The Holocene 16,4 (2006) pp. 589–603

The oxbow sedimentary subenvironment: its value in palaeogeographical studies as illustrated by selected fluvial systems in the Upper Odra catchment, southern Poland

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Received 7 February 2005; revised manuscript accepted 24 November 2005

A HOLOCENE RESEARCH PAPER

Abstract: Research was conducted in valleys of sinuous rivers that drain medium-high mountain, foreland basin and upland areas, where loose Quaternary deposits predominate. The cyclic pattern determined for deposits of the oxbow sedimentary subenvironment in the Upper Odra Basin can be expressed as a few alternative sequences. The best-developed cycle occurring on a relatively high level of probability, is represented by the unilateral transition from channel to overbank deposits and upwards-bilateral oscillations between overbank and biochemical, as well as biochemical and slope deposits. In the first stage, oxbow filling processes are usually determined by autocyclic factors (resulting from spatial relations between abandoned channels and the active channel). As a consequence, overbank and/or biochemical sediments usually overlie channel deposits. Later, allocyclic processes could easily dominate autocyclic processes. In these cases, overbank, slope and late-Holocene alluvial fan deposits were delivered to oxbow basins as a result of the influence of outside factors such as climate or human impact. In the Upper Odra catchment, facies succession in the sequences of deposits infilling abandoned channels was mainly determined by climatic factors (in the Late Vistulian, early and mid-Holocene) and anthropogenic factors (in the late Holocene, especially in the last dozen centuries or more). The course of sedimentary processes conditioned by climate and human activity was modified by orographic factors associated with spatial relations among abandoned channels and both the active channel as well as valley slopes. However, the geological structure had a smaller influence on the course of sedimentary processes in the oxbows. The diversity of bedrock lithology in the individual drainage areas determined the thickness and lithological features of the given series of deposits but not the facies succession.

Key words: Oxbow Environment, fluvial environment, cut-off, palaeochannel, facies model, Holocene, Oder River, Poland.

Introduction

In this paper, the term 'oxbow' is understood as a fragment of an abandoned river channel, which was formed by neck cut-off, chute cut-off or avulsion processes (Allen, 1965; Schumm, 1985). This abandoned river channel, initially an oxbow lake, is gradually filled through (1) the accumulation of authigenic sediments and (2) the accumulation of allogenic deposits. Authigenic sediments, including material deposited by biogenic, biochemical or chemical processes, occur inside the oxbow basin. Allogenic deposits, including mainly minerogenic components, are delivered by fluvial (vertical accretion deposits), slope (including valley-side sheetwash deposits) or aeolian processes. This potential heterogeneity of deposits is a distinguishing feature for the oxbow subenvironment, whereas in subenvironments connected with the river channel and the proximal floodplain only fluvial processes are responsible for the accumulation of deposits. As a result, the difference between the terms 'oxbow fill' (abandoned channel fill, cut-off fill) and 'channel fill' must be emphasized. The latter is characterized by the distinct predominance of lateral accretion deposits and, as such, is treated by the author as deposits of the active channel and thus beyond the focus of this paper.

The effective utilization of the sedimentological record registered in oxbows in palaeogeographical reconstructions requires the prior resolution of the following issues: (1) cyclic sedimentation (or its absence) in this sedimentary subenvironment and (2) the relationship between environmental variables

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controlling the fluvial system and the nature of sedimentation in oxbows.

Cyclic sedimentation in the oxbow subenvironment

The essence of the solution to this problem is an attempt to establish a model succession for deposits infilling oxbows. In existing facies models, deposits infilling abandoned channels are usually treated as part of the fluvial environment succession, characteristic particularly for environments of sandy meandering and fine-grained meandering rivers (Miall, 1996). Few attempts have been made, however, to determine model sequences for oxbow fills as a separate sedimentary subenvironment; existing attempts have usually involved qualitative study. Erskine *et al.* (1982), Kozarski (1983) and Peiry (1994) have elaborated on the relationship between the phases of oxbow development and the succession of deposits in the abandoned channel fills. Based on generalized stratigraphic sections they showed that in the first stage after cut-off, the accumulation of lake environment deposits, such as gyttja or lacustrine clay, occurs in oxbows. Furthermore, Brown (1996) presented successional stages of vegetation resulting from the terrestrialization or paludification of oxbow lakes. Other research trends are analyses of sedimentation changes in relation to short-term or long-term changes in environmental conditions. Lorente (1990) elaborated a model of sedimentation in oxbows under the impact of seasonal climatic changes in the tropical zone. Florek and Mycielska-Dowgiałło (1991) presented synthetic cross-sections indicating changes of deposit succession in abandoned channel fills of the Vistula River in the Late Vistulian and Holocene.

Physiography of the drainage area and the sedimentary record in the oxbow subenvironment

According to the fluvial system concept, the oxbow filling process is conditioned by control variables, which are responsible for energy and matter flows (cascading system) in the drainage area (Figure 1). Climatic conditions influence the course of vegetation succession and denudation (Kozarski, 1983; Mansikkaniemi and Maki, 1990; Cotton *et al.*, 1999; Srivastava *et al.*, 2003). First, they determine the character of the hydrological regime and the activity of fluvial processes within valley bottoms (Alexandrowicz *et al.*, 1981; Nanson *et al.*, 1993; Wohl and Georgiadi, 1994; Straffin, 1996; Xu-Qinghai *et al.*, 1996a). Geological structure influences the character and intensity of denudation in the drainage area. It also determines the soil cover development and land use trends in particular fragments of the catchment (Taylor and Lewin, 1997; Klimek, 2003). Diastrophic movements determine the position of the temporary base level and, consequently, valley incision or aggradation (Koutaniemi, 1987; Peiry, 1990; Xu-Qinghai *et al.*, 1996b). Sea-level fluctuations are responsible for the periodic inundation of lower reaches of valleys near river mouths (Colman and Mixon, 1988; Mulrennan and Woodroffe, 1998). Hypsometric relationships influence the character and intensity of the transport processes of weathering products within both the slope and channel systems (Turkowska, 1988; Taylor and Brewer, 2001). The configuration of the valley bottom and position of the active channel determine the local course of erosion and accumulation processes on the floodplain (Kalicki, 1991; Jones and Harper, 1998; Citterio and Piegay, 2000) as well as modifications of vegetation patterns within perifluvial aquatic zones (Piegay *et al.*, 2000). Among selected human impacts that seem to exert the largest influence on sedimentary processes in valley bottoms, it is possible to enumerate deforestation, agriculture and water management. These forms of human activity lead in particular to disturbance of the water circulation and to intensification of the erosion and transport of deposits in the drainage areas analysed (Szumański, 1986; Hunt and Gilbertson, 1995; Klimek, 1999; Moores *et al.*, 1999; Salvador *et al.*, 2004).

This paper attempts: (1) to establish a modal sequence for deposits infilling oxbows, enabling the determination of a mechanism for deposition in this sedimentary subenvironment and (2) to estimate the impact of individual environmental variables on the sedimentary record in oxbows in the Late Vistulian and Holocene. To achieve these objectives, the example of sinuous rivers of the temperate zone, which drain medium-high mountain, foreland basin and upland areas where loose Quaternary deposits dominate, is used.

Background to the study area and methodology

The study area

Investigations were conducted in the middle and lower courses of the Ruda, Kłodnica and Osobłoga valleys, which are parts of the Racibórz Basin, in southern Poland (Figure 2). According to Schumm's (1977) classification, the valley reaches investigated belong to the transfer zone of the fluvial system. Broad and flat-bottomed valleys are present here, thus denudation products are mainly caught at the foot of the valley sides and reach a river channel in small amounts only. The rivers over the courses investigated are characterized by gentle gradients (about 1 m/km) and a smooth, longitudinal profile. The Rivers Ruda and Kłodnica as well as the lower Osobłoga were meandering rivers before partial regulation. The Osobłoga River in its middle course is an anastomosing river and its channels have been regulated by locks and used as millstreams. It should be emphasized that both the Rivers Ruda and Kłodnica, which drain the Racibórz Basin, the Rybnik Plateau and the Silesian Upland, are autochthonous rivers. Their character, ie, their hydrological regime and sediment yield, are a result of the impact of the natural environment of the area through which they flow. The Osobłoga River, originating in the Orska Vrchovina Mountains (the Czech Republic), in its middle and lower courses has features of a transit river. Its hydrological regime and sediment yield are mainly conditioned by factors occuring in the upper part of the catchment.

Sampling

Fragments of buried river channels located within the Late Vistulian/Holocene valley bottoms were examined. Based on diversity of (1) age, (2) hydraulic geometry, (3) location and (4) type and succession of infilling deposits, older and younger generation palaeochannels were distinguished (see Figures 3–5). Sediment sequences for use in facies analysis were collected with a Russian sampler, which enabled the extraction of intact cores. The most suitable location for cores within the palaeochannel cross-section seems to be the thalweg zone; also in the case of palaeomeanders, the zone of maximum curvature. The conducted studies show that a core with the greatest thickness can be obtained in that zone as well as that which well represents the sediment succession in both the cross-section and the longitudinal section (Rotnicki and Borówka, 1985; Gonera, 1986).

Facies approach

The valley deposits analysed were described using the genetic approach. This approach allows the correlation of particular depositional episodes with a specific type of sedimentary

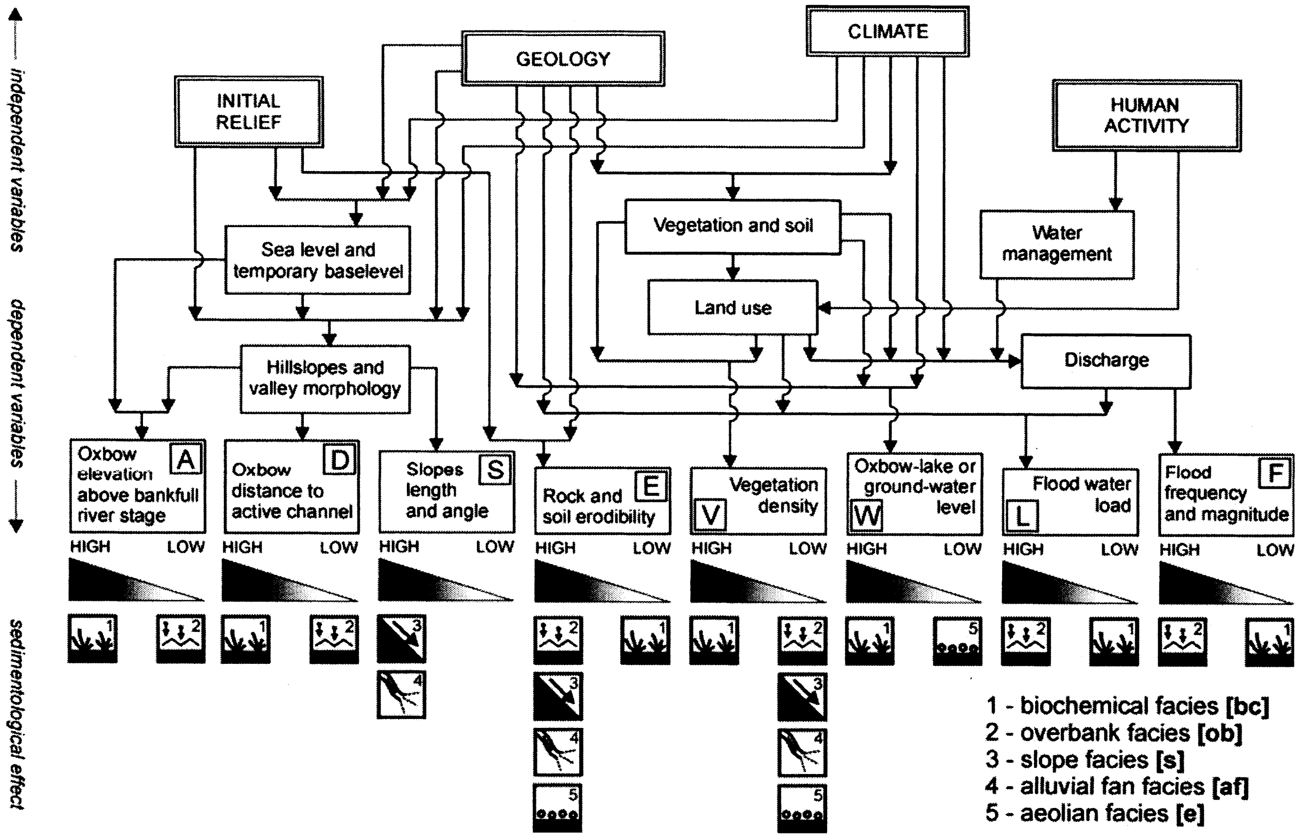

Figure 1 Generalized model of environmental variables controlling facies distributions in abandoned channel fills

process and environmental conditions that are responsible for the appearance of these processes. It was assumed that oxbows can be filled by authigenic sediments of biochemical facies [bc] or allogenic deposits, among which the sediments of: [ob] overbank facies, [s] slope facies, [af] alluvial fan facies and [e] aeolian facies were distinguished. Among deposits of [bc] facies, biogenic sediments (peat) definitely dominated. Biochemical as well as chemical deposits such as carbonate mud or limonite appear more rarely. The presence of macrofossils of peat-forming plants, particularly their root systems, was treated as a good indicator that the analysed deposits were accumulated *in situ* and belong to biochemical facies. Deposits accumulated in conditions of episodic flow events in the formerly abandoned channels and occurring during overbank discharges were treated as [ob] facies. In the valleys studied, usually rhythmically bedded sand or muddy sand was accumulated within the proximal floodplain, whereas massive or finely laminated mud was deposited within the distal floodplain. The sediments mentioned above are commonly poorly sorted and positively skewed. In contrast to [ob] facies, deposits of [ch] channel facies are better sorted and commonly near-symmetrical (see Rotnicki and Borówka, 1985). Channel deposits usually have a fining-upward texture with cross-bedded sand, occasionally gravely sand, at the bottom and muddy sand on top (eg, Miall, 1996; Zieliński, 1998). Alluvial fan facies could be easily recognized, thanks to alluvial cones situated at the mouth of tributaries to a main valley. They are legible in the relief of the valley bottom because expansion of the lithofacies building them decreases and thickness increases towards the apex of the fan. Textural features of these deposits are connected with lithology of a tributary catchment, thus grain-size distribution as well as roundness and surface texture of sand-size grains is usually different from the fluvial deposits of the main river. Among the deposits analysed of [af] facies, late-Holocene alluvial fan sediments that were accumulated at the mouth of ephemeral stream valleys dominated. Slope facies could be found in zones adjacent to valley slopes or edges of higher terraces. Deposits of [s] facies build wedge-shaped layers whose thickness increase towards the slope. Like [af] facies, textural features of slope deposits are also usually different from the main river alluvia. Grain-size distribution as well as roundness and surface texture of sand-size grains is connected with the lithology of slopes. Deposits of [s] facies tend to be positively skewed. Finally, five facies underwent statistical analysis and the starting point was the facies of channel deposits [ch]. The aeolian facies [e], however, was omitted from the analysis because of its small significance to the stratigraphy of the deposits studied.

Stochastic Markovian processes in the facies analysis of the oxbow fills

Markov chain analysis is applied to such geological problems as detecting and interpreting cyclic sedimentary mechanisms, examination of cyclic sedimentation over time or determining associations between the sedimentary environment and the character of cyclic sedimentation (eg, Miall, 1973; Krumbein, 1975). Markov chain analysis is a useful tool for ascertaining the existence (or non-existence) of 'the memory' in deposit successions. Further, it should be emphasized that Markov behaviour is not influenced by the presence of erosional or non-depositional features in sedimentary sequence (Nemec, 1981). Distinct from conventional qualitative analysis, the main advantage of the application of Markov chain models is the opportunity they provide to conduct a more objective analysis (statistically justified, testable and yielding comparable results). In the natural sciences the embedded Markov model is mostly used, which considers only the transition from one state to another. In the alternative Markovian model, the so-called regular Markov chain, deposit succession observations are made at equal spatial intervals and the transition from an individual state to the same

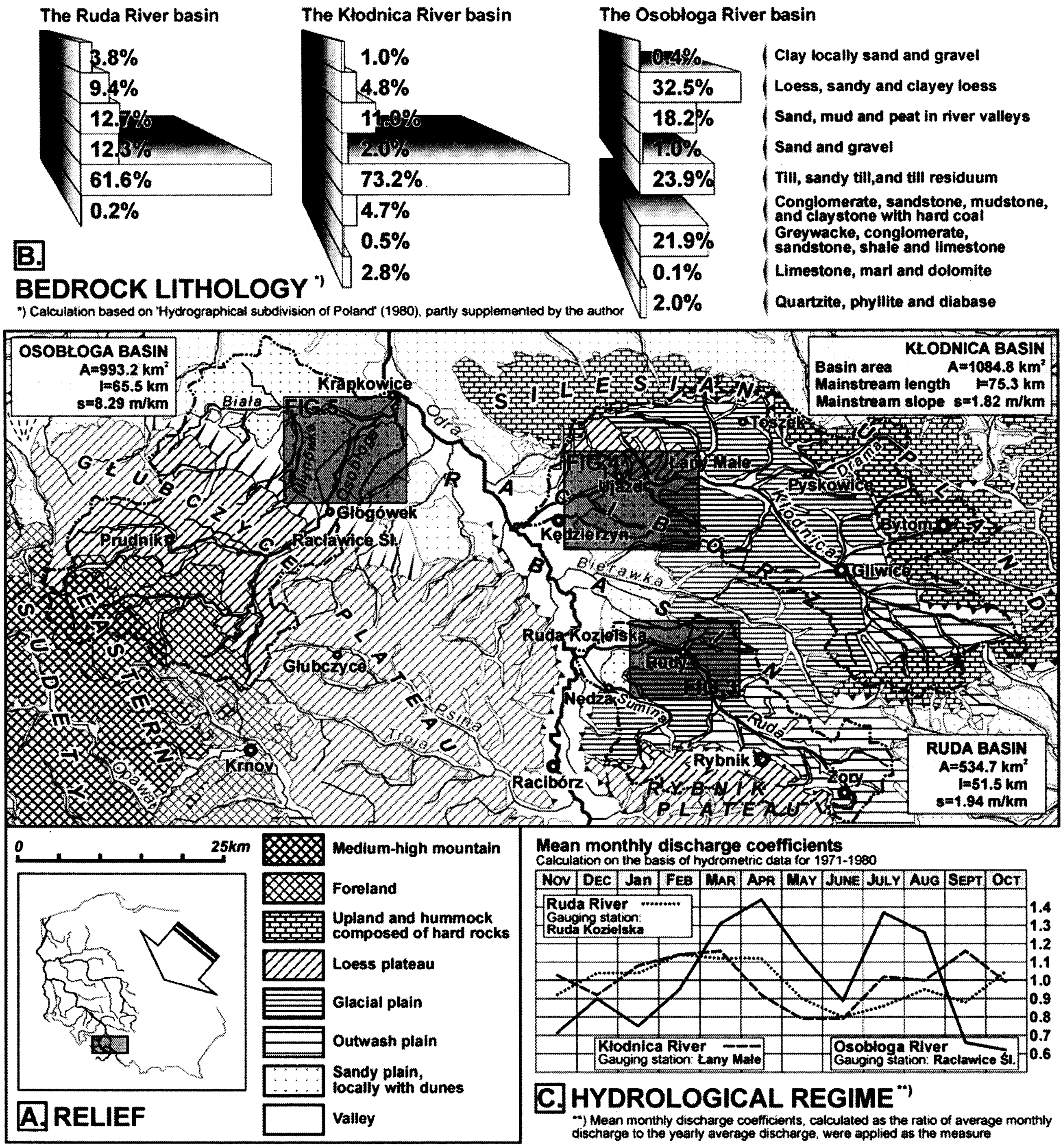

Figure 2 The study area – natural conditions of the Ruda, Kłodnica and Osobłoga basins. (A) Location of the study area with respect to the geomorphological units of the Racibórz Basin and adjacent areas. (B) Participation of individual rock formations exposed on the Earth's surface in relation to the total area of drainage basins studied. (C) Discharge variability in the annual cycle of the Ruda, Kłodnica and Osobłoga Rivers

state is possible. The model made it possible to take into account the relationships resulting from the thickness of particular facies in the vertical sections examined.

In this paper, the embedded Markov model was used to detect regularities that are responsible for the oxbow filling process. In this part of the work, the regular Markov chain was not applied because it was difficult to find the proper interval for the observation because of thickness variability of fill sequences in particular valleys. The analysis using the embedded Markov model focused on sequences of deposits infilling both older and younger generations of oxbows (see Figures 3–5). Calculations were based on the total of 159 occurrences of particular facies in 48 cores, which yielded 111 transitions among the distinguished facies. The analysis of relationships between environmental variables in individual catchments and the sedimentary record in oxbows was carried out using the regular Markov model. In the Kłodnica valley, where sequences of fills have the greatest thickness, the interval of 40 cm was applied, while in the Osobłoga valley 30 cm was used and 20 cm in the Ruda valley. In effect, the analysis was carried out for populations of 101 occurrences of facies and 85 transitions among them in the Ruda valley, 97 occurrences and 81 transitions in the Kłodnica valley, and 110 occurrences and 94 transitions in the Osobłoga valley. The statistical analysis

Generations of the Ruda oxbows	Estimated age of forming	Palaeochannels hydraulic geometry		Geomorphic setting		
		Radius of meander curvature	Width/depth ratio	Oxbows situation in relation to valley zones and their topography	Oxbows distance to present channel	Oxbows elevation above modern average river stages
Younger RY1, RY2, RY3, RY4, RY5, RY6, RY7, RY8;	the Sub-Atlantic Interval; mainly the previous millennium	15 - 28 m	5.0 - 8.5	in the axis of the valley; within flat floodplain (elevation differences below 1 m)	60 - 150 m	1.8-2.3 m in the middle and 0.7-1.1 m in the lower course of the valley
Older RO1, RO2, RO3, RO4, RO5, RO6, RO7, RO8;	the Late Vistulian(?), the early and middle Holocene, the Sub-Boreal Interval(?)	50 - 110 m	7.3 - 22.3	at the foot of valley slopes (5-7.5 m high) and higher terraces (1.5-3 m high)	140 - 500 m	2.6-3.6 m in the middle and 0.8-1.4 m in the lower course of the valley

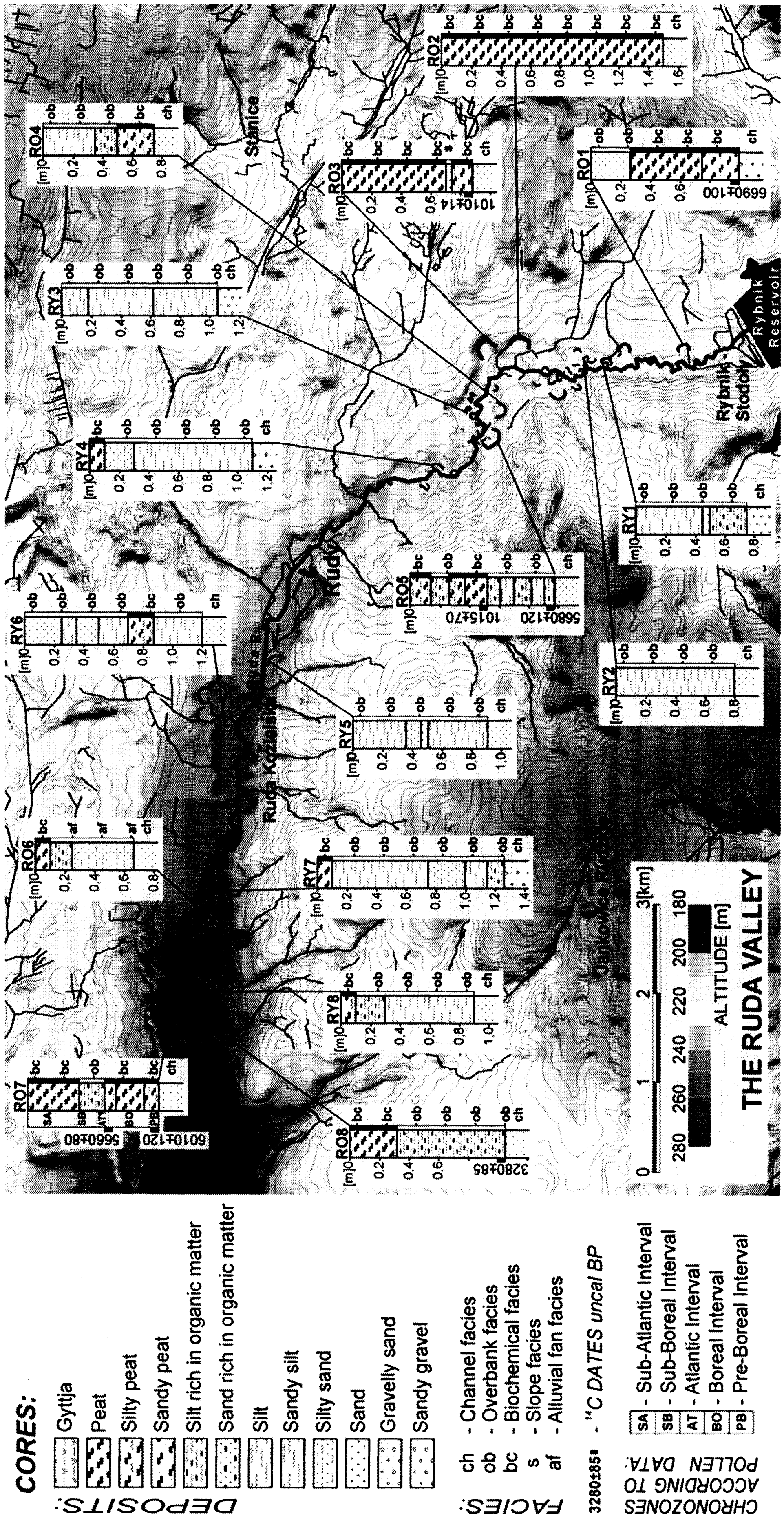

Figure 3 Generations of oxbows as well as lithostratigraphy and genetic interpretation of deposits for abandoned channel fills of the Ruda River (see Figure 2 for location of the study area)

Generations of the Kłodnica oxbows	Estimated age of forming	Palaeochannels hydraulic geometry		Geomorphic setting		
		Radius of meander curvature	Width/depth ratio	Oxbows situation in relation to valley zones and their topography	Oxbows distance to present channel	Oxbows elevation above modern average river stages
Younger KY1, KY2, KY3, KY4, KY5, KY6, KY7, KY8;	the late Holocene; mainly the previous millennium	21 - 40 m	5.3 - 10.7	in the axis of the valley; within flat floodplain (elevation differences below 2 m)	50 - 160 m	2.0-3.4 m in the middle and 1.1-1.9 m in the lower course of the valley
Older KO1, KO2, KO3, KO4, KO5, KO6, KO7, KO8;	the Late Vistulian as well as the early and middle Holocene	120 - 190 m	12.1 - 22.7	at the foot of valley slopes (8-17 m high in the middle and 3-8 m high in the lower course of the valley)	180 - 810 m	1.7-2.8 m in the middle and 2.4-5.8 m in the lower course of the valley

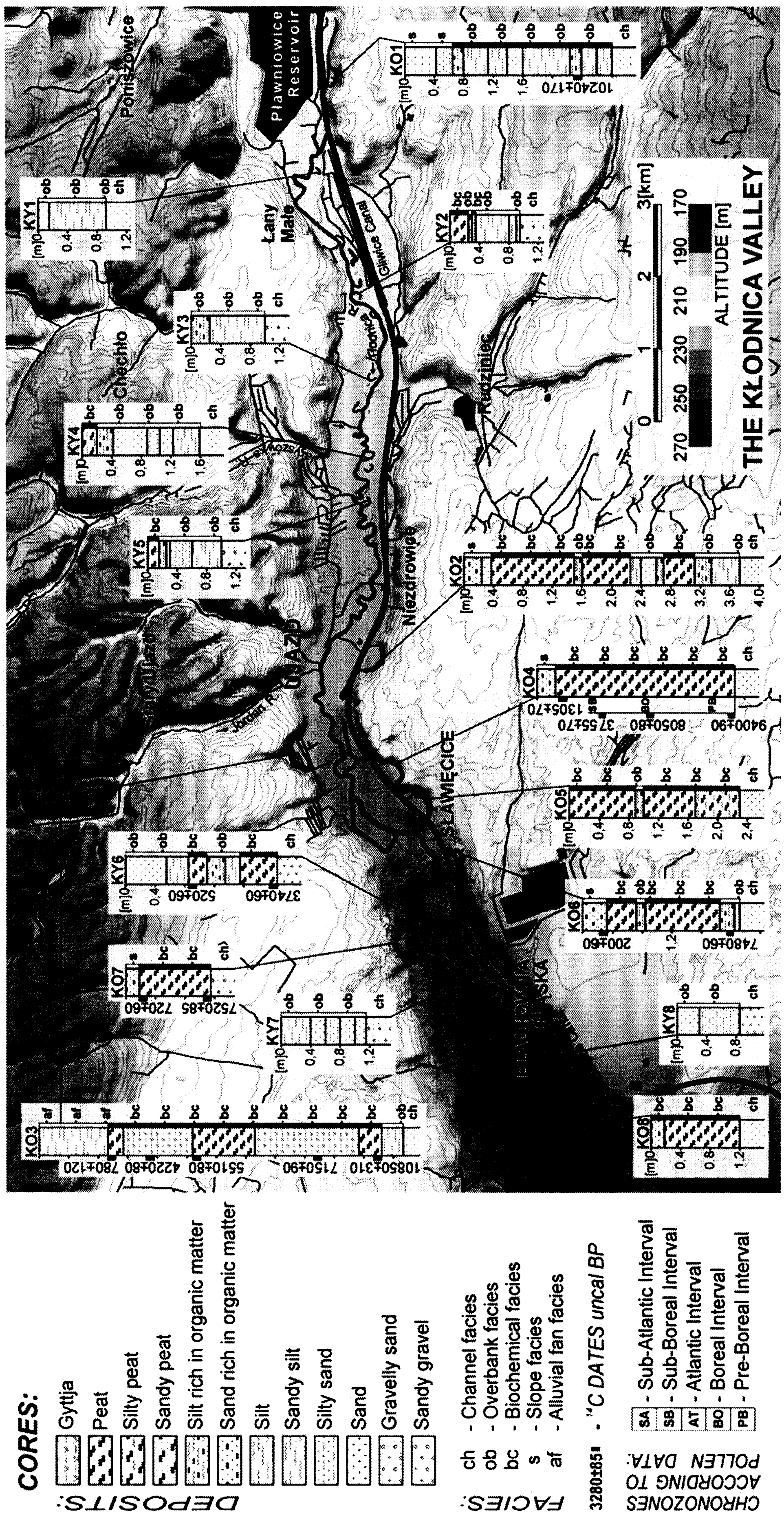

Figure 4 Generations of oxbows as well as lithostratigraphy and genetic interpretation of deposits for abandoned channel fills of the Kłodnica River (see Figure 2 for location of the study area)

Generations of the Osobłoga oxbows	Estimated age of forming	Palaeochannels hydraulic geometry		Geomorphic setting		
		Radius of meander curvature	Width/depth ratio	Oxbows situation in relation to valley zones and their topography	Oxbows distance to present channel	Oxbows elevation above modern average river stages
Younger OY1, OY2, OY3, OY4, OY5, OY6, OY7, OY8;	the late Holocene	11 - 50 m	4.3 - 8.6	in the axis of the valley; within flat floodplain (elevation differences below 2 m)	75 - 200 m	1.0-1.8 m in the middle and 1.1-1.9 m in the lower course of the valley
Older OO1, OO2, OO3, OO4, OO5, OO6, OO7, OO8;	the Late Vistulian as well as the early and middle Holocene	65 - 120 m	8.8 - 16.4	at the foot of valley slopes (15 m high) in the middle and higher terraces (5-9 m high) in the lower course of the valley	320 - 540 m	2.0-2.6 m in the middle and 1.5-2.4 m in the lower course of the valley

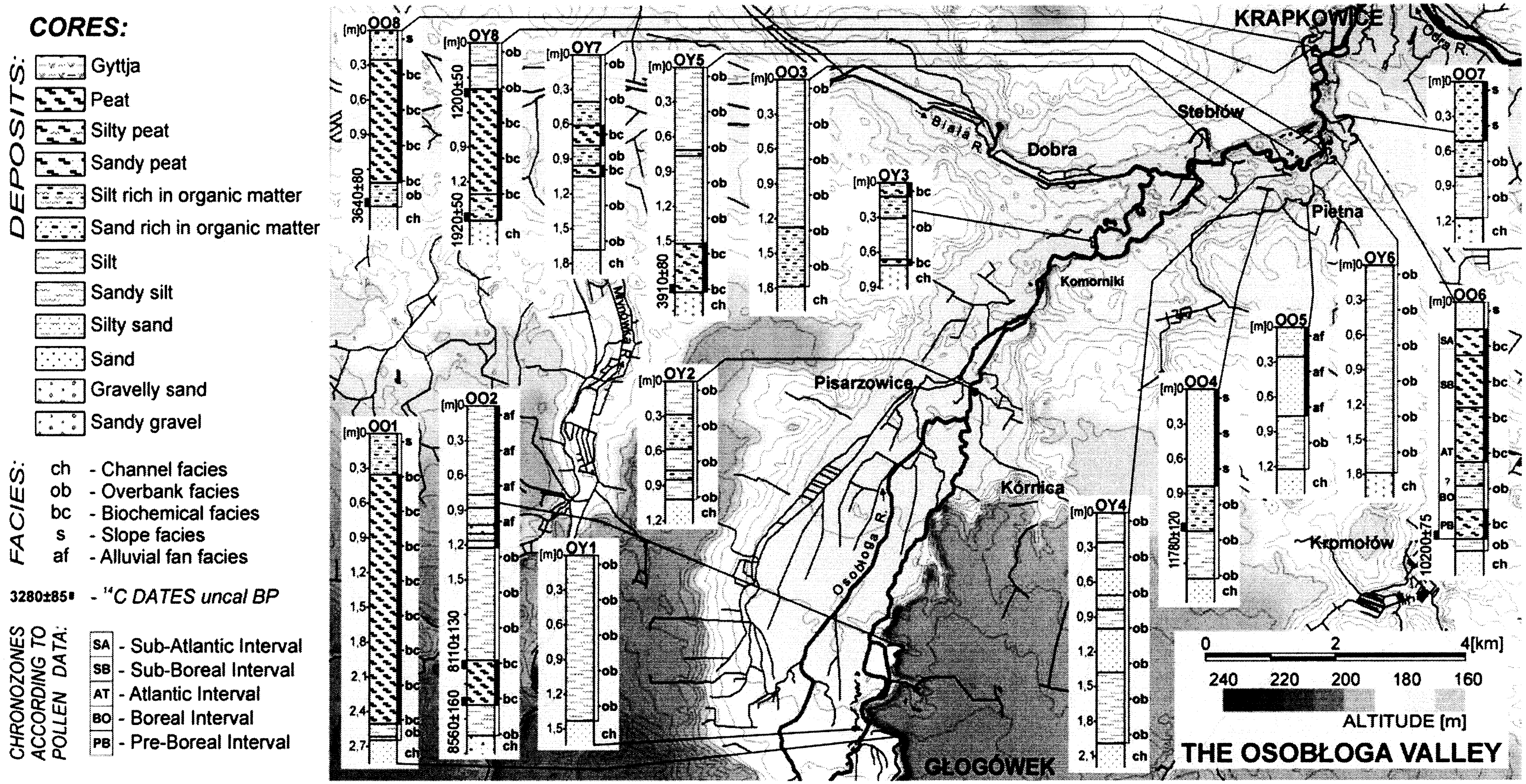

Figure 5 Generations of oxbows as well as lithostratigraphy and genetic interpretation of deposits for abandoned channel fills of the Osobłoga River (see Figure 2 for location of the study area)

was limited to the calculation and interpretation of the observed transition probability matrices that best reflect all of the registered transitions. This approach enabled an estimate of the frequency of individual lithological transitions in the valleys studied. The analysis was conducted separately for the older and younger generation of oxbows in order to emphasize the influence of environmental variables on the sedimentary processes throughout the Holocene.

Results and discussion

The oxbow filling process based on statistical analysis

Application of the embedded Markov chain analysis led to the construction of an observed transition probability matrix and a difference matrix, whose windows contain differences between observation-based and expected transition probabilities (Figure 6). Positive elements of the difference matrix represent transitions that have probabilities greater than random and are considered to be favoured by sedimentary mechanisms. Applying the χ^2 test (Nemec, 1981) yields a value of $\chi^2_{obs} = 274.37$– clearly higher (at 15 degrees of freedom and 95% significance level) than the critical tabular value of $\chi^2_{0.05} = 24.996$. Based on this result, the model of independent transitions can be rejected and we can assume that the sedimentary processes that formed the sequence examined possess features of a Markov process.

The analysed sequences of abandoned channel fills most often begin with the sandy silt or silt layers of flood genesis and transition [ch]→[ob] occurs at a greater than random probability. Less common, channel deposits directly underlie deposits of biochemical accumulation [ch]→[bc] and this transition has a random character. Among frequently observed transitions, it is also possible to enumerate the bilateral oscillations between the overbank facies and the biochemical facies [ob]⇄[bc], as well as the biochemical facies and the slope facies [bc]⇄[s]. These transitions occur on a relatively high probabilistic level. Slope and alluvial fan deposits usually appear in the top of the fill sequences. In only isolated cases did biogenic deposits cover them. In effect, for transitions [s]→[bc] and [af]→[bc] very high values of probability were calculated. The remaining observed transitions occurred at low probabilities. The cyclic pattern established for the vertical sequences of deposits representing oxbow sedimentary subenvironments in the Upper Odra catchment is presented in the transitions diagram (Figure 6). It appears that the origin of a basic part of the modal sequence, namely transitions [ch]→[ob]→[bc], should be attributed to the strong influence of the fluvial environment. In effect, the oxbow sedimentary subenvironment inherited some traits of the fluvial environment's 'autocyclicity' (Beerbower, 1966), meaning that no change in energy and matter flows were required in the fluvial system but that a change only in the three-dimensional relationships between oxbows and the active channel was sufficient for the accumulation of the aforementioned sequence. The presence of flood deposits in the lower part of the modal sequence [ch]→[ob] can be explained by proximity of the active channel to the new abandoned channels. This situation occurs especially in cases of neck or chute cut-off (Erskine *et al.*, 1982; Lewis and Lewin, 1983) and seems to be typical particularly for late Holocene sequences of oxbow fills. Overbank deposits directly overlying channel sediments are common around the world and were described as beginning model sequences, eg, in valleys of the Rivers Murrumbidgee (Erskine *et al.*, 1982), Warta (Kozarski, 1983), Rhone (Peiry, 1994) and Mississippi (Guccione *et al.*, 2001). In the course of time, the active channel enlarges the distance to oxbows as an effect of its lateral migration and incision. What is more, channels which are rapidly abandoned deposit bars at the entrance to the abandoned meander. These bars, which gradually increase in height, successively limit sediment input into the oxbow lake (Guccione *et al.*, 2001). Conditions favouring the accumulation of organic matter [ob]→[bc] appear as a consequence of the oxbows' location out of the reach of flood waters.

The next transition [bc]→[ob] is known from many river valleys (eg, Gonera, 1986; Koutaniemi, 1987; Kalicki, 1991; Moores *et al.*, 1999). Finely laminated inorganic silt interbedded with organic-rich silt or peat suggests that the sedimentary record in oxbow fills can reflect, as well as individual events, also phases of enhanced flood frequency (Moores *et al.*, 1999). Oscillation [bc]⇆[ob] could be caused both by autocyclic factors (distance changes between formerly abandoned channels and the active channel because of its lateral migration) or allocyclic factors (allogenic component delivery to an oxbow subenvironment changes in response to climate fluctuations or human activity). The presence of charcoal in vertical accretion deposits suggests that overbank deposition was controlled by allocyclic factors. In this case, the direct reason for the temporary increase in transport and accumulation of deposits was post-fire soil erosion. The remaining transitions that appear in the modal sequence seem clearly to be determined by allocyclic processes. Oscillation [bc]⇆[s], as well as unilateral transitions [ob]→[s] or [ob]→[af] are the effect of denudation rate changes within the fluvial system. Expansion of synanthropic plants in pollen diagrams directly preceding changes in

Embedded Markov Chain

observed transition probability matrix

p_{ij}	bc	ob	s	af
ch	0.271	0.708	0.000	0.021
bc		0.678	0.286	0.036
ob	0.848		0.091	0.061
s	1.000	0.000		0.000
af	1.000	0.000	0.000	

difference matrix

d_{ij}	bc	ob	s	af
ch	-0.173	+0.184	-0.016	+0.005
bc		+0.280	+0.274	+0.024
ob	+0.489		+0.078	+0.048
s	+0.745	-0.300		-0.009
af	+0.745	-0.300	-0.009	

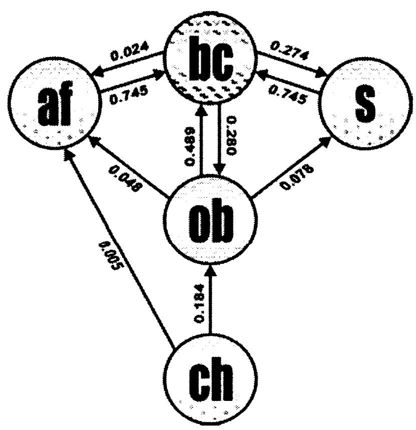

Figure 6 Observed transition probability matrix (p_{ij}), difference matrix (d_{ij}) and diagram showing observed modal transitions established for abandoned channel fills of the Ruda, Kłodnica and Osobłoga valleys

sediment succession is evidence that these changes occurred in response to human impact (M.Nita, personal communication, 2000).

The cyclic pattern described above is generally compatible with the sequence lacustrine clay → peat or silty peat with inwashes of sand/silt → silt/clay, presented by Erskine *et al.* (1982) for an abandoned channel, which was created as a result of chute cut-off. Also the succession of deposits infilling Late Vistulian oxbows of the Warta River, namely: silt or fine sand → gyttja → peat, sometimes covered by a thin layer of mud (Kozarski, 1983), is similar to the modal sequence established for the oxbow fills of the Ruda, Kłodnica and Osobłoga Rivers. Nevertheless, Florek and Mycielska-Dowgiałło (1991) elaborated synthetic cross-sections of the Vistula palaeochannels showing that the sedimentation style in the oxbow subenvironment could have changed during the last 15 000 years. Consequently, in the middle Vistula valley, the succession gyttja → peat is characteristic of sequences of deposits infilling Late Vistulian oxbows, whereas fills of Holocene oxbows are rather homogeneous and consist of peat or minerogenic deposits.

Influence of environmental variables on the sedimentary record in oxbows in the Late Vistulian and Holocene

The analysis of observed transition probability matrices (Figure 7) shows that in the Ruda valley [bc] facies predominate in fills of older generation oxbows. Biogenic deposits usually directly overlie channel deposits and they have considerable thickness. In some cases deposits of [bc] facies pass upwards into overbank deposits, usually of considerable thickness. After periods of suspension load increase, the conditions favourable for biogenic accumulation usually returned; thus [bc] facies is common in the upper parts of fills of the older generation oxbows (eg, RO5, RO7, RO8 cores). Oxbows of the younger generation in the Ruda valley are filled almost solely by flood deposits (eg, RY1, RY2, RY3, RY5 cores). Deposits of [bc] facies appear most often in the upper part of the fills analysed and are of very small thickness. In the Kłodnica valley, [bc] facies dominate in fills of older generation oxbows, although in half of the cases its appearance is preceded by the presence of a thin layer of overbank sediments (eg, KO2, KO3, KO6 cores). Deposits of biochemical accumulation infilling of older generation abandoned channels are of considerable thickness. Most often, they pass to slope deposits, more rarely to flood or alluvial fan deposits. Slope and alluvial fan deposits, sometimes of considerable thickness, complete fill sequences from the top (eg, KO1, KO3 cores). Younger generation oxbows in the Kłodnica valley are filled mainly with overbank deposits. As in the Ruda valley, deposits of [bc] facies appear most often in the upper part of analysed fills and are of very small thickness (eg, KY2, KY4, KY5 cores).

In the Osobłoga valley, [bc] and [ob] facies predominate in fills of older generation oxbows. Directly above channel deposits, overbank facies appear more often than biochemical facies. The aforementioned facies, although predominant, relatively rarely form transitions between themselves and more often create layers of considerable thickness. In the Osobłoga valley (as in the Kłodnica valley), slope and alluvial fan deposits are present in the upper part of fill sequences of the older generation oxbows. The transition to these facies occurs both from biogenic (eg, OO1, OO6, OO8 cores) or overbank deposits (eg, OO4, OO5, OO7 cores). Younger generation oxbows in the Osobłoga valley are filled mainly with flood deposits. In contrast to the Ruda and Kłodnica valleys, biochemical deposits appear more often in the sequences from the Osobłoga valley. They usually occur in the lower parts of fills, passing upwards into overbank facies (eg, OY5, OY8 cores).

The above analysis showed significant differences in succession of deposits infilling older and younger generations of oxbows in the individual valleys. This must be connected with environmental variables, whose fluctuations exerted an influence on changes within the oxbow sedimentary subenvironment. In the remainder of this paper, the main tendency of environmental variable changes will be presented and evidence to support the suggested direction of change of each factor will be discussed.

Biochemical accumulation dominated in older generation oxbows in the Ruda valley and especially in the Kłodnica valley. In contrast to the modal sequence, deposits of [bc] facies often appear directly above channel deposits. This can be linked to climatic factors and, connected with them, the history of vegetation and denudation rate changes (Figure 8). A basis does exist for suggesting that the accumulation of allogenic deposits dominated in the oxbows in the Late Vistulian. In the lower parts of KO1, KO3, OO4 and OO6 cores (see Figures 4 and 5), which according to radiocarbon dating belong to the Late Vistulian, deposits of [ob] facies are present. The occurrence of [bc] facies in the period preceding the beginning of the Holocene has been documented so far only at site KO3 (10 850 ± 310 BP ^{14}C date). In the Preboreal Climatic Interval, forests dominated by pine and pine–birch assemblages spread in the adjacent areas to the valleys studied, while willow–poplar assemblages spread

Regular Markov Chain

Older generation oxbows

THE RUDA VALLEY

P_{ij}	bc	ob	af
ch	0.625	0.250	0.125
bc	0.800	0.200	0.000
ob	0.364	0.636	0.000
af	0.333	0.000	0.667

THE KŁODNICA VALLEY

P_{ij}	bc	ob	s	af
ch	0.500	0.500	0.000	0.000
bc	0.788	0.060	0.122	0.030
ob	0.455	0.455	0.090	0.000
s	0.000	0.000	1.000	0.000
af	0.000	0.000	0.000	1.000

THE OSOBŁOGA VALLEY

P_{ij}	bc	ob	s	af
ch	0.375	0.625	0.000	0.000
bc	0.737	0.105	0.158	0.000
ob	0.125	0.625	0.125	0.125
s	0.000	0.000	1.000	0.000
af	0.000	0.000	0.000	1.000

Younger generation oxbows

THE RUDA VALLEY

P_{ij}	bc	ob
ch	0.000	1.000
bc	0.000	1.000
ob	0.118	0.882

THE KŁODNICA VALLEY

P_{ij}	bc	ob
ch	0.125	0.875
bc	0.000	1.000
ob	0.250	0.750

THE OSOBŁOGA VALLEY

P_{ij}	bc	ob
ch	0.375	0.625
bc	0.500	0.500
ob	0.074	0.926

Figure 7 Observed transition probability matrices for deposits infilling abandoned channels of older and younger generations in the Ruda, Kłodnica and Osobłoga valleys

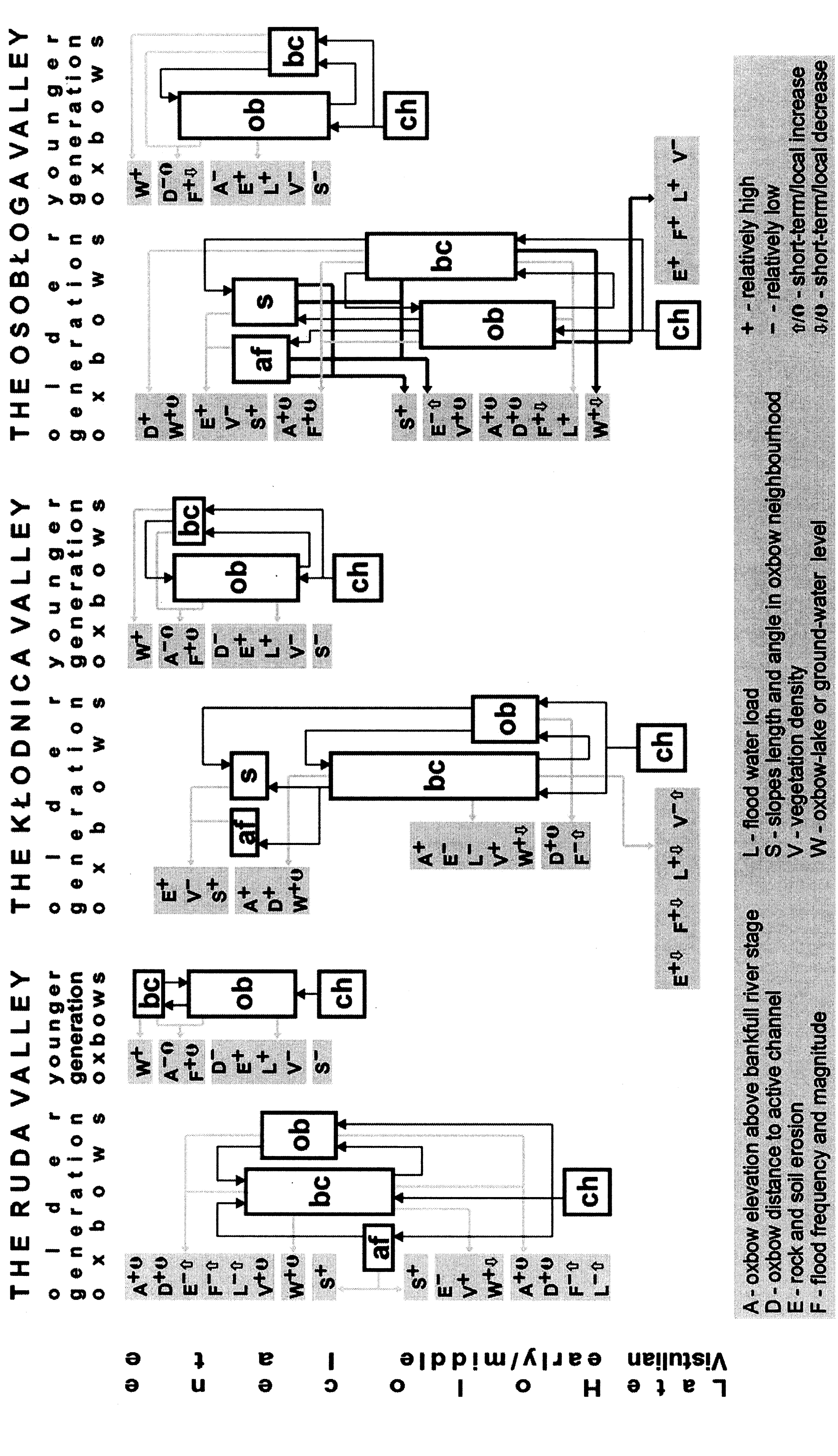

Figure 8 Environmental variables controlling oxbow filling processes and their changes in the Late Vistulian and Holocene based on interpretation of facies successions in the Ruda, Kłodnica and Osobłoga valleys

in the valley bottoms (M. Nita, personal communication, 2000). The high peat accumulation rate at site KO4 indicates that conditions favouring the development of peat-forming plant communities appeared after the start of the Holocene. The succession of vegetation corresponding to climatic warming probably affected the limitation of mantle transport rate within hill slopes and increasing bank resistance. As a consequence, river load probably decreased. Moreover, at the beginning of the Holocene river regimes became more equable (Kozarski, 1983) and runoff coefficient decreased (Rotnicki *et al.*, 1989) in the territory of Poland. The hydrological condition changes caused a reduction in hydraulic geometry parameters of meanders in the Ruda, Kłodnica and Osobłoga valleys (see Figures 3–5). Significant narrowing of the meander belt obviously brought about a difficulty with the delivery of overbank deposits to large palaeochannels abandoned in the Late Vistulian and at the Pleistocene–Holocene boundary.

In contrast to the Ruda and Kłodnica valleys, in the Osobłoga valley flood deposits form a significant ingredient of sequences infilling abandoned channels of the older generation. The main reason for this may be the character of the river Osobłoga, which in its upper course drains the medium-high mountain area of the Eastern Sudety (see Figure 2A). The Osobłoga River basin is characterized by the highest relief coefficient ($\psi = 25.95$), calculated as a ratio of the denivelation and square root of the area of drainage basin. Significantly lower values of the relief coefficient were obtained for the Kłodnica ($\psi = 5.83$) and Ruda ($\psi = 5.28$) drainage basins. As a consequence, we can expect that the degree of connections between the slope and channel systems and amount of deposits eroded and transported by the river network to be the highest in the Osobłoga fluvial system. Additionally, it should be emphasized that the Osobłoga drainage basin is characterized by the highest accumulation of loess deposits (see Figure 2B), which are very susceptible to erosion.

In contrast to the Rivers Ruda and Kłodnica, the Osobłoga River also exhibits the largest variability of discharges both in the annual cycle (see Figure 2C) and in the multiannual period (a variability coefficient (C_V) of the average yearly discharges, expressed as the quotient of the standard deviation of discharges to their average value, was applied as the measure). The C_V coefficient calculated for the Ruda River is 0.244, for the Kłodnica River 0.316 and for the Osobłoga River 0.389. Following Choiński (1988) and his three-gradual scale of C_V coefficient diversity, the Ruda and Kłodnica basins are areas with average variability of discharges ($0.225 < C_V < 0.325$), whereas the Osobłoga drainage basin is among those areas with most variable discharges ($C_V > 0.325$). High flow amplitudes caused by the mountain regime of the Osobłoga River were obviously the cause of frequent floods, which also affected the lower course of its valley in the Holocene. Holocene climatic oscillations, however, were probably too small to be reflected in the Ruda and Kłodnica drainage areas situated beyond the mountains and characterized by high retention. Sequences of fills contain the record of relatively few episodes of an increase in the delivery of allogenic components to older generation abandoned channels.

Slope and alluvial fan deposits dominate in the upper parts of sequences infilling the abandoned channels of the older generation in the Kłodnica and Osobłoga valleys. A connection between these facies and older generation oxbows is orographically conditioned. The location of Late Vistulian or early Holocene oxbows at the foot of higher terraces or valley slopes created potential conditions for the development of slope processes or progradation of alluvial cones. It should be emphasized, however, that these processes were initiated on a large scale only in the late Holocene and it is necessary to correlate them with human activity. The initiation slope deposit deliveries at site OO6 was synchronous with the deforestation of the adjacent area, as recorded in the pollen diagram by the sudden increase in herbaceous plants (NAP) and appearance of numerous indicators of crop agriculture and pastoral activity (M. Nita, personal communication, 2000). In the Kłodnica valley, the accumulation of alluvial fan deposits at site KO3 was initiated at about 2240 ± 100 BP by radiocarbon dating, ie, in the late phase of the Lusatian culture settlement activity, but its intensive progradation took place in the Mediaeval period (Klimek, 2003). Peat covering by sand of the slope facies was dated to the Middle Ages (1305 ± 70 ^{14}C BP at site KO4 and 720 ± 60 ^{14}C BP at site KO7) and modern times (200 ± 60 ^{14}C BP at site KO6). In contrast to the Kłodnica and Osobłoga valleys, the presence of slope deposits in the fills of the Ruda oxbows was confirmed incidentally. It proves the high stability of the valley slopes and indirectly attests to the low extent of agriculture in the lower part of the Ruda catchment, where forests still dominate today. Based on the map of the Upper Silesia vegetation in the eighteenth century (Kaczmarski *et al.*, 1984), the area of forest amounted to 48% for the Ruda River basin, 30% for the Kłodnica River basin and only 18% for the Polish part of the Osobłoga River basin.

Overbank facies dominate in sequences of deposits infilling oxbows of the younger generation. It appears that intensive flood deposition in the valleys examined started in the early Middle Ages and continued to modern times. In the OY8 core from the Osobłoga valley the top of the peat layer, which was covered by alluvium, has been dated at about 1280 ± 50 ^{14}C BP. In the Kłodnica valley, a final cessation of biogenic accumulation by overbank deposition has been dated at 1215 ± 70 ^{14}C BP in the area around site KY3 (Wójcicki and Nita, 2004) and at 520 ± 60 ^{14}C BP at site KY6. Younger generation oxbows in the Ruda valley, which are filled with flood deposits from soil erosion in the upper part of the catchment, are associated by Klimek (1999) with the inset terrace system formed in the last millennium. The location in the central zone of the valley bottom was unquestionably conducive to deliveries of overbank deposits to the younger generation of oxbows, while oxbows of the older generation were situated beyond the zone of the flood impacts in the late Holocene. Apart from the fine-grained suspension from soil erosion, charcoal is common in analysed sequences of deposits and coal-dust is present in some cores (KY4, RY8). The presence of charcoal is an indicator that a main reason for intense mechanical denudation was deforestation connected with the development of iron metallurgy. The presence of coal-dust from mines located in the upper parts of the Kłodnica and Ruda drainage areas is evidence that large-scale overbank deposition also occurred in the last two centuries. Recent observations suggest that in some younger generation oxbows, especially in the Ruda (sites RY4 and RY7) and the Kłodnica valleys (sites KY2, KY4 and KY5), biogenic accumulation was initiated recently. In spite of the general conformity of the sequence [ch] → [ob] → [bc] with the cyclic pattern, it appears that the reason for this state is the activity of allocyclic processes. Despite the collapse of the 'small retention' system in the middle of the nineteenth century, human impact on the hydrological regime of the Upper Odra tributaries considerably increased in the last century (Absalon *et al.*, 1996). It can be observed for example in more equable distribution of discharge as a result of the construction and

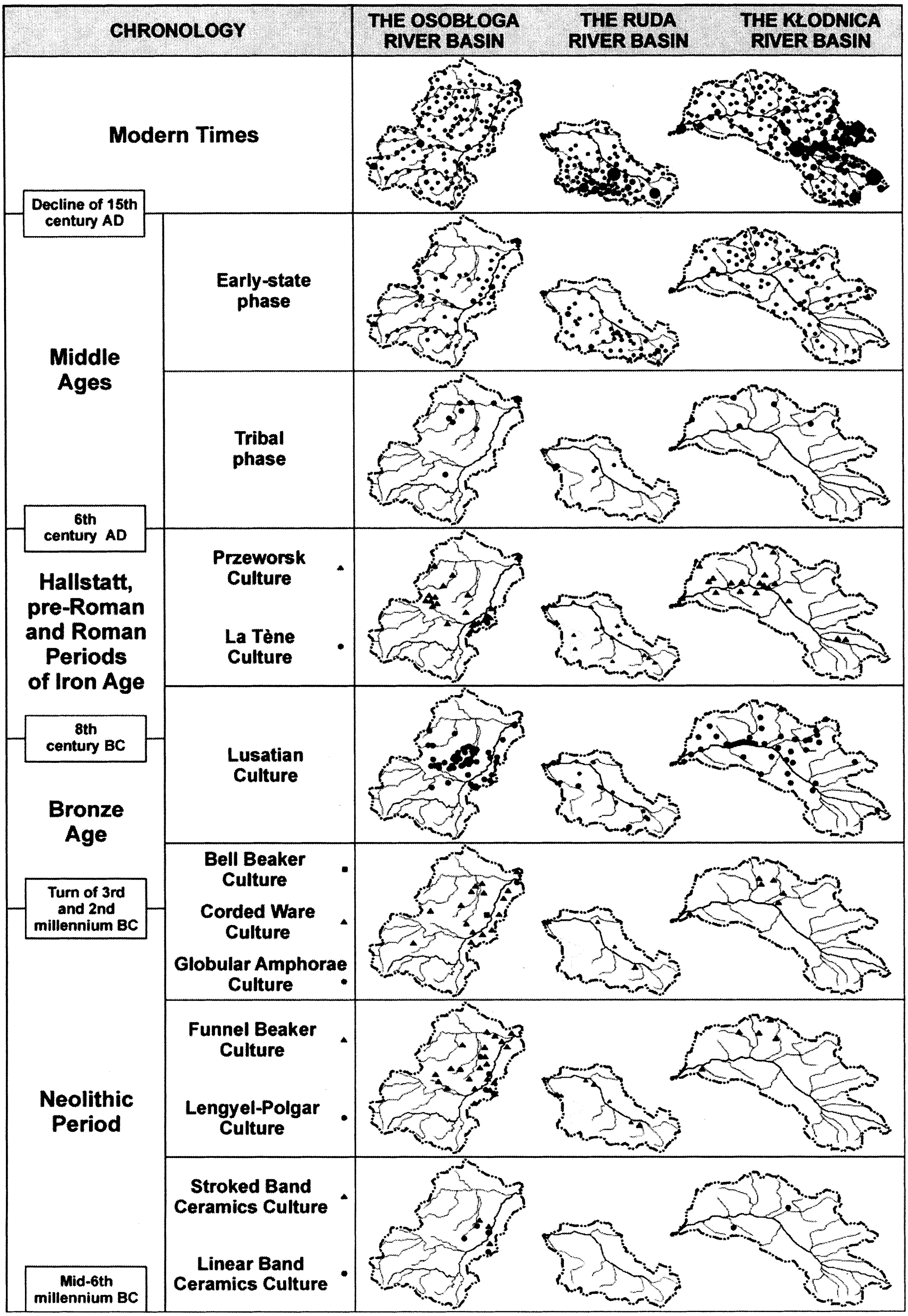

Figure 9 Main stages of settlement in the Ruda, Kłodnica and Osobłoga basins according to archeological and historical data (Godłowski, 1980; Parczewski, 1982; Panic, 1992; Kulczycka-Leciejewiczowa, 1993; Mierzwiński, 1994; Abłamowicz, 2004; Foltyn *et al.*, 2004)

utilization of the Gliwice Canal and dammed reservoirs in the Klodnica drainage basin (the Dzierżno Duże, Dzierżno Małe and Pławniowice reservoirs) and in the Ruda drainage basin (the Rybnik Reservoir). River regulation and channel straightening caused strong incision on some of the valley reaches, which is not conducive to the frequent inundation of oxbows, although they are still located in the zone adjacent to the active channel.

The examples presented above show that the upper parts of deposit sequences infilling older generation oxbows and deposit sequences infilling younger generation oxbows were strongly affected by human impact. To date, the attempt to substantiate the connection between the sedimentary record and the oldest phases of settlement in analysed catchments (Figure 9) has not been successful. According to Kulczycka-Leciejewiczowa (1993), the homeostasis violation on the loess plateau in the central part of the Osobłoga River basin took place already in the middle of Neolithic Period (about the middle of the fourth millennium BC). In the more attractive parts for colonization of the Kłodnica River basin (Abłamowicz and Śnieszko, 2001) and the Ruda River basin (Foltyn *et al.*, 2004), this may have taken place at the decline of the Bronze Age. Only the activity of settlers of the late phase of the Lusatian culture and the Przeworsk culture, however, found their local record in the Kłodnica valley (Klimek, 2003; Wójcicki and Nita, 2004). This could be associated with the technique of farming progress practiced at the beginning of the Iron Age, which allowed the use of less fertile soils (Godłowski, 1980). The very clear and widespread record of human impact registered in the valley environment was initiated in the early Middle Ages. It was probably connected with a limitation on forest areas as a result of the rapidly increasing number of settlements, especially in the thirteenth and at the turn of the thirteenth and the fourteenth centuries (Panic, 1992).

Conclusions

(1) The cyclic pattern determined for deposits in the oxbow sedimentary subenvironment in the Upper Odra catchment could be expressed in the form of a few alternative sequences. The best-developed cycle occurring at a relatively high probability, is represented by the transitions [ch] → [ob] ⇆ [bc] ⇆ [s]. Optional sequences [ch] → [ob] ⇆ [bc] ⇆ [af], [ch] → [ob] → [s] ⇆ [bc], [ch] → [ob] → [af] ⇄ [bc], and especially [ch] → [af] ⇄ [bc] are developed at a significantly lower probability.
(2) The sedimentary record in the oxbow subenvironment is determined by autocyclic processes (resulting from spatial relations between abandoned channels and the active channel) and allocyclic processes (causing changes in allogenic component deliveries to the oxbow basins under the influence of outside factors such as climate or human impact). The diversity of oxbow fill sequences in each valley, in relation to the modal sequence, is evidence that allocyclic processes could easily dominate over autocyclic processes. Consequently, succession of deposits infilling abandoned channels can be treated as a record of the influence of environmental variables on the processes occurring within the fluvial system.
(3) In the Upper Odra catchment, facies succession in the sequences of deposits infilling abandoned channels was determined mainly by climatic factors (in the Late Vistulian, early and mid-Holocene) and anthropogenic factors (in the late Holocene, especially in the last dozen centuries or more). The very essential change in the accumulation type within the oxbow basins occurred from human impact in the late Holocene, when allogenic deposition replaced authigenic sedimentation. Throughout the Late Vistulian and Holocene, the course of sedimentary processes conditioned by climate and human activity was modified by orographic factors connected with spatial relationships among abandoned channels and both the active channel as well as the slopes of the valley. The geological structure, however, had a smaller influence on the course of sedimentary processes in the oxbows. The diversity of rock formations exposed on the surface in the individual drainage areas determined the thickness and lithological features of the given series of deposits but not the facies succession.

Acknowledgements

The National Science Foundation under the 'Track' programme and the Silesian University provided financial support for this research. Special thanks go to Professor Kazimierz Klimek for his support and advice, Dr Małgorzata Nita for permission to use the results of her palaeobotanical analyses and Dr Dominik Abłamowicz for sharing his knowledge of the prehistoric settlement of the Upper Silesia. I am grateful to Professor Tomasz Zieliński for his helpful reviews of the initial manuscript and my wife Monika for her help with the translation of the text.

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