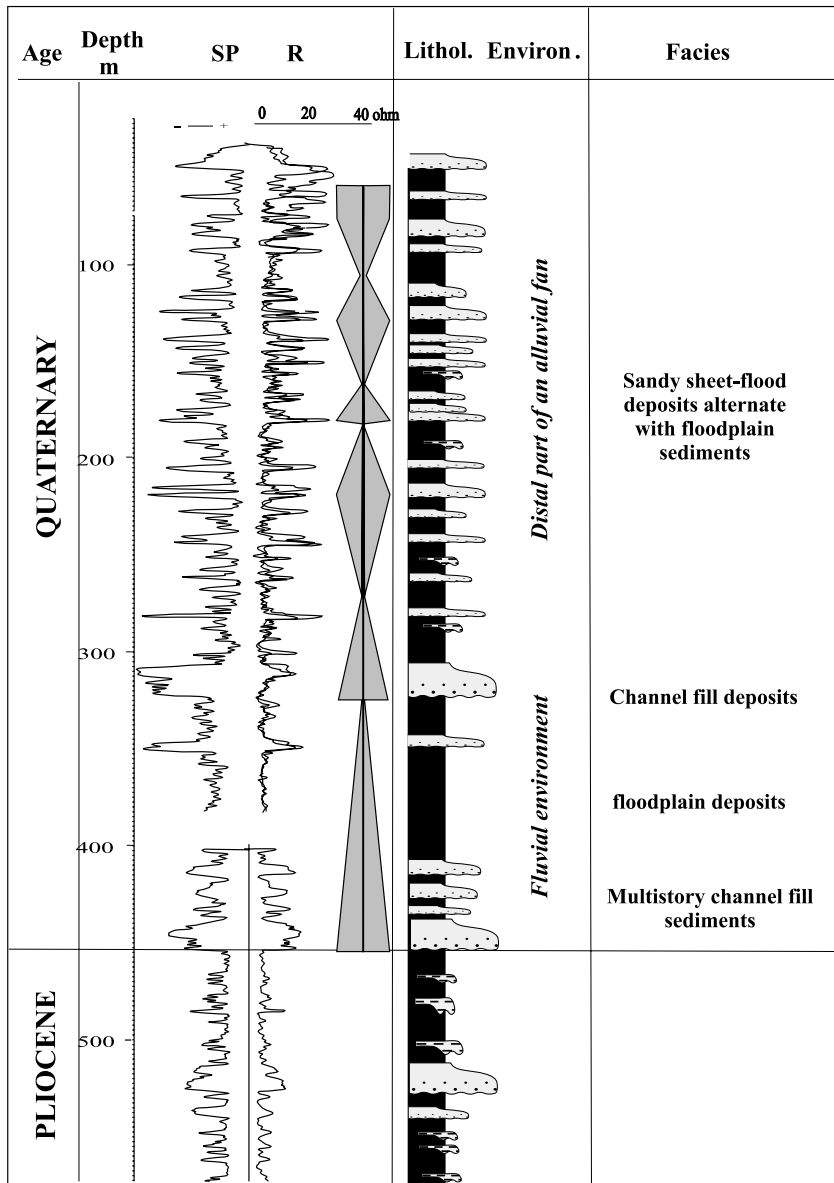


Fig. 8 Characteristic sedimentary succession in the zone of the frequent interbedded sand–mud lithofacies. Sandy flood-sheets and poorly defined, sheet-like channel bodies represent the area of the distal zone of an alluvial fan.

stratigraphic principles to terrestrial successions beyond the influence of sea-level, was considered to be in its “infancy” (SHANLEY & McCABE, 1994). The most serious limitation for short term progress in terrestrial sequences, especially interior basins, is the relative scarcity of well-documented actual examples studied from a sequence stratigraphic perspective (LEGARRETA & ULIANA, 1998).

The main problems in terrestrial sequences include defining the role of tectonics, the usage of terminology which is still confusing, and the discrimination of autocyclic and allocyclic phenomena. In thick fluvial successions the crucial point in the recognition and interpretation of allocyclic processes is to find regionally extensive and correlatable erosional surfaces. Flowing across a plain, a river can respond to base-level change by adjusting the channel pattern, width, depth

and roughness and (only if the change is very large) by incision, but the rate of change is of great importance (SCHUMM, 1993).

The first comprehensive review of sequence stratigraphic models for continental strata was published by SHANLEY & McCABE (1994). They discussed a larger scale architectural pattern and systematic variations in the controlling processes focusing on the effects of accommodation space and sediment supply. They use the term accommodation space for continental strata, and also stratigraphic base level as the local groundwater tables which reflect regional potentiometric surfaces. They stated that in interior basins recognition of alluvial sequence boundaries rests almost entirely on changes in alluvial stacking patterns. They stated that multilateral, multistorey channel units were often thought by many authors to represent low rates of stratigraphic base level

rise and to overlie sequence boundaries associated with allocyclic phenomena. Perhaps one of the best case studies for continental interior (hinterland) basins, and providing a useful model is that of LEGARRETA & ULIANA (1998) on Upper Cretaceous fluvial strata in Argentina. They introduce new sequence stratigraphic terms for a terminating desert fluvial system. In a thick fluvial succession they found the repeated appearance of sandy forward stepping stacks, followed by sandy-shaly backstepping complexes and mudstone-rich aggradational stacks which was a common depositional motif in some hinterland basins dominated by alluvial infilling. These stacks or complexes correspond to the systems tracts of a marine sequence. The basinward and also the backward shift of the depositional system could be followed.

A concept 'base profile' was proposed representing the continental extension of base level by QUIRK (1996). It is defined as the ideal graded profile of a drainage basin at a specific moment. Rivers tend to aggrade up or degrade down to base profile, so it describes changes in accommodation space. New accommodation space is created by the rise of base profile and degradation happens if there is a fall in base profile. The concept, however, has not come into use. The shortcomings of the previous and current models were summarized by ETHRIDGE et al. (1998), who dealt with the problems and perspectives of the cyclic variables controlling fluvial sequence development and the difficulties of distinguishing various controls. The usage of cycles of different scales at the same time, are rather rare in practice. In the context of carbonate systems, not fluvial cycles, STRASSER et al. (1999) show a hierarchical stacking of depositional sequences, and define small-scale, medium-scale and large-scale sequences. They speak about sequences and not cycles in the Milankovitch frequency band.

A complete and comprehensive literature review, together with comprehensive predictions of fluvial responses to climate and sea-level change based on Quaternary and pre-Quaternary records, was given by BLUM & TÖRNQVIST (2000). They differentiate three types of fluvial responses: stratigraphic, morphological and sedimentological. Stratigraphic responses are caused by aggradation, degradation and lateral migration, and produce cycles or sequences which reflect allogenic controls. They concluded that fluvial systems in subsiding basins are characterized by long-term net aggradation, punctuated by relatively short periods of incision and/or lateral migration. Morphological responses reflect changes in channel geometry. Sedimentological responses can be viewed within the context of alluvial architecture, as the geometry, proportion and spatial distribution of different types of fluvial deposits. They introduced the terms *accumulation space* and *preservation space*. As to the preservation potential, the role of basin subsidence is very important. They emphasized the importance of palaeosol-bounded floodplain facies. They also provide a broad range of

case studies in the paper and state that there is a particular need for studies on this theme. In their summary they describe a general stacking pattern that is the amalgamated high net-to-gross channel belts that rest on what is interpreted to be a sequence boundary and overlain by isolated ribbon-like sand bodies. These are encased in laterally extensive mudstone dominated successions.

In terms of non-marine sediments PLINT et al. (2001) use the terminology of *low-accommodation* and *high-accommodation system tracts*. WEISSMANN et al. (2002) interpreted an alluvial fan succession in terms of *accumulation space cycles* driven by glacial climate changes. They introduced the terms *low-*, *increasing-* and *high-accumulation space deposits* for systems tract terminology in a purely alluvial system, which up-to-now seems to be the best for characterizing the different fluvial processes and depositional units, and it is therefore applied in the following sections.

6.2. Depositional cycles in the Quaternary succession of the Körös Basin

The Körös Basin is a continental interior basin which has existed since the Pliocene. The four modern transverse rivers draining the Apuseni Mountains and their alluvial plain form a floodbasin rather than a floodplain, as it is a wide and extremely flat area. Before the regulation of these rivers at the end of the 19th century, almost the entire area was covered by water during flood periods and to a lesser extent under normal conditions. The area is presently distant from the Black Sea as it was during the Quaternary, and in this respect conditions were presumably very similar to the present-day.

Therefore the main allogenic factors controlling the architecture and morphology of the alluvial complex of the Körös Basin may have been climate and tectonics, as well as changes in local base level and sediment supply which are both connected to the previous factors. Tectonics was responsible both for the subsidence of the basin and uplift of the hinterland in the Apuseni Mountains. Climate influenced sedimentation through sediment supply, discharge variability as well as vegetation.

It is rather difficult to unravel the effect of the various controlling factors. Most authors' work and most models are based on eustatic (base level) changes or consider only one controlling factor. In fact there is a complex interplay between these factors.

Most of the literature cited above agrees on the importance of recognizing stacking patterns in the alluvial sequences. In interior basins, recognition of alluvial sequence boundaries rests almost entirely on changes in alluvial stacking patterns (SHANLEY & McCABE, 1994). Multilateral (amalgamated), multi-storey channel units are often thought by many authors to represent low rates of stratigraphic base level rise and to overlie sequence boundaries associated with allocyclic phenomena (POSAMENTIER et al., 1988; SHANLEY & McCABE, 1994; AITKEN & FLINT,

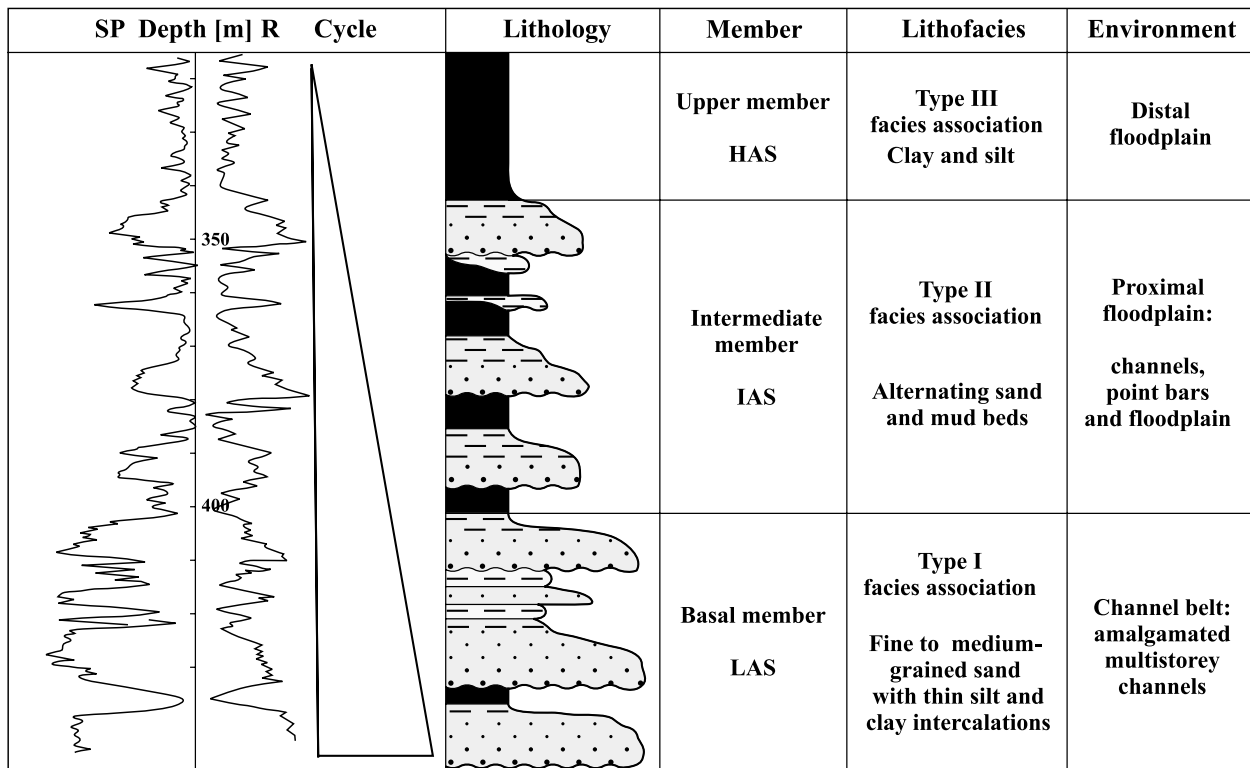


Fig. 9 An ideal depositional cycle in the Quaternary fluvial succession. Legend: HAS – high-accumulation space; IAS – increasing-accumulation space; LAS – low-accumulation space; CB – cycle boundary. Terminology: see in text.

1995; LEGARRETA & ULIANA, 1998). According to different authors, local base level is referred to as stratigraphic base level (SHANLEY & MCCABE, 1994), or base profile (QUIRK, 2000), and all of them have a slightly different approach to this. The sand bodies become more isolated upward and the succession is terminated by aggrading floodplain sediments.

The Quaternary of the Körös Basin started with a period of erosion as shown in most of the studied wells, which resulted in an unconformity truncating the Pliocene alluvial succession. In many wells, fining-upward cycles can be repeatedly observed in parts of the studied Quaternary sedimentary succession in the Körös Basin (Fig. 9). In the alluvial ridge and in the proximal floodplain, the different recognized facies associations discussed in the sedimentological sections are superimposed into a vertical pattern which shows that they form a sedimentary cycle in this order. They indicate a successive evolution from fluvial channels to floodplain and wetland deposits. The different “systems tracts” can also be defined in this cycle or sequence.

The *basal member of the cycle* comprises a type I facies association with stacked multistorey channel fills and with hardly any fine-grained intercalations, and it represents the *low-accumulation space deposits* (“lowstand or early transgressive systems tract” in the sequence stratigraphic terminology). This means that during this period the rivers adjusted their course and fluvial style to the changing conditions by lateral migration. The thickness of this unit can vary between

0–50 m. In the muddy facies zone or the wetland area (see facies map on Fig. 4) low-accumulation space deposits may be represented by only one single channel fill body, or may be completely absent.

The *intermediate member of the cycle* is represented mainly by the type II facies association, and is built up by 5–20 metre thick alternating sand and mud beds. This reflects increasing-accommodation due to a rise in the ground-water table/stratigraphic base level or caused by basin subsidence. Alternatively, it can reflect a decreasing sedimentation rate. It represents the *increasing-accumulation space deposits* (“transgressive systems tracts” in sequence stratigraphic terms).

The *upper member of the cycle* is built up by a type III facies association comprising thicker or thinner floodplain deposits with no or very few isolated thin sandstone–siltstone intercalations. It represents aggradation and the *high-accumulation space deposits* (“highstand systems tract”). In the terminology of LEGARRETA & ULIANA (1998) it is called the aggradational systems tract which is the best expression for this unit. In some places this aggrading unit was thinned out or completely eroded by the overlying channel system. Its thickness is variable, it can reach 50–60 m, but it can be eroded completely.

The above ideal depositional cycle shows up in an extremely varying form in the basin depending on the environment where it was formed. Therefore the general lithofacies map can reveal a lot about the succession. There are areas where the cycles are not complete. In

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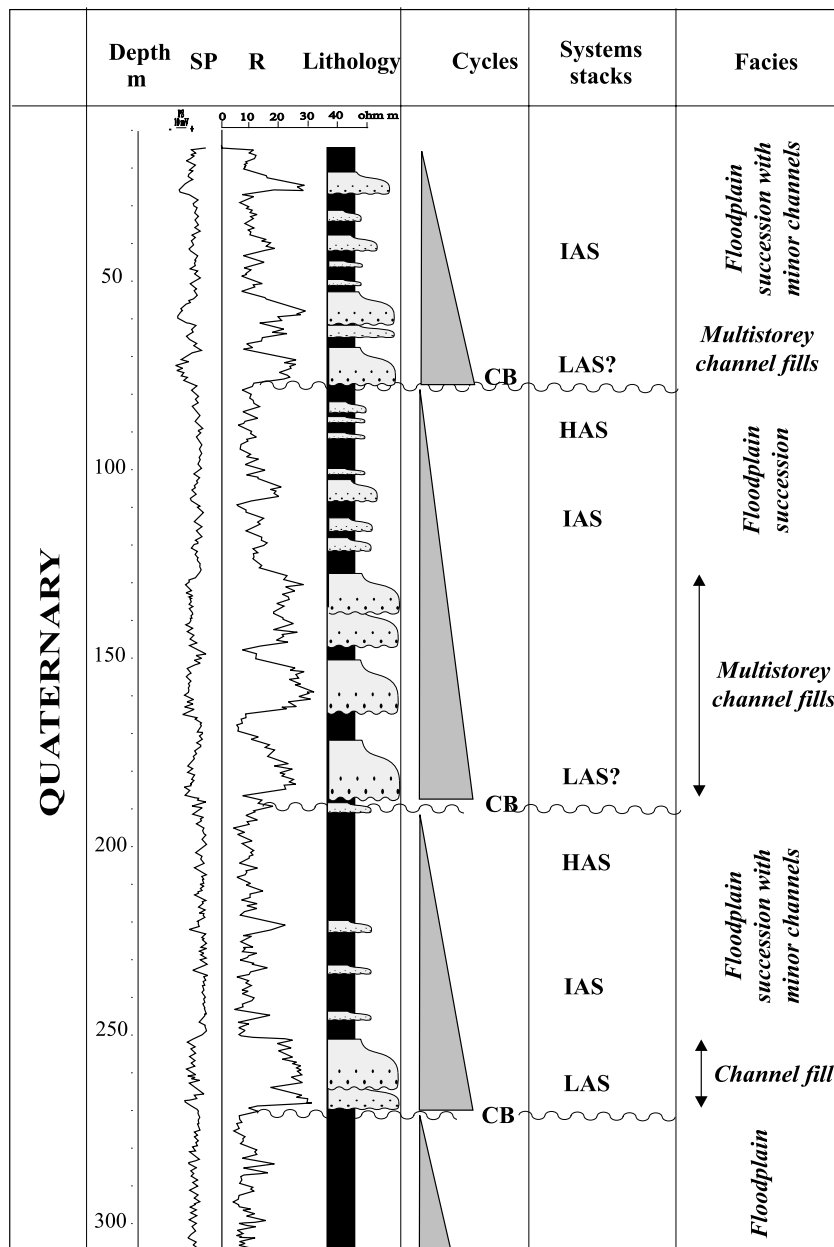


Fig. 10 Sequence stratigraphic interpretation of a well in the proximal floodplain zone (detail). Legend: HAS – high-accumulation space; IAS – increasing-accumulation space; LAS – low-accumulation space; CB – cycle boundary. Terminology: see in text.

the channel belt, the upper and maybe the intermediate member of the cycle could be eroded or it was not formed at all. Moving away from it towards the proximal and distal floodplain the thickness of the basal member gradually decreases. In the area of the flood-basin the lower and intermediate member of the cycle can be represented by a thin single sand or silt bed. In the muddy facies zone the identification and correlation of the depositional cycles seem to be problematic and dubious.

The above cycles are demonstrated in two wells. The first represents the sandy–muddy facies zone, or proximal floodplain on the facies map (Fig. 10). The appearance of the cycles is easily detectable, and three

cycles can be observed above each other, but this does not represent the whole Quaternary succession. Sand bodies show systematic changes in thickness, and the fining upward stacking pattern is clear, showing the different facies associations discussed above.

The second well is located in the sandy lithofacies zone, or channel belt, penetrating the whole Quaternary succession and all the identified cycles are shown (Fig. 11). The succession is much more sandy but incision did not entirely remove the uppermost member of the cycles, the aggrading floodplain or high-accumulation space deposits (“highstand systems tract”). Consequently we may assume that every cycle was recorded and the cycles can be figured out and identified properly. In this

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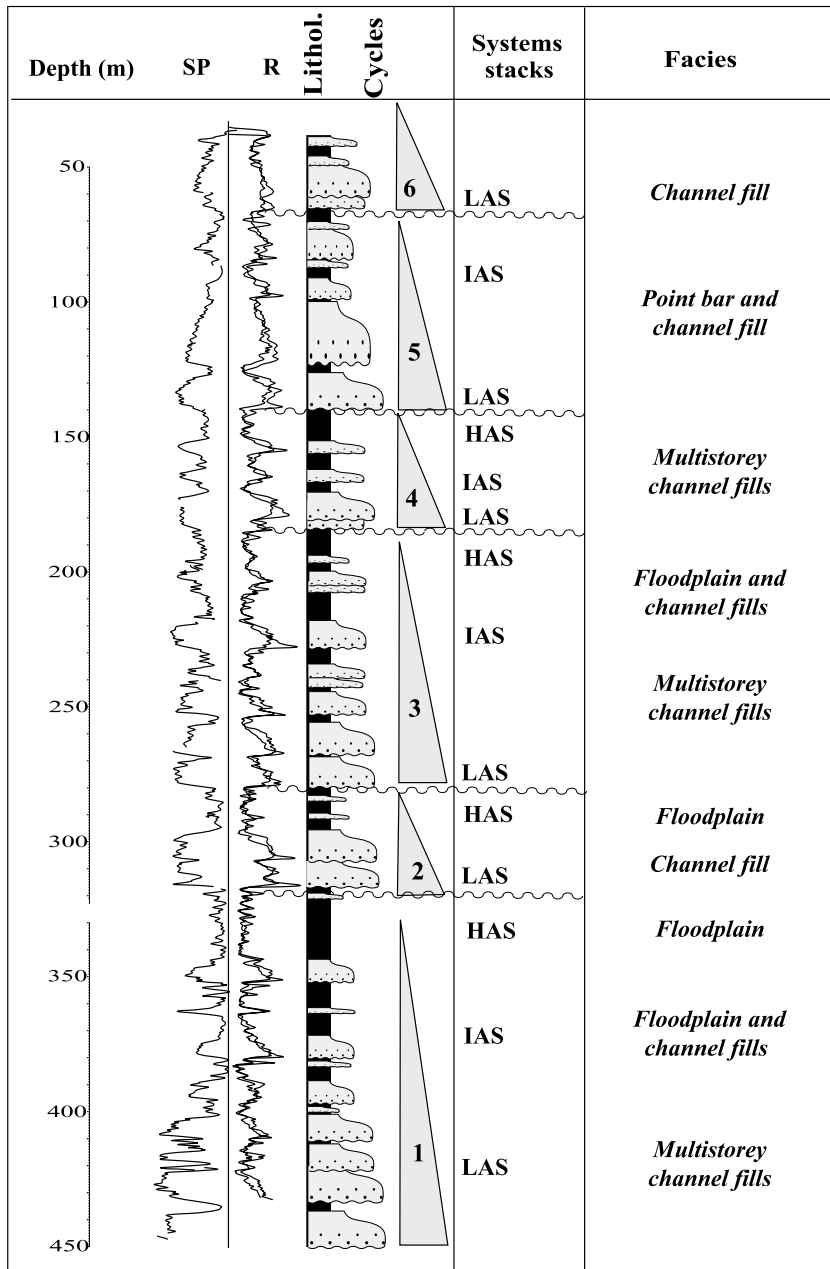


Fig. 11 Six large-scale, approx. 400 ka Milankovitch cycles and sequence stratigraphic interpretation of a well in the channel belt. Legend: HAS – high-accumulation space; IAS – increasing-accumulation space; LAS – low-accumulation space; CB – cycle boundary. Terminology: see in text.

well, which represents the whole Quaternary succession, six successive cycles could be recognized.

We do not know precisely the allocyclic controlling factors of these cycles, but the fact that there are six cycles in the succession representing the whole Quaternary (2.6 Ma) suggests orbital forcing in the Milankovitch frequency band, most probably the 400 ka long eccentricity cycles. However, even if they were driven by climatic changes they were also influenced by tectonic forces through their thickness and internal architecture. Bundles of short-term fining-upward cycles can also be traced in certain wells or areas but they are not correlatable either regionally or over long distances.

7. CORRELATION

Correlation in a fluvial sedimentary succession is always dubious or uncertain as the discontinuous nature of alluvial strata makes it difficult. For this reason, large-scale, basin-wide correlation is not a matter of sedimentology but belongs to the subject of cycle or sequence stratigraphy. Differentiation between allocyclic and autocyclic phenomena is rather difficult. Finding regionally extensive erosional surfaces, which were driven by allocyclic phenomena, is the key to the correlation of fluvial strata.

The identified large-scale cycles in this study represent several 100 ky of deposition. The long-term (4th order) Milankovitch-cycles are also of this time

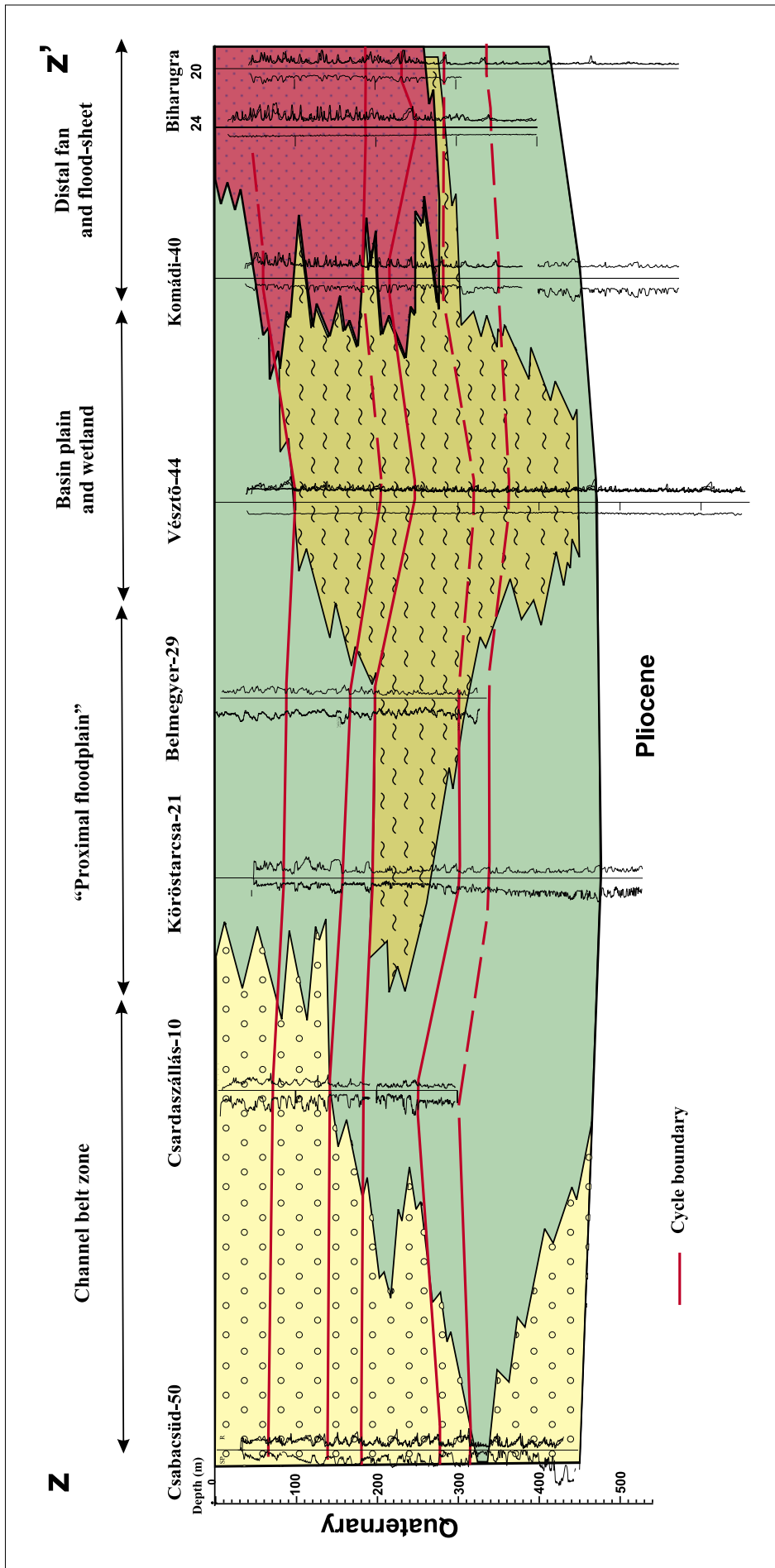


Fig. 12 Sedimentological and sequence stratigraphic cross section through the Quaternary facies zones. Shifting of the facies zones can be observed through time. Legend: see on Fig. 4.

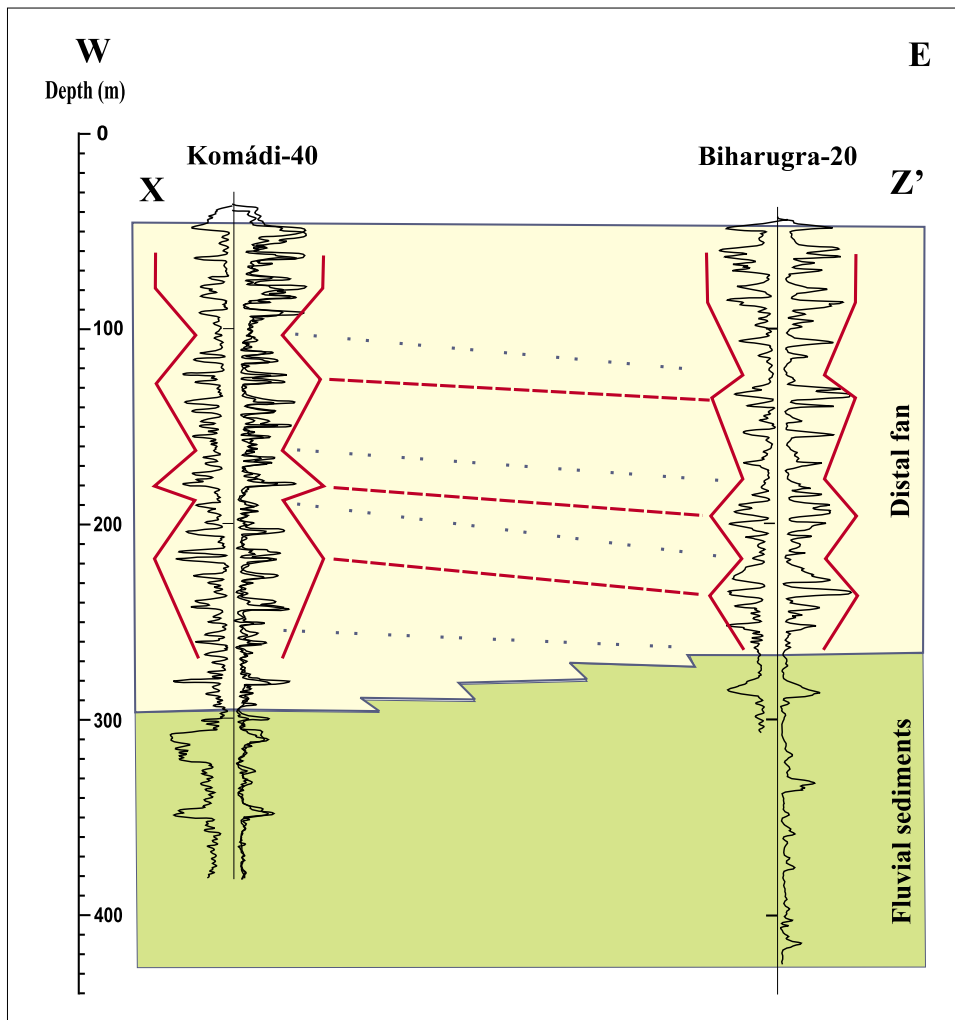


Fig. 13 Geological cross section in the E part of the Koros Basin. The uppermost 300 m on the profile was deposited as flood-sheets intercalated by floodplain deposits in the distal fan zone. The forestepping and backstepping of the system can be clearly observed. The lower part was deposited under normal fluvial conditions.

duration. Deposits of this scale are typically regionally extensive and are mappable. During this time interval the generation and abandonment of entire depositional systems may be accomplished (MIALL, 1996).

Correlation of the identified large-scale cycles was carried out along the geological and stratigraphic profiles indicated on Fig. 4. Sedimentological correlation of the main lithofacies zones can be seen on a regional profile on Fig. 12, where the shift of the facies zones can be detected in time. Alternatively, sequence stratigraphic correlation between the studied wells can be detected throughout the whole basin.

Correlation is easy in some areas, i.e. in the areas of the sandy and sandy–muddy facies zones, or through the channel belt zone and the “proximal” floodplain zone, but is difficult in the muddy facies zone, or in the wetland. Dashed lines represent interpolations in the ambiguous parts.

There are questions about the correlation in the E part of the basin where the distal alluvial fan sediments were found. On the sedimentological profile in this zone we can see the forestepping and backstepping nature of the distal fan system, causing coarsening- and thickening-upward, and fining- and thinning-upward trends of

the sand bodies in the upper 300 m of the studied wells (Fig. 13).

In some wells shorter-term cycles can be seen either in the fluvial or in the alluvial successions, which makes the overall pattern a little confused, but these cycles cannot be traced regionally.

8. DISCUSSION

Sediments described here were finer-grained in the lower part of the Pleistocene succession on the basin scale in the study area. More floodplain deposits can be found in the lowermost part of the sequence while the sandy facies become more prevalent upwards in a few areas. In the uppermost 150–200 m, however, sediments become much more sandy, channel fill beds can be detected even in the muddy facies zone.

This corresponds to the results of recent provenance studies and tectonic models of the area (THAMÓNÉ BOZSÓ & KERCSMÁR, 2000; THAMÓ-BOZSÓ et al., 2002). These revealed changes of transport directions at about 1.95 Ma related to significant changes in the uplift history of the Apuseni Mountains catchment

area. Earlier sediment supply came from a NE direction while a synsedimentary trap was formed inbetween the Apuseni Mountains and the study area. This probably caused the sedimentation of fine-grained deposits in the lower part of the succession. After this time tectonic events resulted in the infilling of the trap and the development of transverse drainage characterized by SE transport directions and an increased sediment flux. At this time an alluvial fan reached the area of the Körös basin from the emerging Apuseni mountains and is well represented in the sedimentary succession in Fig. 8.

The cyclic nature of the Quaternary sedimentary succession in the Körös Basin was studied recently in two boreholes with continuous cores. The Dévaványa and Vésztő boreholes are located in the central part of the Körös Basin, one in the muddy facies zone, and the other in the sandy–muddy facies distribution zone (Fig. 4). Different parameters (average grain size, magnetic susceptibility, palaeontological data) show cyclic changes in the boreholes. It was pointed out that a 40 ka cyclicity characterizes the older Pleistocene (greater than 1 Ma), while 100 ka cyclicity occurs in the younger Pleistocene. A remarkably good correlation was found between these data and the oxygen isotope variations of the marine ODP 677 site, suggesting continuous sedimentation in the basin, at least on the scale of the above mentioned Milankovitch cycles (NÁDOR et al., 2000, 2003).

In the present study, well-logs used for interpretation and correlation provided a larger-scale approach. For this reason the above mentioned high-frequency cycles cannot be recognized, although in some places traces of them were detected. In the upper two large-scale cycles, however, where the 100 ky cycles were prevalent, they can possibly be detected on the logs, disturbing the interpretation on a basin scale.

Six large-scale cycles were recognized in the sedimentary succession. At this stage there is no firm evidence of whether these cycles were driven by climatic or tectonic forces. Taking into account the quasi continuity of the sedimentary succession in the Körös Basin, estimation of the time range suggests 400 ka cycles in the Milankovitch frequency band (4th order cycles).

A good correlation of the present study with previous results of the continuous cores can be assumed by the fact that the uppermost two large-scale cycles correspond to the interval where NÁDOR et al. (2000) identified the 100 ka periodicity medium-scale cycles. The lower boundary of the second large-scale cycle from above lies on the boundary where the cyclicity changes from 40 to 100 ka in the high-frequency investigations.

9. CONCLUSIONS

- (1) Based on the interpretation of the different alluvial depositional elements in the Quaternary succession of the Körös Basin various depositional facies, and four types of facies associations were defined.
- (2) A basin-scale facies map of the study area was drawn. Besides the average fluvial architecture (where single channel sands alternate with alluvial plain muds), three areas were depicted where the multistorey stacked sandy channel fill sediments are predominant indicating pre-existing channel belts. In the central part of the basin, probably representing the deepest areas, muddy sediments of the floodplain and a probable wetland are prevalent. In the E part of the basin sediments of the distal part of an alluvial fan alternate with floodplain deposits.
- (3) The characteristic facies associations overlying one another in succession indicate a fining-upward fluvial depositional cycle on a scale of several tens of metres. On a regional scale, six cycles were recognized in the Quaternary succession. The base of the cycles is an extensive erosional surface which can be correlated regionally across the basin. The cycles are probably allocyclic but the question of whether they were tectonically or climatically driven has not been firmly proven. The fact however, that six cycles have been identified in an approximately 2.6 Ma Quaternary interval, suggests that they are 400 ka large-scale Milankovitch cycles. The tectonic overprint can be detected in the thickness and internal architecture of the individual cycles.
- (4) Internally, the structure of the cycles was subdivided into three units. The basal stacked multistorey, multilateral channels form the low-accumulation space deposits. The alternation of channel and floodplain sediments above comprises the increasing-accumulation space deposits. At the topmost part of the cycle the aggrading floodplain muds and silts of the high-accumulation space deposits can be found. These units correspond to the lowstand, transgressive and highstand systems tracts in sequence stratigraphic terms, respectively.
- (5) Correlation through the wetland, i.e. the central part of the study area has not been entirely solved. Compilation of the correlation throughout the whole basin is one of the main goals for future studies. It would be important to determine the facies distributions on a cycle scale and thus to define palaeogeographic maps and interpret individual cycles.

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