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Late Quaternary channel avulsions on the Danube deep-sea fan, Black Sea

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Abstract:

Analysis of new high-resolution seismic-reflection profiles, chirp profiles and previously published sidescan data, together with piston cores on the Danube Fan provide new insight into the recent sedimentation processes in the deep northwestern Black Sea.

The latest channel-levee system on the Danube Fan developed probably during the Neoeuxinian lowstand (oxygene isotope stage 2) in a semi-freshwater basin with a water level about 100 m lower than today. Sediment supplied by the Danube was transported to the deep basin through the Viteaz Canyon, which was directly connected to the leveed channel of this system on the middle slope. Channel avulsion was common in the middle fan, as indicated by four main phases of bifurcation. Each phase developed after the same pattern: breaching of the lower and narrower left levee by turbidity currents, building of a unit of High Amplitude Reflection Packets (HARP) by the unchannelized flow while the former channel was abandoned, followed by initiation of a new meandering leveed channel. The northward migration through successive bifurcations is influenced by the asymmetry between levees, hence by the Coriolis effect. In the lower fan where the levees became too low to maintain a stable pathway for the turbiditic flows, channel migration occurred. Locations of HARPs and channels after bifurcation are controlled by the pre-existing bathymetry. Sedimentary deposits are confined between the high levees of unit 0 (the initial phase of the youngest channel-levee system) to the south, and the steep relief of the Dniepr Fan to the north.

The HARPs of the most recent phase of avulsion are the most severely constrained by local topography and form a very narrow elongate structure that is at most half as thick as the previous HARPs. Their distal part is not covered by channel-levee systems and is visible both on sidescan mosaics and on chirp profiles and was sampled in core BLKS 98-20.

Sea level controlled fan activity but the evolution of the last channel-levee system with several bifurcations during a single sea level lowstand suggests that the primary control of channel avulsion and sand delivery is probably autocyclic.

The presence of important HARP sand bodies in the mud-rich Danube Fan is presumed by analogy with a similar seismic facies on the Amazon Fan and indicated by the sands cored in BLKS98-20. However, only drilling of the HARP units could verify this interpretation.

Keywords: Black Sea; Deep-sea fan; Avulsion; Late Quaternary; High-resolution seismic

1. Introduction

The Danube deep-sea fan developed in the northwestern part of the Black Sea from sediments fed by the Danube but also by the northern rivers: the Dniepr, the Dniestr and the Bug (Fig. 1a). It extends for about 150 km downslope of the shelfbreak, and the distal end of the fan reaches the abyssal plain at 2200 m water depth. Depositional processes are located essentially on the middle and lower slope. The surface of the fan is covered by a distributary network of meandering channels which represent different phases in the evolution of two distinct channel-levee systems. The southern system is controlled by the Danube sediment supply through the Viteaz canyon, whereas the Dniepr, the Dniestr and the Bug probably built up the northern system (Wong et al., 1997, Fig. 1b). The Black Sea was a freshwater lake during most sea-level lowstands when fan deposition was active. Thus, it is conceivable that despite the many similarities between the Danube fan and other mud-rich fans, the potentially different conditions of sedimentation could have influenced the characteristics of turbidity flows.

Turbidite sedimentation in the deep northwestern Black Sea was not well-investigated before the 1990s (Winguth et al., 2000 and references therein). Recent contributions (Wong et al., 1994; Wong et al., 1997; Winguth, 1998; Winguth et al., 2000, but also Konyukhov et al., 1997; Sorokin et al., 1998) improved considerably our understanding of the architecture and growth pattern of the Danube and Dniepr deep-sea fans.

This paper is based on data collected during the French-Romanian BLASON cruise in April-May 1998. 24-channel high-resolution reflection profiles, single-channel very-high-resolution seismicdata, Xstar chirp profiles and piston cores were collected on the northwestern margin of the Black Sea. Previous data from three German-Romanian-Russian cruises in 1992, 1993 and 1994 (high-resolution reflection seismic and sidescan data) were also used (Fig. 2).

The main results refer to the recent sedimentary evolution of the southern Danube fan, focusing on the avulsions of the last channel-levee system during the Neoeuxinian (stage 2), the last water-level lowstand in the Black Sea.

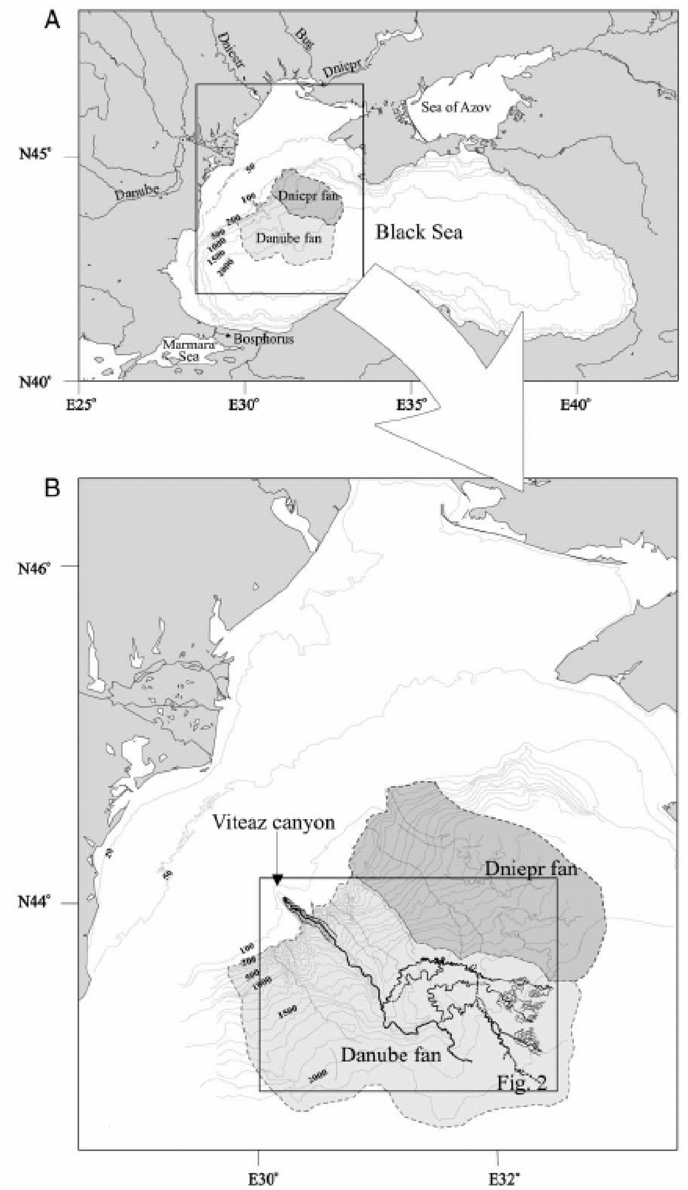

Fig. 1 Map of the Black Sea, showing (a) location of Danube and Dnieper deep-sea fans; and (b) bathymetry and channel location on the present-day fan surface (modified after Wong et al. (1997) and Winguth et al. (2000)).

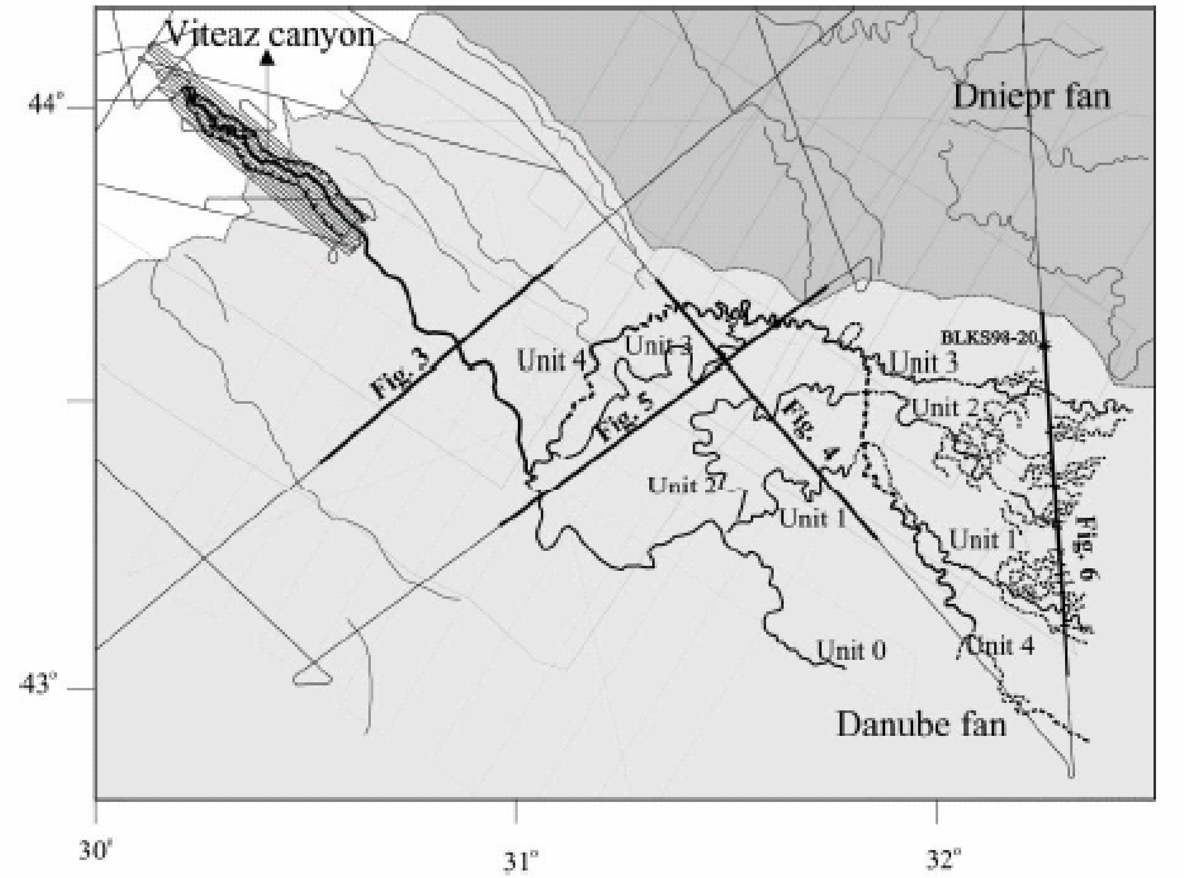

Fig. 2 Location of seismic lines and core station BLKS 98-20 in relation to the surficial channel systems. BLASON profiles (1998) in bold line, profiles of German-Romanian-Russian cruises (1992, 1993, 1994) in thin lines. Dashed lines mark channel courses that are uncertain.

2. Geological setting

The Danube fan (Fig. 1a, b) is located in the western Black Sea basin, which is generally considered to be the result of back-arc extension associated with the northward subduction of the Tethyan plate (Robinson et al., 1995). It is a fine-grained turbidite system fed by an important river and separated from the highstand coastline by a very wide shelf (up to 120 km). The Viteaz canyon was probably the most important path for sediment supply to the deep sea. Currently, this canyon is directly connected to the youngest channel-levee system on the Danube fan.

Submarine fan activity was controlled by changing sea level. In the marginal basin of Black Sea, the sea level development was complicated by the link to the Mediterranean through the Strait of Bosphorus and the Sea of Marmara. When the Mediterranean water level fell bellow the Bophorus during glacial periods, the Black Sea was isolated from the world ocean (Ross and Neprochnov, 1978) and its level oscillated synchronously with the wet-dry cycles in Eurasia. At the same time, the Black Sea catchment areas were considerably enlarged, redirecting part of the meltwater discharge towards the Caspian Sea, the Black Sea and the Mediterranean (Arkhipov et al., 1995). Temporary absence of marine water influx associated with large freshwater inputs from the Danube and other important rivers changed the Black Sea in a freshwater lake during times of fan activity, thus creating special conditions for turbidite deposition (Flood et al., 1999). A re-establishment of the connection to the Mediterranean during highstands resulted not only in a rise in the water level of the Black Sea and interruption of fan activity, but also in an increase in salinity, the Black Sea becoming a highly-stratified marine anoxic basin. Presently, the Black Sea is the world's largest permanently anoxic basin, with a surface layer of aerated brackish waters and deeper more saline and anoxic waters. Sedimentary discharge is directed mostly southward along the western coast as a consequence of the prevalent winds and currents (Panin, 1997).

The development of the northern turbidite complex supplied by the Dniepr and the other Ukrainian rivers appears independent but coeval. Winguth (1998) and Winguth et al. (2000) estimated ages of ca. 900 ka for the Danube fan and ca. 800 ka for the Dniepr fan. Both fans are composed primarily of channel-levee systems, intercalated with mass transport deposits. Wong et al. (1994, 1997) separated 8 seismic sequences in each of these fans; only the 6 upper sequences, however, contain large meandering channel-levee systems.

3. Seismic facies of the Danube Fan

In the Danube fan, as well as in many other fine-grained fans, the channel-levee systems consist of lenticular deposits with high amplitude reflectors (HAR) at the channel axis typically associated with coarse-grained sediments, and lower amplitude continuous reflectors representing fine-grained overbank turbidites (Fig. 3, 4 and 5). Our data suggest that the distributary channel network on the surface of the Danube is the result of repeated channel bifurcations. Since distinct channel-levee systems onlap one another, bifurcation is probably due to levee breaching and avulsion, and only one channel was active at a time. These results are consistent with previous studies of Wong et al. (1997) in the subsurface of the Danube and Dniepr fans, in which they assumed that only one main channel was active at any given time for the Danube and Dniepr fans respectively. Several abandoned meandering channels can be identified on the seafloor indicating that subsequent deposition was not sufficient to bury them. Channel migrations were bathymetrically-controlled and did not affect the general location of the Danube or Dniepr fans, which maintained their positions during fan construction (Wong et al., 1997). This suggests that possibly the sediment supply followed more-or-less the same path across the shelf during fan deposition.

On the middle fan near channel bifurcations, every channel-levee system overlies high-amplitude reflection packets (HARPs) as shown in Figs. 4 and 5. HARP units were first described in the Amazon Fan (Flood et al., 1991) and were associated with the development of channel bifurcation by avulsion. They were deposited after the breaching of the levee by unchannelized turbidity flows which follow a new path along the topographic depression. ODP drilling in the Amazon fan shows that HARPs are thick, bedded sand bodies forming in most cases multiple lenticular units with a significant fraction of material remobilized from upslope channel deposits and eroded levees (Pirmez et al., 1997).

In the subsurface, the channel-levee systems are intercalated with commonly structureless reflective bodies (Fig. 3, 4 and 6) interpreted generally as mass-transport deposits *sensu lato* including slides, slumps and debris-flows (Wong et al., 1994). On the present-day seafloor, most mass-transport deposits (MTD) are found in the Dniepr fan, while only minor occurrences were observed in the Danube fan (Wong et al., 1997).

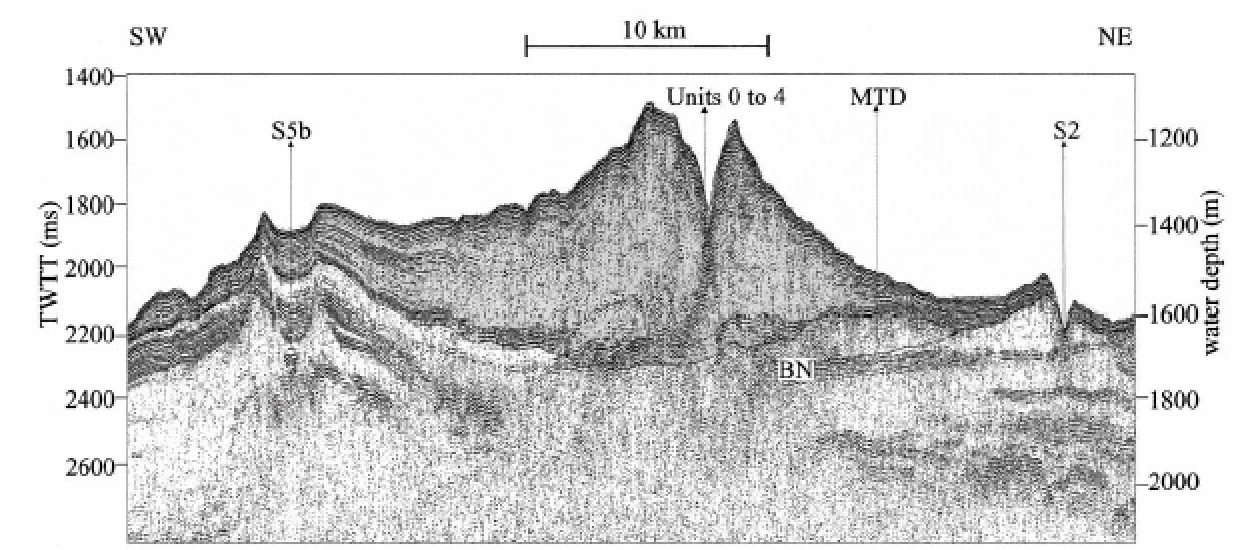

Fig. 3 Part of BLASON 24-channel seismic line 39 (location in Fig. 2). The last sequence (Neoeuxinian, stage 2) is interpreted. Older channels are identified as s5b and s2 respectively, in Winguth (1998).

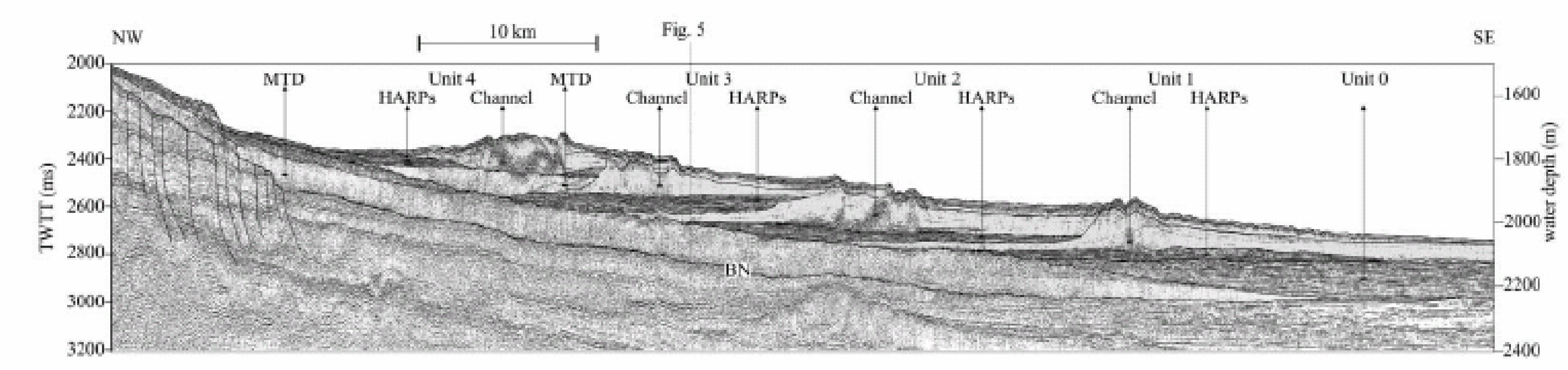

Fig. 4 Part of BLASON 24-channel seismic line 7 (location in Fig. 2). The last sequence (Neoeuxinian, stage 2) is interpreted.

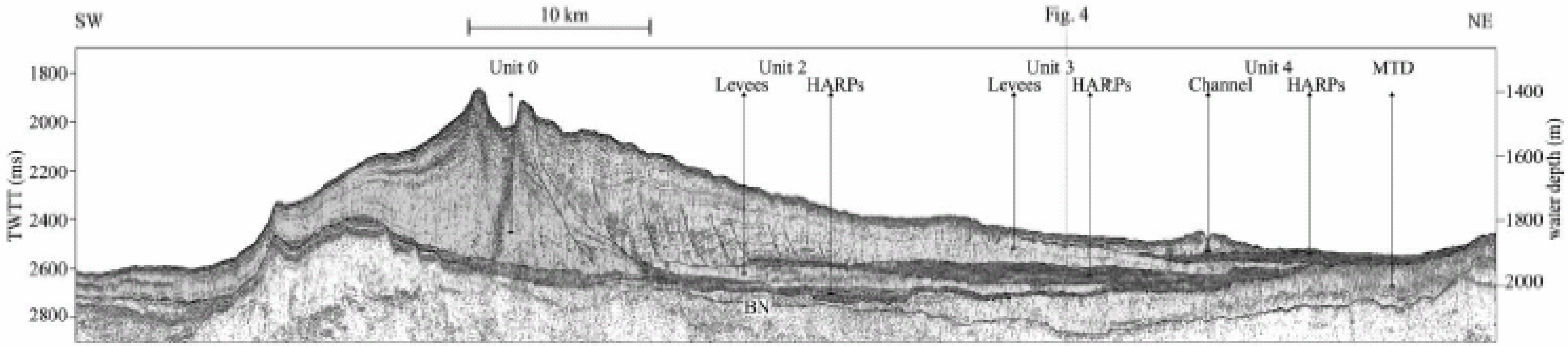

Fig. 5 Part of BLASON 24-channel seismic line 18 (location in Fig. 2). The last sequence (Neoeuxinian, stage 2) is interpreted.

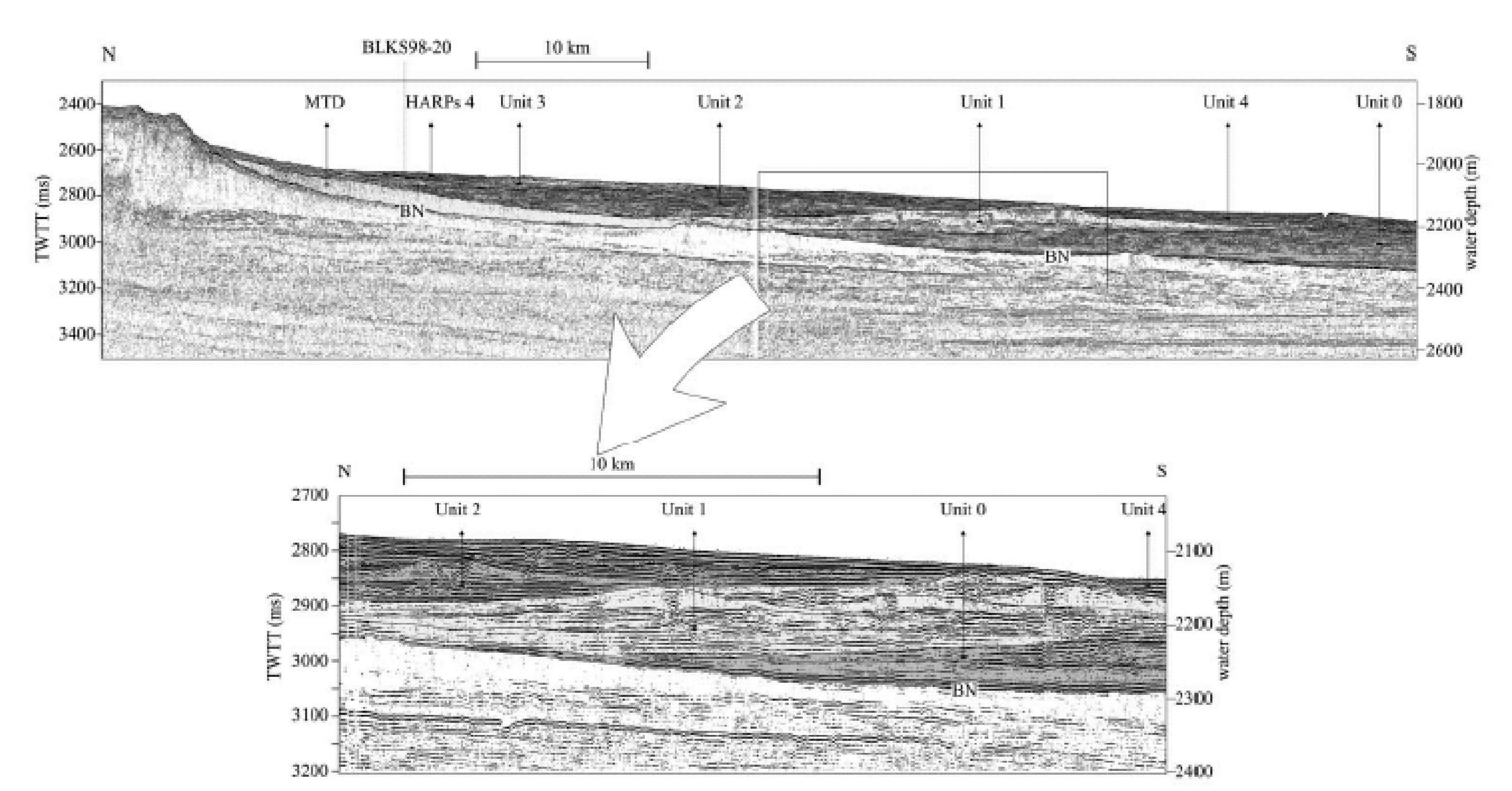

Fig. 6 Part of BLASON 24-channel seismic line 6 (location in Fig. 2). The last sequence (Neoeuxinian, stage 2) is interpreted.

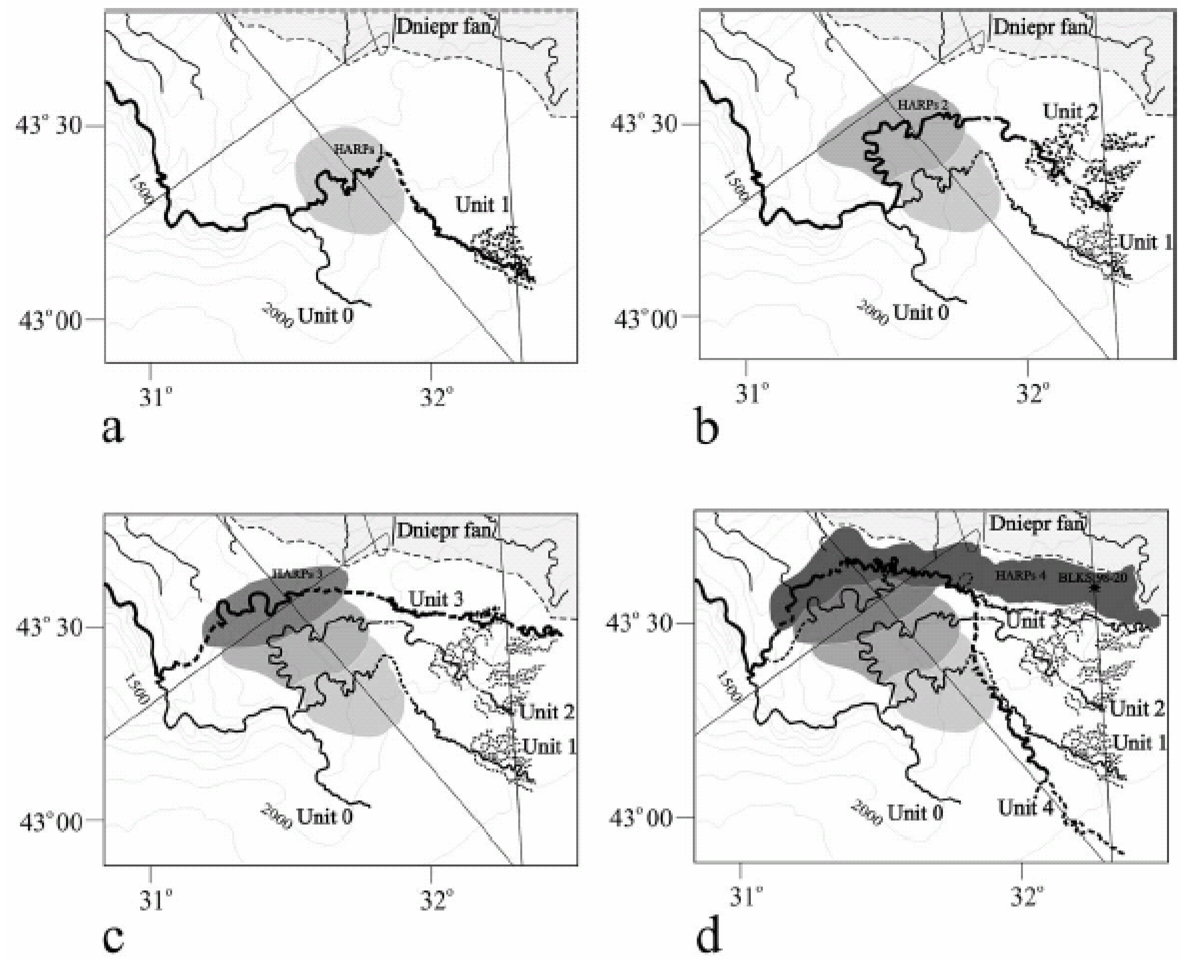

Fig. 7 Channel and HARP units of the four main avulsion phases: (a) unit 1; (b) unit 2; (c) unit 3; (d) unit 4. Dashed lines mark channel courses that are uncertain. Location of core BLKS98-20 is indicated.

4. Recent growth pattern of the Danube fan

The youngest channel-levee system on the Danube fan (s8a of Wong et al., 1997; s5 of Winguth, 1998; and units 0 to 4 in this paper) is the most important bathymetric feature in the deep basin. According to Wong et al. (1997) and Winguth (1998), this channel-levee system represents the upper part of sequence 8, the last depositional sequence in the Danube fan. Sequence 8 was correlated with isotope stages 4 to 1 (Winguth et al., 2000); however, radiometric dates were not available. Undoubtedly, this channel was the last active channel of the last sequence and is directly connected to the present Viteaz canyon, unlike older channel-levee systems of sequence 8 (s1 to s4, Winguth, 1998). Consequently, it is likely that this channel was active during the Neoeuxinian (isotope stage 2), the last sea-level lowstand in the Black Sea.

The Neoeuxinian basin was substantially different from the modern Black Sea basin. The water level was more than 100 m lower and only a narrow shelf existed, while a large part of the present-day northwestern shelf was subaerially drained under the most severe climatic conditions of the Pleistocene. Still, the water depth exceeded 2000 m in the central part of the basin. During this time, influx of marine waters from the Mediterranean was interrupted so that the basin freshened to 3-7 ‰ and the water mass was completely oxygenated (Chepalyga, 1985).

The last channel-levee system is connected to the Viteaz canyon which is deeply incised into the shelf (about 24 km landward of the shelfbreak). The present-day Viteaz canyon consists of a 2.5 to 4 km wide, northwest-southeast trending main trough with steep flanks and a meandering erosional thalweg which continues on the upper slope as a V-shaped, slightly sinuous, unleveed valley.

At about 800 m water depth, the upper-slope canyon changes to a large single-leveed channel that is 2.4 km wide (between the top of the levees) and 360 ms twt deep (between the channel floor and the top of the levees, measured at about 1200 m water depth). The levees are well developed attesting to significant overbank deposition, and strongly asymmetrical, being higher and wider on the right-hand side looking downstream (Fig. 3). This asymmetry decreases basinward and can be attributed to the Coriolis effect (Wong et al., 1997; Winguth et al., 2000). Beneath 1400 m water depth, the fan morphology is modified by the bifurcation of this single channel; several highly-meandering channels developed as a result of avulsions. The onlap relationships between these channels (Fig. 4 and 5) indicate that only one channel was active at a time. Four main phases of avulsion were identified, each of which is associated with a basal HARP unit basinward of the bifurcation point.

The single middle-slope channel continues as an important morphological feature beneath 1400 m water depth in the southeastward direction (Fig. 2). This channel is considered to represent the initial phase (unit 0) in the evolution of the youngest channel-levee system, since an older phase cannot be clearly identified. It is notably larger than the younger channel-levee units 1 to 4 (up to 700 ms twt high in Fig. 5), implying either that it was active for a much longer time or that depositional rates were significantly higher during this phase. Deposition within the two levees is still asymmetric at 1500 m water depth (Fig. 5). Less data are available from the lower part of this channel-levee unit because of the distribution of the seismic lines. However, the coarse facies that developed at the base of unit 0 (Fig. 3 and 5) continues basinward as a more distal facies visible in Fig. 4.

The first phase of avulsion initiated when the narrower left levee of unit 0 was breached at about 1750 m modern water depth. Turbidity currents followed a new path, spreading laterally in the topographic depression and deposited the HARPs at the base of unit 1 while the old channel 0 was abandoned (Fig. 7a).

The lower boundary of the HARPs of unit 1 is very distinct where it overlies chaotic mass transport deposits (MTD) but is elsewhere hardly distinguishable from the distal facies of unit 0 (Fig. 4).

The upper boundary marks the abrupt change to a more transparent levee facies and is associated with the fast initiation of the channel-levee unit 1. As Pirmez et al. (1997) pointed out, this abrupt facies change occurred when the local topography was sufficiently modified by the deposition of a thick sandy HARP unit and the adjustment of the longitudinal profile of the channel was complete, so that the redistribution of older coarse-grained channel-floor deposits ceased. As levees began to develop and extend down-fan, the sand supply diminished or was channelized.

The channel of unit 1 followed a stable highly-meandering path basinward, with diminishing height and width of its levees, to around 2050 m modern water depth, where the channel became unstable and began to migrate laterally. This distal facies appears in Fig. 6 as a shingled stacking of small channel-levees onlapping one another. The survey area does not extend to the most distal region of the fan. Thus, it is not known whether these channels continued with unchannelized sheet sands as predicted by models for fine-grained, mud-rich turbidite systems (Reading and Richards, 1994; Richards et al., 1998; Bouma, 2000) and demonstrated for certain other large mud-rich fans such as the Mississippi and the Amazon (Stow and Johansson, 2000).

Units 2, 3 and 4 developed after the same pattern (Fig. 7 b, c, d): breaching of the narrower left levee; deposition of a HARP unit by unchannelized flows which are progressively constrained by the topography of the pre-existing channel-levee complexes; and initiation of a new meandering leveed channel. Unit 3 onlaps the steep northeastern levee of unit 0 and is apparently affected by growth faulting close to the breaching point, most probably due to a high sedimentation rate (Fig. 5). The leveed channels in all units but especially in unit 2 are highly meandering and usually follow a stable path to about 1950 m modern water depth; below this depth several bifurcations can be identified (Fig. 6).

Control of sedimentation by the pre-existing topography was the most severe in unit 4. Here, the HARPs are constrained between the steep northern slope and the channel-levee complex of unit

3 and, but also by the high levees of a channel belonging to the Dniepr fan at the distal margin. This results in a very narrow and elongate structure which descends to a much greater depth than the older HARPs, reaching a modern water depth of 2000 m. The HARPs of unit 4 have also at most half the thickness of the other HARPs (between 50 ms twt in its upper part and 25 ms twt at the distal end). This could be related to the mass-transport deposits (MTD) that overlied unit 3 and partially filled up the local topographic depression, so that the complete adjustment of the longitudinal profile was attained faster than in previous HARP units (Fig. 4). At some point the channel that developed above abandoned the path of the HARPs for a more southerly course. As a result, the distal HARP unit is not covered by the usual channel-levee and is visible both on sidescan mosaic (as a highly reflective lobe, see Winguth, 1998) and on chirp profile (as an echo type without penetration). The channel of unit 4 has a highly-meandering course which is easily distinguishable on the sidescan mosaic (Winguth, 1998). Its distal section lies outside of our survey area but several bifurcations can be identified at the southern end of our profiles. Thus, it probably followed the same distal pattern as the older channels.

The uppermost part of the sandy body of HARPs in unit 4 has been sampled in core BLKS 98-20 retrieved from 2001 m water depth (Fig. 8). The presumed HARP sediments in this core consist of a 30 cm thick layer of fine-to-very-fine, generally well-sorted sand containing two levels of mud clasts. Except for slight normal grading, bedding structures are absent. The sand-size fraction (studied in 5 samples) includes mainly quartz particles (48-73 %) and non-organic carbonate (up to 29 %), but also feldspars (9-17 %), micas (5-11 %) and heavy minerals (up to 0.75 %). Occasional occurrences of reworked benthic foraminifers indicate a much shallower sediment source: the foraminifer assemblage is largely dominated by *Ammonia beccarii* (but also includes species of *Elphidium*, *Quinqueloculina* and *Nonion*). In addition, the ostracod specimens characterize a semi-freshwater to brackish basin (mostly the species *Leptocythere* and *Loxoconcha*).

Sand beds containing mud clasts have been described from the HARP units of the Amazon fan as a sedimentary facies related to the erosive ability of these flows (Pirmez et al., 1997; Facies 2 of Normark et al., 1997; Rimington et al., 2000). Levees breached during channel bifurcation are considered the most probable sediment source for the mud clasts. A similar process could be postulated for the sand layer in core BLKS 98-20; however, the short length of the core does not allow verification.

The sand bed underlies only 10 cm of much finer freshwater pelagic gray mud (banded lutite or Unit 3 of Ross and Degens, 1974) and typical marine Holocene pelagic sediments: sapropels and fine coccolith laminae known as Units II and I respectively (Hay et al., 1991; Fig. 8). The best estimate for the age of the beginning of sapropel deposition (base of Unit II) is ca 7500 years BP, while the age of the boundary between Units I and II was determined to be ca 2700 years BP (Jones and Gagnon, 1994).

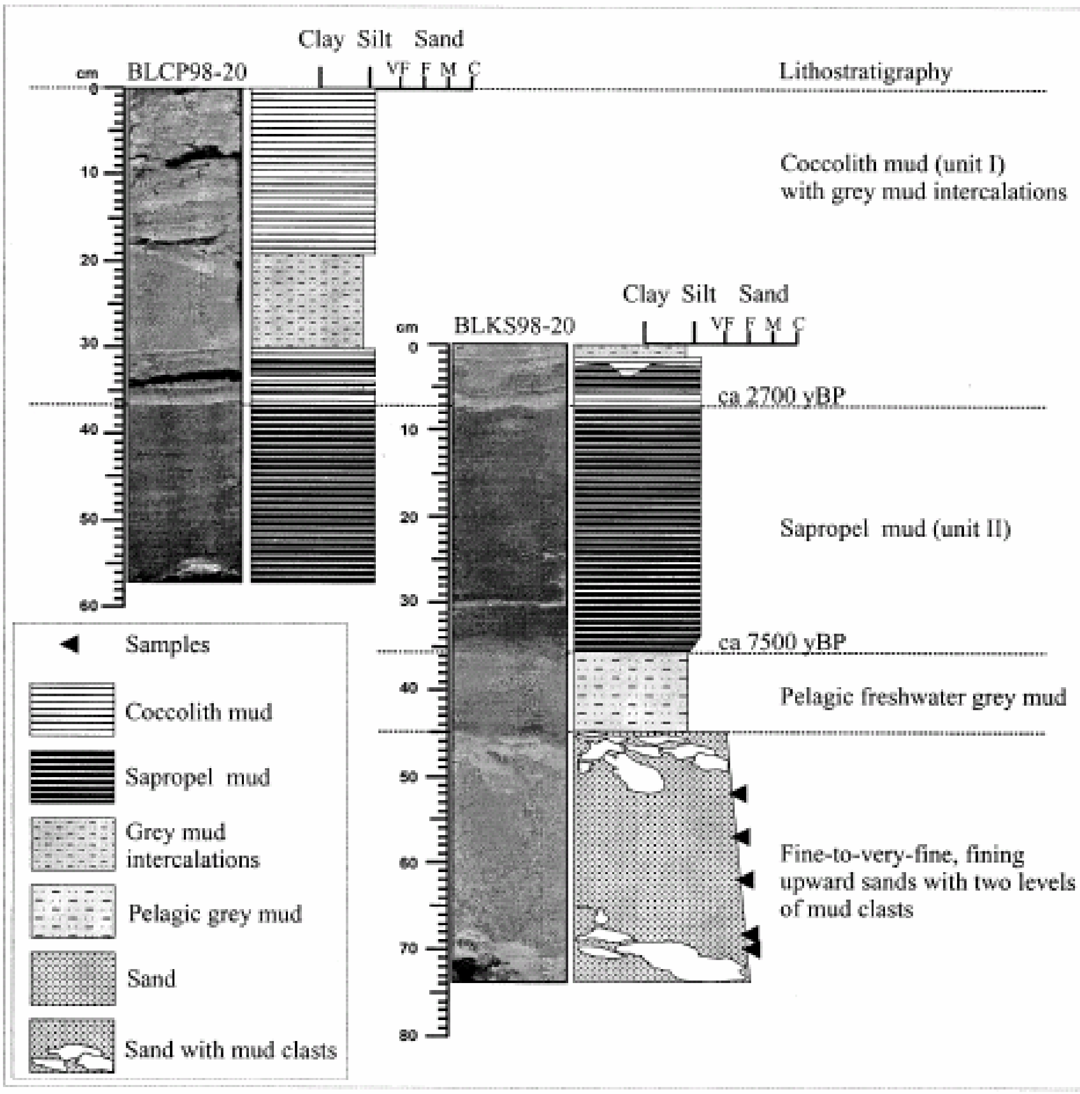

Fig. 8 Photograph and description of core BLKS98-20 and its pilot core BLCP98-20, both located at 2001 m water depth (43° 35.684’ N, 32° 15.781’ E). Correlation between cores is indicated. Radiocarbon ages are from Jones and Gagnon (1994). Two levels of fine grey mud are intercalated within Unit I which is composed of three lithostratigraphic units: a zone of the first invasion of the coccolithophore Emiliania huxleyi, a sapropelic transition and a zone of the final invasion of E. huxleyi (Hay et al., 1991).

5. Conclusions

The youngest channel-levee system on the Danube deep-sea fan developed most probably during the Neoeuxinian lowstand in a semi-freshwater basin with a water level at least 100 m lower than that of today. Sediments supplied by the Danube were transported over the narrow shelf to the deep basin through the Viteaz canyon, which was directly connected to the leveed channel of this system. Distinct HARP units associated with four bifurcations in this channel-levee system have been identified on the middle fan. By analogy with a similar seismic facies of the HARPs on the Amazon fan and as indicated by the sands cored in BLKS98-20, HARP units possibly represent important sand bodies in the mud-rich Danube fan.

A definite relationship exist between water level and Danube fan sedimentation: when water level is close to the shelfbreak during lowstands, fluvial sediments are transported to the deep-sea fan, while fan construction is essentially interrupted during water level highstands. However, several bifurcations developed during a single lowstand (Neoeuxinian - stage 2), so that channel avulsion and sand delivery are not directly related to water level fluctuations; rather, the primary control is autocyclic.

The Coriolis effect, on the other hand, is a factor that strongly influenced channel bifurcation. The right levee looking down-channel is higher (first order influence of the Coriolis force). The four avulsion phases we identified initiated by breaching of the lower and narrower left levee, which resulted in a migration of the active channel towards the left. Therefore, the northward migration pattern of the last channel-levee system is likely to be the result of second order of Coriolis effect.

The location of HARPs and channel-levee units was primarily controlled by the local bathymetry. Deposition was confined to the topographic depression between the high levees of unit 0 (to the south) and the steep relief of the Dniepr fan (to the north). Northward migration progressively constrained the development of HARPs and channel-levees as shown by mapping of the HARPs and the channel of unit 4.

Fan growth in a semi-freshwater basin produced essentially the same basic depositional features as in a marine basin. The seismic and sedimentary facies are similar to those described in most large mud-rich fans, so that the same depositional processes must have been active. Nevertheless, the semi-freshwater environment harbors a greater density contrast to the inflowing river water than a marine environment. This possibly induced the prevalence of hyperpycnal flows, and with it a higher frequency and larger size of turbidity currents. Movement of these flows was under the influence of the Coriolis force. However, the question whether the Coriolis effect on fan deposition was stronger in the semi-freshwater Black Sea compared with a marine environment remain unanswered.

Acknowledgements

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