THE DANUBE AND DNIEPR FANS: MORPHOSTRUCTURE AND EVOLUTION

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Abstract. Two distinct but interfingering fans exist in the northwestern Black Sea: the Danube fan fed by the River Danube during fan accretion, and the Dniepr fan built up by the Ukranian rivers Dniepr, Dniestr and Bug. Within each of these fans, the six upper seismic sequences comprise fan-typical facies associations with pronounced channel-levee systems and levees which pass laterally into overbank deposits. These sequences are separated from each other by condensed sections. Fan accretion proceeds via channelized turbidity flows and mass transport processes, in the course of which avulsion and channel migration commonly occur. Ten acoustic facies subtypes classified into four facies groups have been identified for the youngest sequence. They allow in turn the distribution of channel deposits, coarse- and fine-grained levees as well as various mass transport units to be mapped. Mass transport processes appear to have been more dominant in the Dniepr fan. Morphometric analysis of the channels suggests that the Danube and Dniepr fans are highly sinuous, mud-rich systems which adjust their channel slopes to accomodate the flow volume and sediment load of the turbidity input. The Danube fan has generally a lower valley slope and a higher sinuosity than the Dniepr fan, indicating that its source material is finer. The Danube and Dniepr fans were accreted during the past 480 ka (sequences 3 to 8). Average deposition rates for the fan sequences range from 2.4 to 7.2 m/ka and the volume of material deposited within a sea level cycle lies between 4,300 km³ and 9,590 km³.

Key words: mass transport, condensed section, accretion, acoustic facies, Danube fan, Dniepr fan, Black Sea

INTRODUCTION

The composite Danube and Dniepr deepsea fans constitute a prominent morphological feature in the northwestern Black Sea. These fans extend from the shelfbreak at about 200 m water depth down to the abyssal plain of over 2,000 m and were fed by rivers that drained into this area, notably the Danube, the Dniepr, the Dniestr and the Bug. The morphology of the Danube and Dniepr fans has been studied by Evsyukov & Goncharov (1987) and Shimkus et al. (1987a, b), and their structure by Goncharov et al. (1972). Goncharov et al. (1972) interpreted this morphological feature as the submarine continuation of the folded structures of Dobrogea and of the Moesian platform. The channel incised into its axis was considered a major fracture. The sedimentary nature of this morphological feature was soon established (Degens & Ross, 1974). Kasanzev & Shaynurov (1978) were among the first to recognize the submarine Danube fan complex and they described the morphology and structure of this fan, including the main submarine channel-levee system.

To our knowledge, Malovitsky et al. (1979) published the first high-resolution seismic profile on the Danube and Dniepr deepsea fans. Although numerous multi-channel seismic profiles have also appeared in the literature (Boccaletti & Finetti, 1988; Morgunov et al., 1981; Tugolesov et al., 1985), their resolution is not sufficient for a detailed study of the structure and development of the Danube and Dniepr fans. The most comprehensive recent study is that carried out by scientists from Moscow State University. Using a combination of seismic reflection profiling and sediment sampling, the general morphometry of the Danube and Dniepr fans was mapped and the associated sedimentary facies characterized (Konyukhov & Ivanov, 1989; Konyukhov et al., 1988). The sedimentary complex was divided into four seismo-stratigraphic units (Konyukhov et al., 1988) by means of which the fan development in terms of four overlapping sediment cones was reconstructed (Starovoitov et al., 1990).

During three German-Romanian research cruises in 1992, 1993 and 1994 in the northwestern Black Sea, high-resolution reflection seismic profiles (3,800 km) as well as sidescan (3,140 km long-range, 150 km high-resolution) and pinger (1,850 km) data were collected within the composite Danube and Dniepr deepsea fans and the adjacent continental margin (Fig.1). Preliminary results based exclusively on data of the 1992 cruise have been published (Wong et al., 1994). In this paper, the morphology of this fan complex will be characterized and the distribution

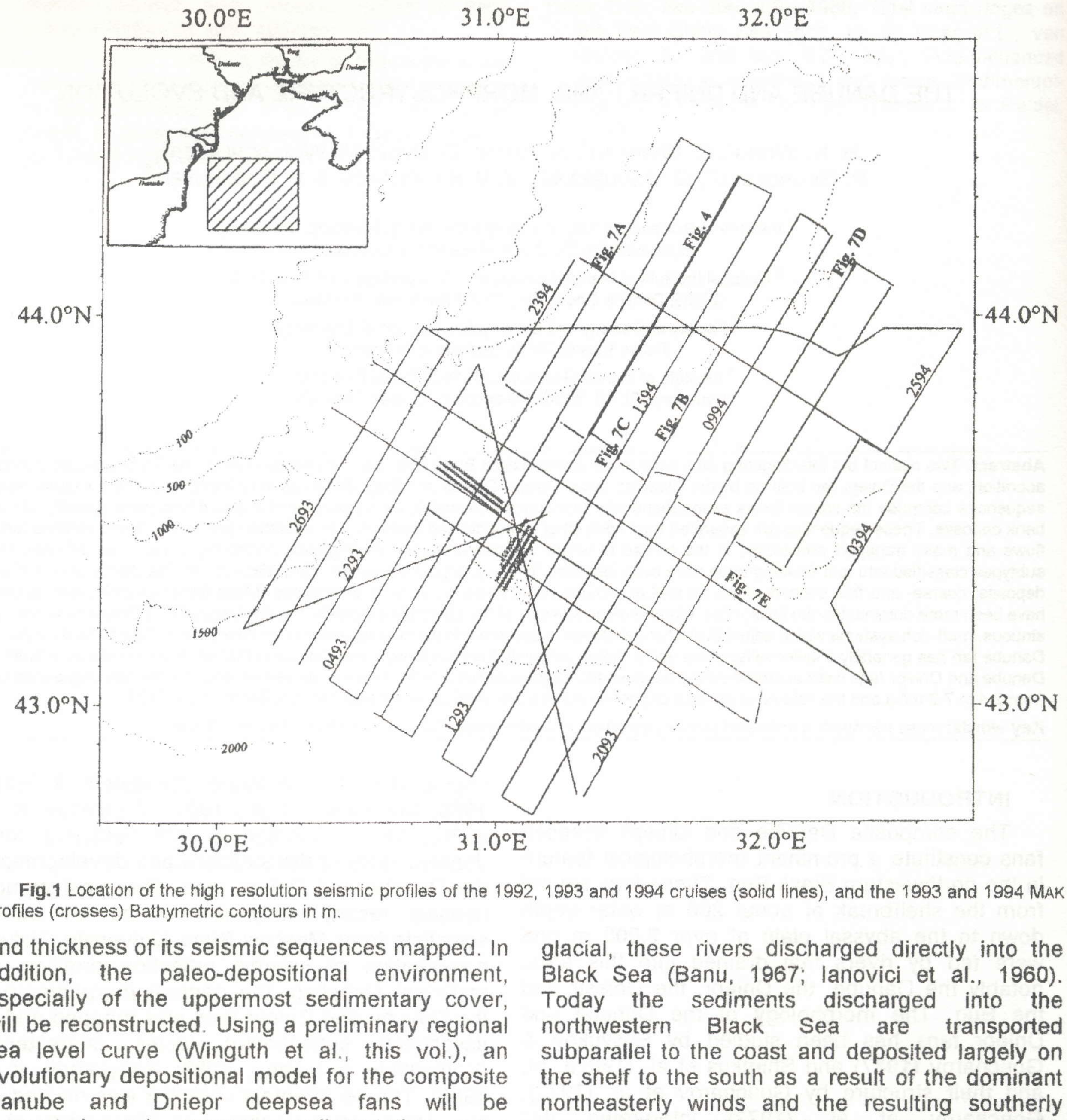

Fig.1 Location of the high resolution seismic profiles of the 1992, 1993 and 1994 cruises (solid lines), and the 1993 and 1994 MAK profiles (crosses) Bathymetric contours in m.

and thickness of its seismic sequences mapped. In addition, the paleo-depositional environment, especially of the uppermost sedimentary cover, will be reconstructed. Using a preliminary regional sea level curve (Winguth et al., this vol.), an evolutionary depositional model for the composite Danube and Dniepr deepsea fans will be presented and average sedimentation rates computed.

MORPHOSTRUCTURE OF THE DANUBE AND DNIEPR FANS

The northwestern Black Sea is characterized by a particularly wide shelf of up to 120 km. It receives an average annual total sediment discharge by the Danube, the Dniestr, the Bug and the Dniepr of 65×10^6 t, of which 81 % (52×10^6 t) is delivered by the Danube (Balkas et al., 1990; Popa, 1992). At present, the Dniestr, the Bug and the Dniepr discharge their sediment loads into a lagoonal system separated from the Black Sea by beach barriers; only a small amount of the suspended load reaches the sea. During the last glacial, these rivers discharged directly into the Black Sea (Banu, 1967; Ianovici et al., 1960). Today the sediments discharged into the northwestern Black Sea are transported subparallel to the coast and deposited largely on the shelf to the south as a result of the dominant northeasterly winds and the resulting southerly currents (Popa, 1992; Shimkus & Trimonis, 1974; Zenkovitch, 1966). During sea level lowstands, however, they must have been channelized by the Viteaz and other canyons and laid down mainly beyond the shelfedge to form a deepsea fan complex.

Fan morphology

The present-day composite Danube and Dniepr deepsea fans are bounded to the northwest approximately by the shelfbreak at about 200 m water depth. To the southeast, they grade into the abyssal Black Sea at water depths of around 2,200 m, thus extending about 150 km in both the NW-SE and the NE-SW directions (Fig.2).

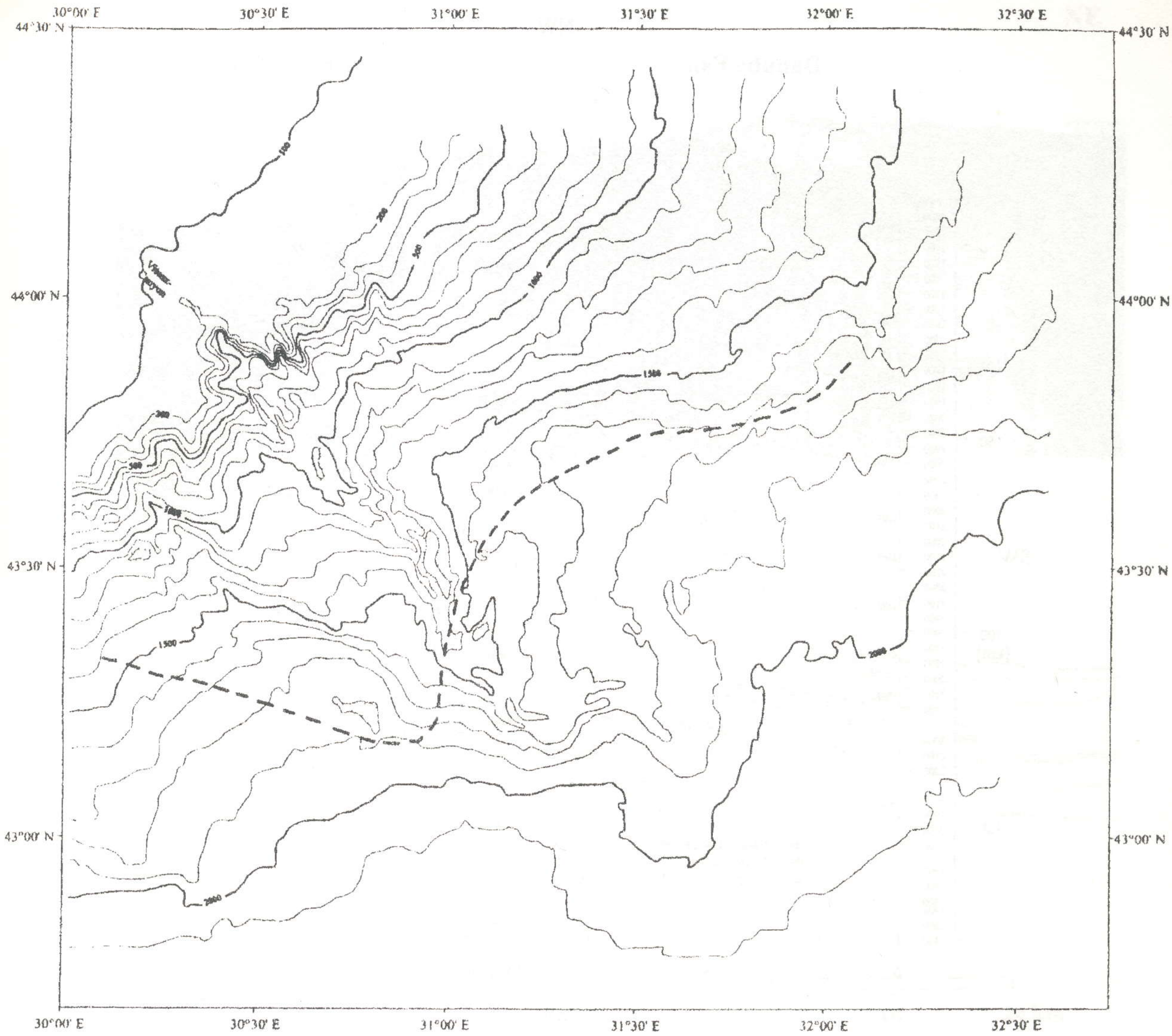

Fig.2 Bathymetric map of the Danube and Dniepr fans based on our depth data and data from Russian charts (Charts 32117 (1966), 32118 (1977), 32124 (1980) of the Principal Office for Navigation and Oceanography of the Soviet Defence Ministry, scale 1:200,000). Dashed line shows the approximate boundary between the upper and middle fans.

Two distinct but interfingering fans can be recognized within this deepsea fan complex. The southern fan (here named the Danube fan) is supplied by the Danube, while bathymetric (Figs. 2 and 3) and our reflection seismic data suggest that the northern fan (the Dniepr fan) was built up by the Dniepr, the Dniestr and the Bug during sea level lowstands when a large part of the continental shelf in the northwestern Black Sea was subaerially exposed.

Seismic sequences and seismic facies

Eight seismic sequences have been recognized within the Danube and Dniepr fans. They are numbered 1 to 8 from old to young (Fig.4). Each of the six upper sequences consists typically of channel-levee systems, overbank sediments and mass transport deposits (such as slumps, slides and debris flows) which comprise the lowstand systems tracts (LST) of a sea level cycle. The sequence boundaries are marked by parallel reflections with good continuity. In the sequences 2 and 1, however, pronounced channel-levee systems are absent; a major part of the deposits consists of mass transport units.

Characteristics of the seismic facies of the sedimentary units are shown in Tab.1. Channels are the pathways for turbidity currents which bring the bulk of the sediments into the deepsea. Our seismic profiles show that many channel-levee systems consist of two or more, sometimes nested, channels. Most channels consist of subparallel to subarcuate highly reflective horizons (high amplitude reflectors = HAR; Weimer, 1990,

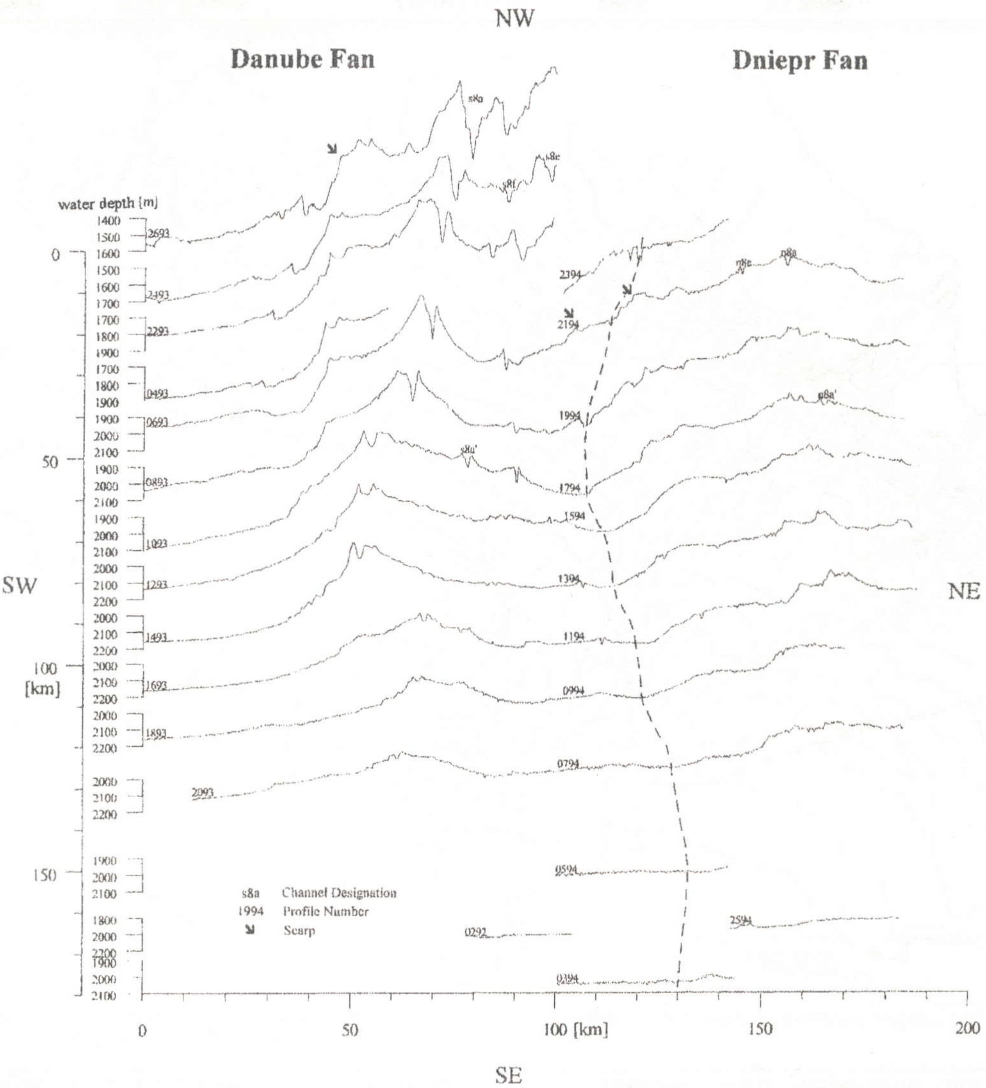

Fig.3 Bathymetric profiles from the cruises of 1993 and 1994 arranged downfan. Arrows show morphological scarps due to buried channel systems.

1991; Weimer & Buffler, 1988; Fig.4). Drilling of the youngest channel floor on the Mississippi fan (Stelting et al., 1985) and of a buried channel on the Amazon fan (Flood et al., 1995, sites 934, 943 and 945) suggests that these high amplitude reflectors are typically associated with sand and gravel in the channel thalweg. The overlying late channel fills (LCF, Fig.4) are finer-grained and are represented by low amplitude, parallel to divergent reflectors with poor to moderate continuity. Studies of the Indus (Kolla & Coumes, 1987), the Amazon (Flood et al., 1995), the Niger (Cochonat et al., 1993) and many other fans suggest that these units consist of homogeneous, fine-grained sediments deposited during the waning stage of turbidity current episodes or during sea level highstands. The uppermost continuous reflectors in the channels represents overbank deposition from neighbouring channels and/or hemipelagic deposition subsequent to the end of turbidity current activity.

The adjacent levees (L, Fig.4) which form the channel margins are characterized by their external wedge shape and subparallel reflectors with low amplitude and moderate continuity. Their semi-transparent to transparent appearance suggests fine-grained, homogeneous deposits. The modern levees show a marked asymmetry with the right hand (southwestern) levee looking downstream standing higher than the left hand (northeastern) levee. This is a result of the Coriolis force, as was reported among others from the Indus (Kolla & Coumes, 1987) and the Mississippi fans (Kastens & Shor, 1985). Laterally the levees grade into overbank deposits which are represented by continuous, subparallel, semi-transparent to moderately strong reflectors. Their external shape is drape-like. These overbank

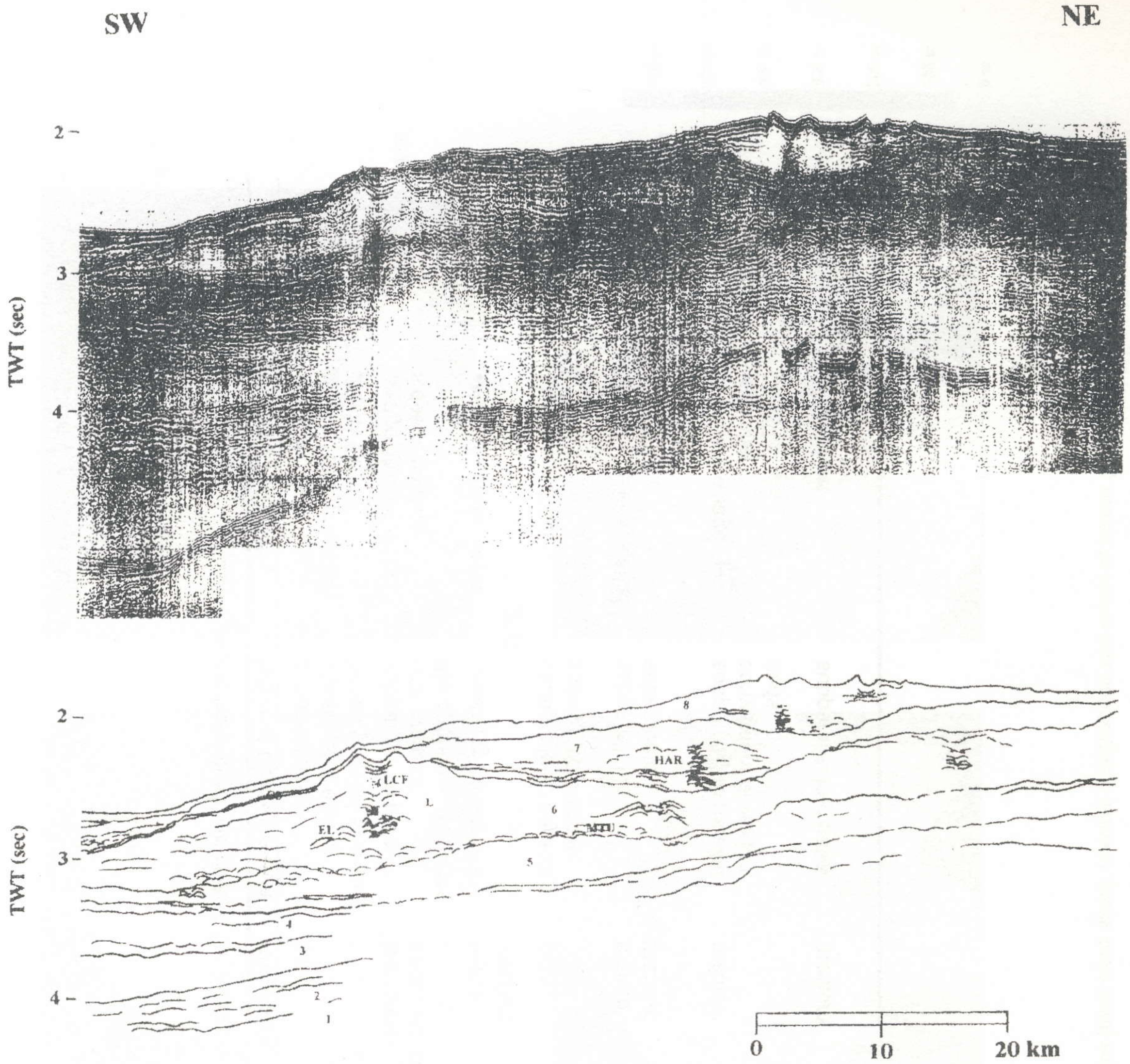

Fig.4 Air gun profile 1794 (original and interpretation). Profile location shown in Fig.1. HAR = high amplitude reflectors, LCF = late channel fill, L = levee, EL = early levee, MTU = mass transport unit, CS = condensed section, 1...8 = sequence numbers.

deposits consist of intercalations of silt and clay, and originate from turbidity currents which overflow the channel walls to flood the adjacent plains. The nascent or early levees (EL, Fig.4) are coarse-grained and limited in extent. As they grow and coalesce, they become finer-grained and therefore seismically more transparent, grading continuously into overbank deposits at greater distances from the channels.

Mounded, hummocky, chaotic or subparallel reflections are characteristic of mass transport units (MTU, Fig.4) that accompany erosion of the condensed sections. They occur as unchannelized slumps, slides, debris flows or turbidites.

The parallel continuous reflectors with moderate to high amplitude which separate the seismic sequences are interpreted as thin condensed sections (CS, Fig.4) of hemipelagic material. They are deposited at very low sedimentation rates (Loutit et al., 1988) during periods of rising and high sea level and therefore comprise the transgressive and highstand systems tracts (TST and HST).

For ease of description, the channels are numbered according to the sequences in which they occur. Different channels within a sequence are differentiated from one another in ascending estimated relative age by a letter in rising alphabetic order (the youngest main channel is 8a). Channels of the Dniepr fan are designated n and of the Danube fan s (the most recent main channel of the Danube fan is thus s8a). A trailing - mark denotes a channel continuation after avulsion.

Table 1 Seismic facies of the sediments in the Danube and Dniepr fans.

	External Geometry	Internal Configuration	Amplitude	Continuity	Remarks
a) channel	valley incised into bottom; with or without clastic fill	subparallel to subarcuate (esp. in buried channel systems)	high	medium	lateral extent highly variable
b) levees	wedge-shaped on both sides of channel	subparallel to parallel with irregular, discontinuous reflectors	low (semi-transparent)	low	lateral extent highly variable
c) hemipelagic deposits	wedge to drape sheet	parallel to convergent	high to medium	high	often beneath levees
	1) drape sheet	subparallel to parallel, sometimes complex	high	high	beneath levees or hemi-pelagic deposits
d) mass wasting deposits	2) wedge or irregular	subparallel to subarcuate	high to medium	medium	mostly adjacent to channel-levee systems
	3) double-wedged or lenticular	subparallel to parallel, convergent at wedge ends	medium	medium to high	superposed on other sediment bodies
e) overbank deposits	drape sheet	subparallel to parallel	medium	medium to high	adjacent to levees

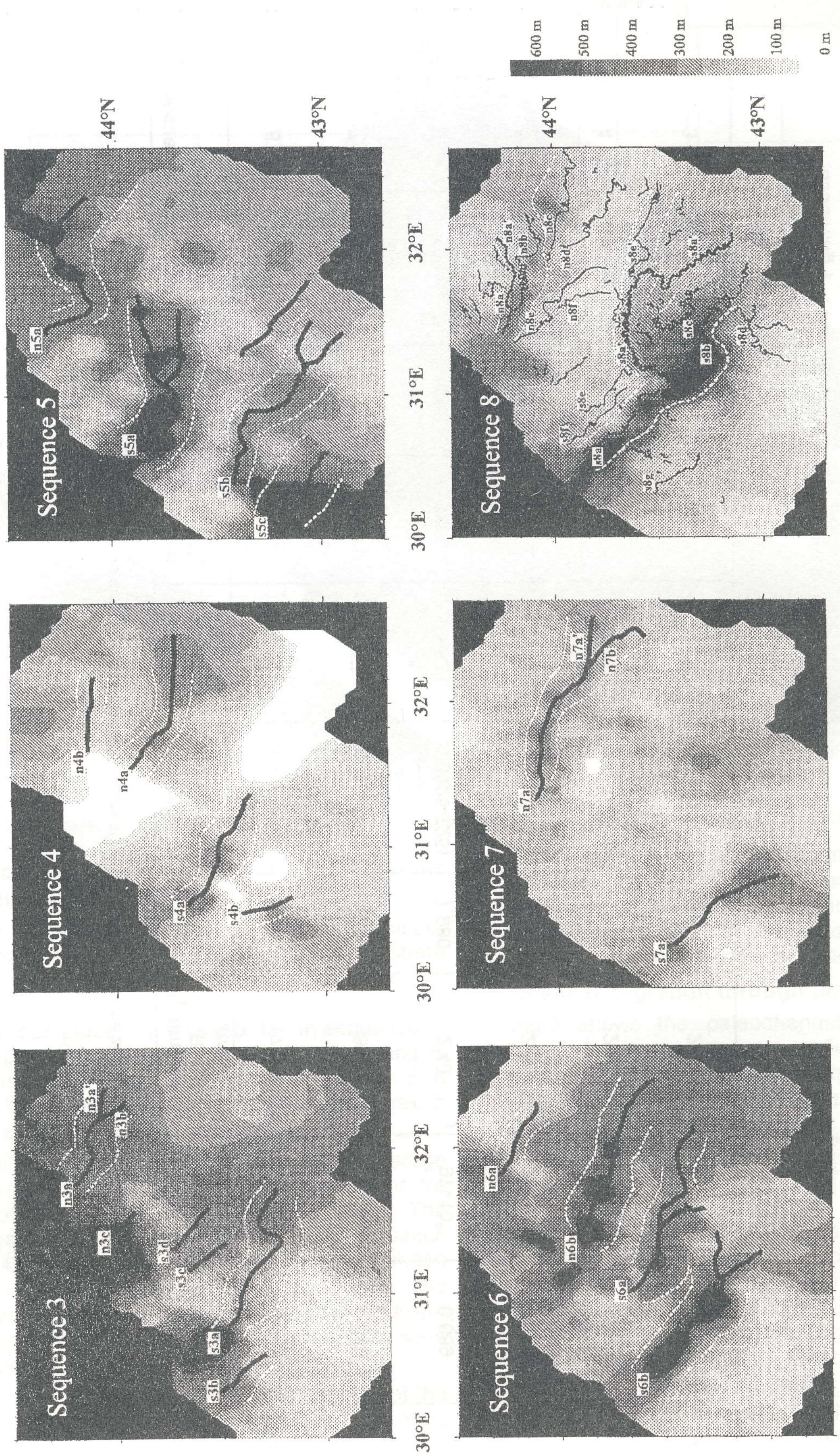

Fig.5 Thickness distribution, location of major channel systems (thick black lines), channel designations and extent of levees (dashed white lines) of sequence 3 to 8.

Table 2 Computed thicknesses, volumes and sedimentation rates of the sequences, Danube and Dniepr fans.

Sequence	Age (ka BP)	Duration (ka)	Thickness (ms TWT)	Interval Velocity* (km/s)	Thickness (m) (min.-max.)	Volume§ (km³)	Sedimentation Rate (m/ka)	Sed. Accum. Rate (t/a)	Sed. Accum. Rate# (km³/a)
8	0-ca. 25	25	205	1.75	180 (0-655)	5,400	7.20	302×10^6	0.216
7	ca. 75-ca. 25	50	190	1.77	170 (0-390)	4,300	3.40	120×10^6	0.086
6	ca. 190-ca. 75	115	325	1.82	300 (25-725)	7,980	2.40	97×10^6	0.069
5	ca. 320-ca. 190	130	320	1.96	310 (100-800)	8,280	2.45	88×10^6	0.063
4	ca.400-ca. 320	80	175	2.17	190 (0-540)	4,810	2.50	88×10^6	0.060
3	ca. 480-ca. 400	80	285	2.38	340 (60-890)	9,590	2.55	168×10^6	0.120

* from Romanian industrial profiles
§ within the study area
# assuming γ=1400 kg/m³

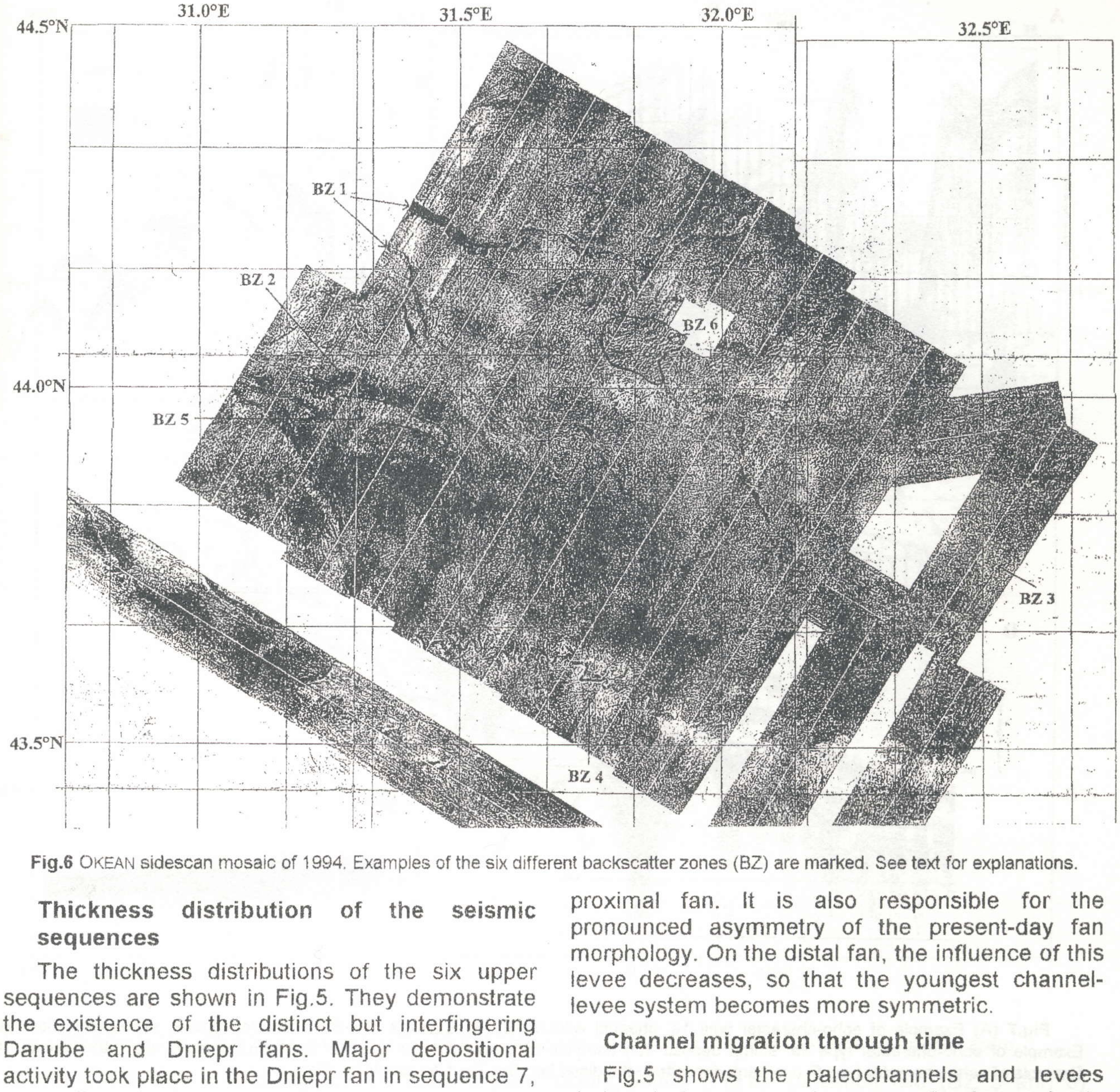

Fig.6 OKEAN sidescan mosaic of 1994. Examples of the six different backscatter zones (BZ) are marked. See text for explanations.

Thickness distribution of the seismic sequences

The thickness distributions of the six upper sequences are shown in Fig.5. They demonstrate the existence of the distinct but interfingering Danube and Dniepr fans. Major depositional activity took place in the Dniepr fan in sequence 7, in the Danube fan in sequences 3 and 4, and is otherwise evenly distributed in the sequences 5, 6 and 8. The levees (marked by dashed lines) reach widths of the order of 30 to 60 km.

Minimum and maximum thicknesses, average thickness and volume have been computed for each of the six upper sequences (Tab.2). The average thickness ranges from 170 m (sequence 7) to 340 m (sequence 3), the volumes from 4,300 km^3 (sequence 7) to 9,590 km^3 (sequence 3). The depocenters were displaced in a landward direction from sequence 3 to 5 and in a basinward direction from sequence 5 to 6.

The channel-levee system of sequence 6 of the Danube fan is barely buried today. The crest of its southwestern levee can still be traced on the present-day seafloor as a scarp, especially in the proximal fan. It is also responsible for the pronounced asymmetry of the present-day fan morphology. On the distal fan, the influence of this levee decreases, so that the youngest channel-levee system becomes more symmetric.

Channel migration through time

Fig.5 shows the paleochannels and levees deduced from our air gun reflection seismic profiles for sequences 3-7. For sequence 8, long-range sidescan and pinger data permit a much more detailed reconstruction. It is assumed that only one main channel has been active for the Danube and Dniepr fans respectively at any given time.

For the Dniepr fan, channel displacement has taken place in a northeastern direction within sequence 3 (from *n3c* to *n3a/n3a'/n3b*), with bifurcation of channel *n3a* into *n3a'* and *n3b* at 44.1° N, 32.3° E (Fig.5). This channel migration may be attributed to channel breaching, or to the activation or clogging of delta arms. Within sequence 4, the corresponding displacement is to the south. For sequence 5, only one major channel-levee system existed which, relative to

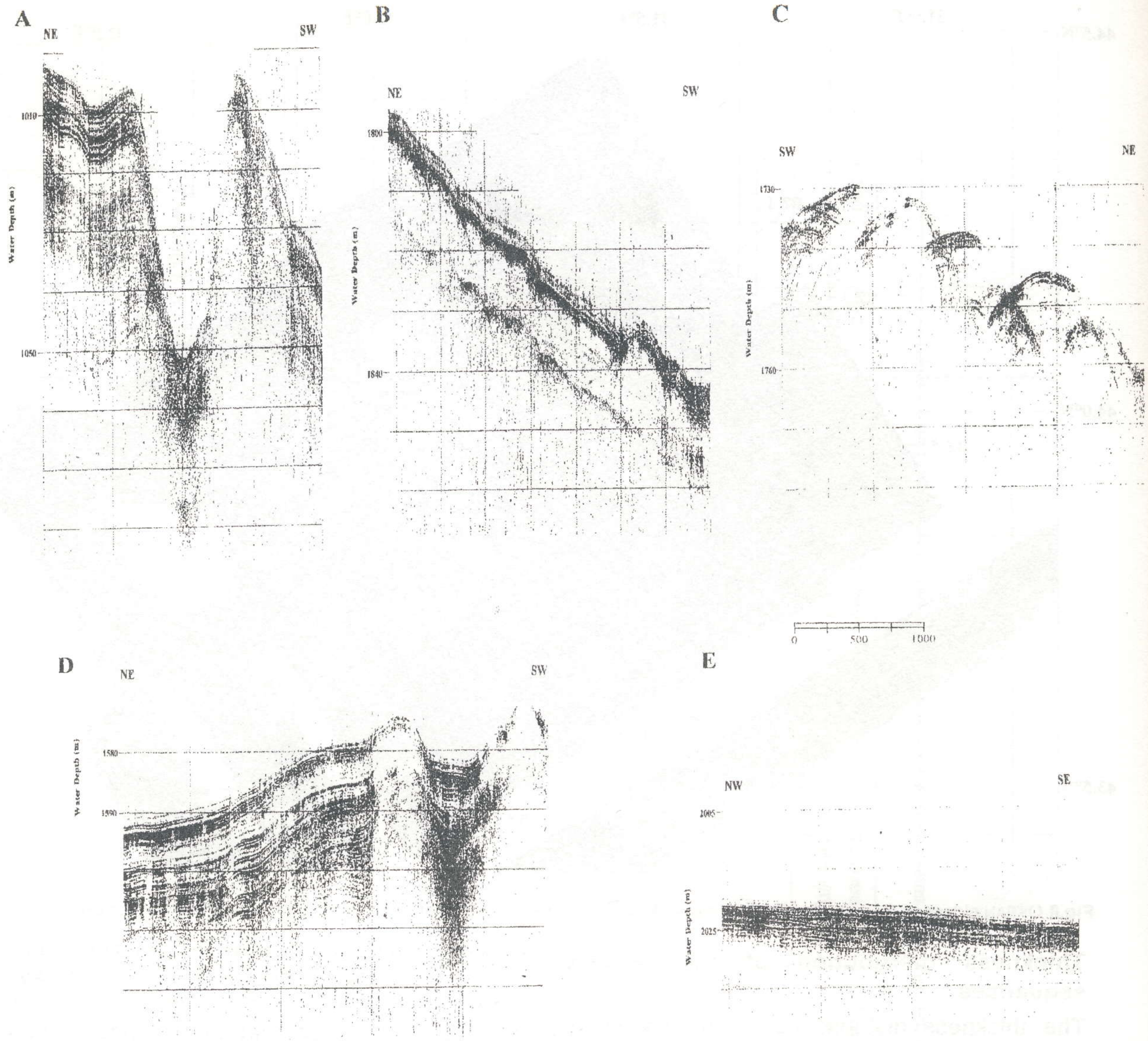

Fig.7 (A) Example of echo-character type 1a: channel without fill. (B) Example of echo-character type 2: slide/debris flow. (C) Example of echo-character type 3a: slump deposit. (D) Example of echo-character type 4a: levee and channel with stratified fill. (E) Example of echo-character type 5: overbank deposits in the distal fan. See Fig.1 for profile location.

sequence 4, has migrated to the north (Fig.5). In sequence 6, two large channel-levee systems again occur. The younger, less-developed system *n6a* is displaced to the north relative to the older systen *n6b* (Fig.5). Within sequence 7, there is only one major system with bifurcated channels located between *n6a* and *n6b*, filling the topographic low between them.

For the Danube fan, the age relationship among the channels *s3b*, *s3c* and *s3d* of sequence 3 is speculative (Fig.5). The channel-levee system *s4a* of sequence 4 has migrated northeastward relative to those of sequence 3. Sequence 5 contains three pronounced channel-levee systems which become progressively younger from southwest to northeast (Fig.5). The older systems *s5b* and *s5a* exhibit channel bifurcation, while the youngest channel (*s5a*) has migrated to the north relative to the channels of sequence 4 (Fig.5). Two large, bifurcated channel-levee sytems occur in sequence 6, while only one relatively small system has been mapped within sequence 7. The latter has migrated southward with respect to the channels of sequence 6 (Fig.5).

The fact that the Danube and Dniepr fans remained in the same positions throughout fan accretion except for minor, paleo-bathymetrically-controlled channel migrations suggests that the rivers responsible for their construction maintained largely the same courses during that time. An exception may be sequence 5. It has been speculated that during parts of the middle-upper Pleistocene, the Danube flowed through the Karasu valley between Cernavoda and Constanza

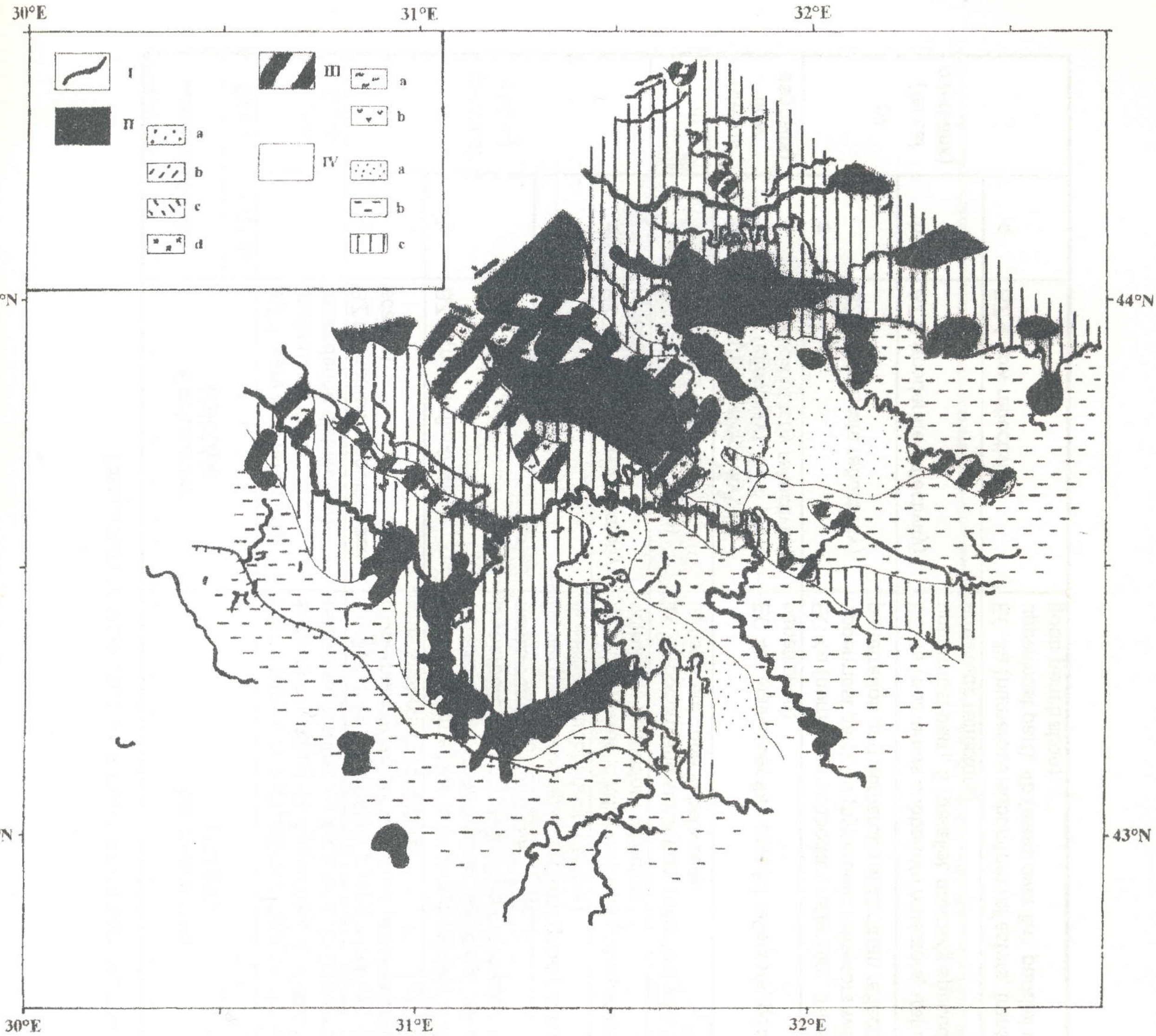

Fig.8 Surficial acoustic facies map of the Danube and Dniepr fans. See text for explanations. Barbed line marks a scarp.

into the Black Sea and changed its course to the north possibly in the Holocene (Pfannenstiel, 1950). Perhaps this former river course is represented in sequence 5 by its southwesternmost channel system.

SEISMIC CHARACTERISTICS OF THE UPPERMOST SEQUENCE

Backscatter facies types (long-range sidescan data)

The sidescan mosaic derived from surface-towed, long-range sidescan data of the Okean system is characterized by large variations in backscatter intensity from poorly (light) to highly (dark) backscattering (low to high bottom reflectivities). Six backscatter zones (BZ) with differing backscattering strengths have been distinguished (Fig.6), of which two (BZ 5 and 6) exhibit in addition specific surface patterns:

- BZ 1 has a very high reflectivity and shows a continuous, linear, meandering distribution. It corresponds to the channel floors.
- BZ 2 shows a high backscattering strength. It is confined to the proximal part of the Danube fan and of the area between the Danube and the Dniepr fans.
- BZ 3 has a moderate backscatter intensity and is widely distributed, especially in the southern half of the study area
- BZ 4 is characterized by low backscattering intensities and flanks the main channel

Table 3 Acoustic facies types of the uppermost sequence and their interpretation.

Acoustic Facies		Backscatter (OKEAN)	Echo Character (Pinger)	Core	Sedimentary Processes and Depositional Environments
Group	Subtype				
I (channel floor)		BZ 1 (very high reflectivity, continuous, linear, meandering distribution)	EC 1a (single distinct bottom reflector); 1b (bottom and subbottom reflectors); 4a (numerous subbottom reflectors, sometimes transparent in uppermost part)	-	channel floor with or without fill
II (slumps/ slides)	a	BZ 6 (mottled irregular back-scatter)	EC 3b (small hyperbolae, low penetration); 4c (hyperbolic reflectors with good penetration and numerous subbottom reflectors)	-	slumps and slides at continental slope of the Dniepr fan, with rugged upper surface
	b	BZ 2 (high reflectivity)	EC 3a (intermediate to large hyperbolae, subbottom reflectors); 3b (small hyperbolae, low penetration); 4c (hyperbolic reflectors with good penetration and numerous subbottom reflectors)	-	slumps and slides at the continental slope with smoother upper surface than IIa
	c	BZ 4 (low reflectivity)	EC 4c (hyperbolic reflectors with good penetration and numerous subbottom reflectors)	-	sediment slides adjacent to or over levees
	d	BZ 5 (heterogeneous patchy reflectivity)	EC 4c (hyperbolic reflectors with good penetration and numerous subbottom reflectors)	-	sediment slides in the upper Dniepr fan
III (debris flow deposits)	a	BZ 2 (high reflectivity); BZ 3 (moderate reflectivity)	EC 2 (bottom and subbottom reflectors with semi-transparent zone in between)	-	debris flow in proximal part of channel-levee system
	b	BZ 2 (high reflectivity); BZ 4 (low reflectivity); BZ 5 (heterogeneous patchy reflectivity)	EC 4b (wavy over flat, parallel reflectors, good penetration)	1/ 1994	small debris flows or sediment slides over or adjacent to levees
IV (levee/ overbank)	a	BZ 3 (moderate reflectivity)	EC 4a (numerous subbottom reflectors, transparent in uppermost part); 4c (hyperbolic reflectors with good penetration and numerous subbottom reflectors)	2/ 1994	coarser grained levees in the upper fan
	b	BZ 3 (moderate reflectivity)	EC 4a (numerous subbottom reflectors, transparent in uppermost part); 5 (parallel, narrowly spaced high amplitude reflectors)	-	fine-grained levee or overbank deposits in the distal fan
	c	BZ 4 (low reflectivity)	EC 4a (numerous subbottom reflectors, transparent in uppermost part); 4b (wavy over flat, parallel reflectors, good penetration)	S24/ 1992	levees and fine-grained channel overflow between channel-levee systems

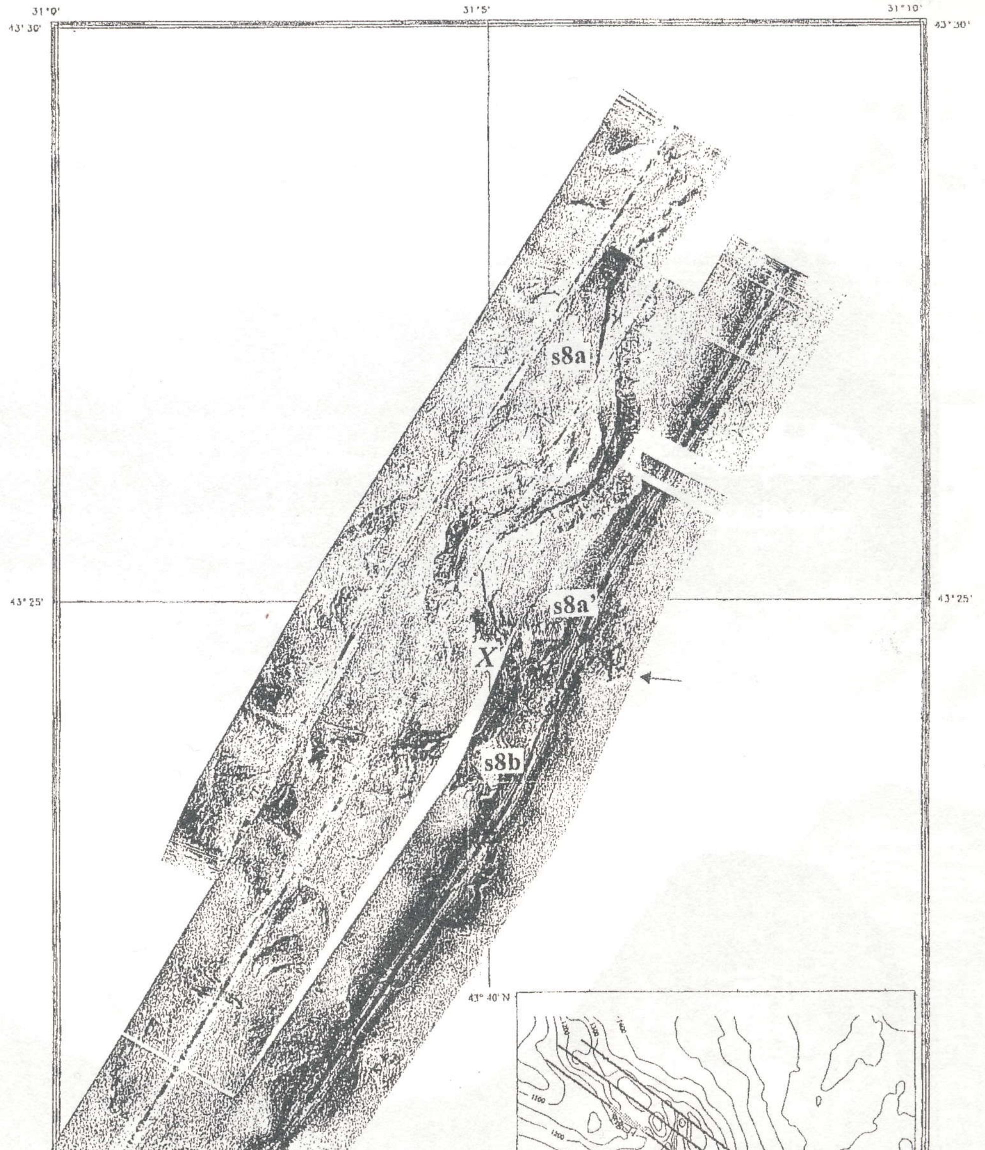

Fig.9 Mosaic of the high resolution MAK sidescan profiles 293, 393 and 493. Channels *s8a*, *s8a'* and *s8b* and the channel bifurcation point *X* are marked. Arrow indicates a crevasse splay. Bathymetric contours in m.

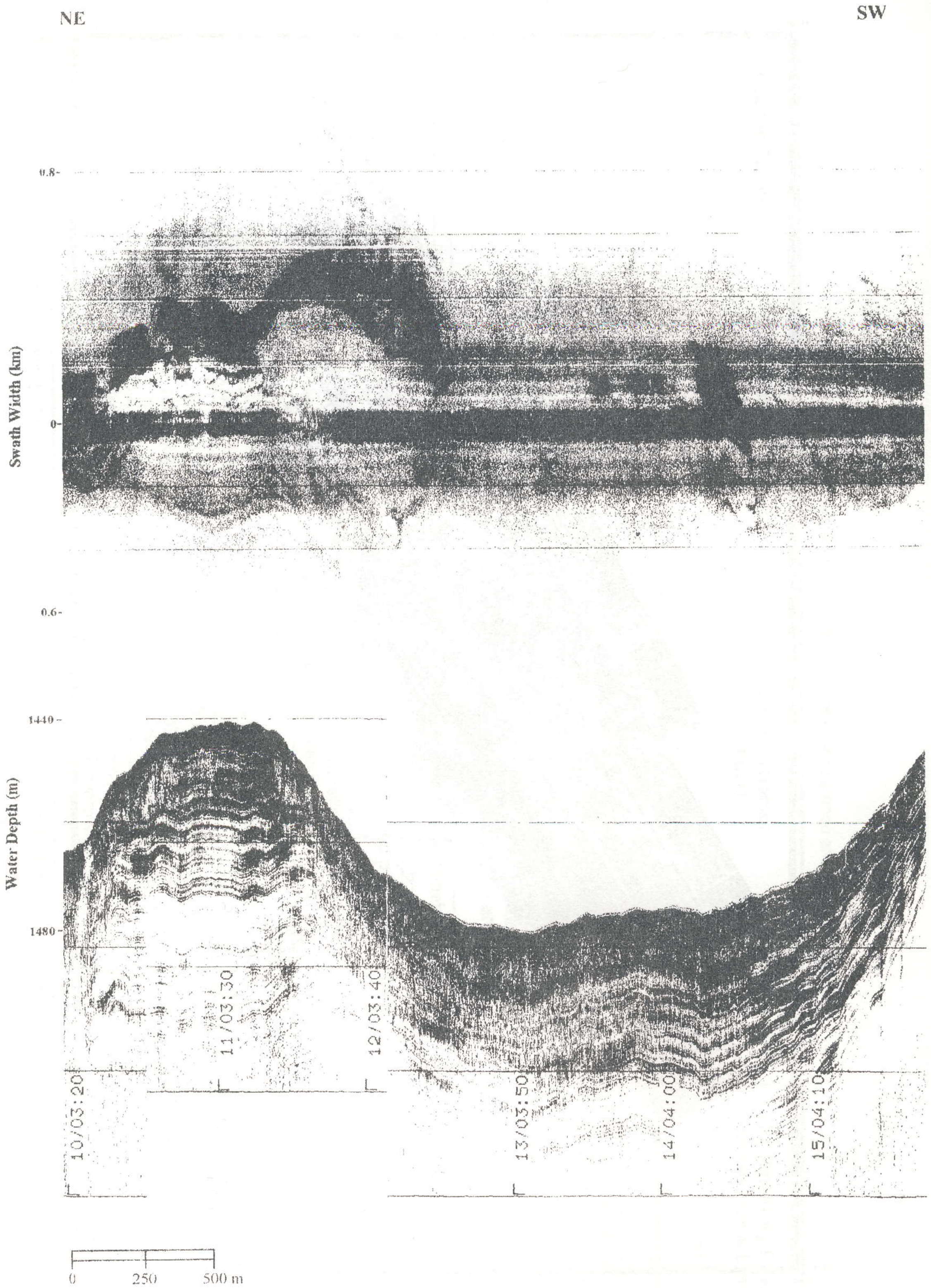

Fig.10 Part of MAK profile 293 (sidescan and pinger) showing channel *s8b* which is has a thick incised valley fill. See Fig.9 for profile location.

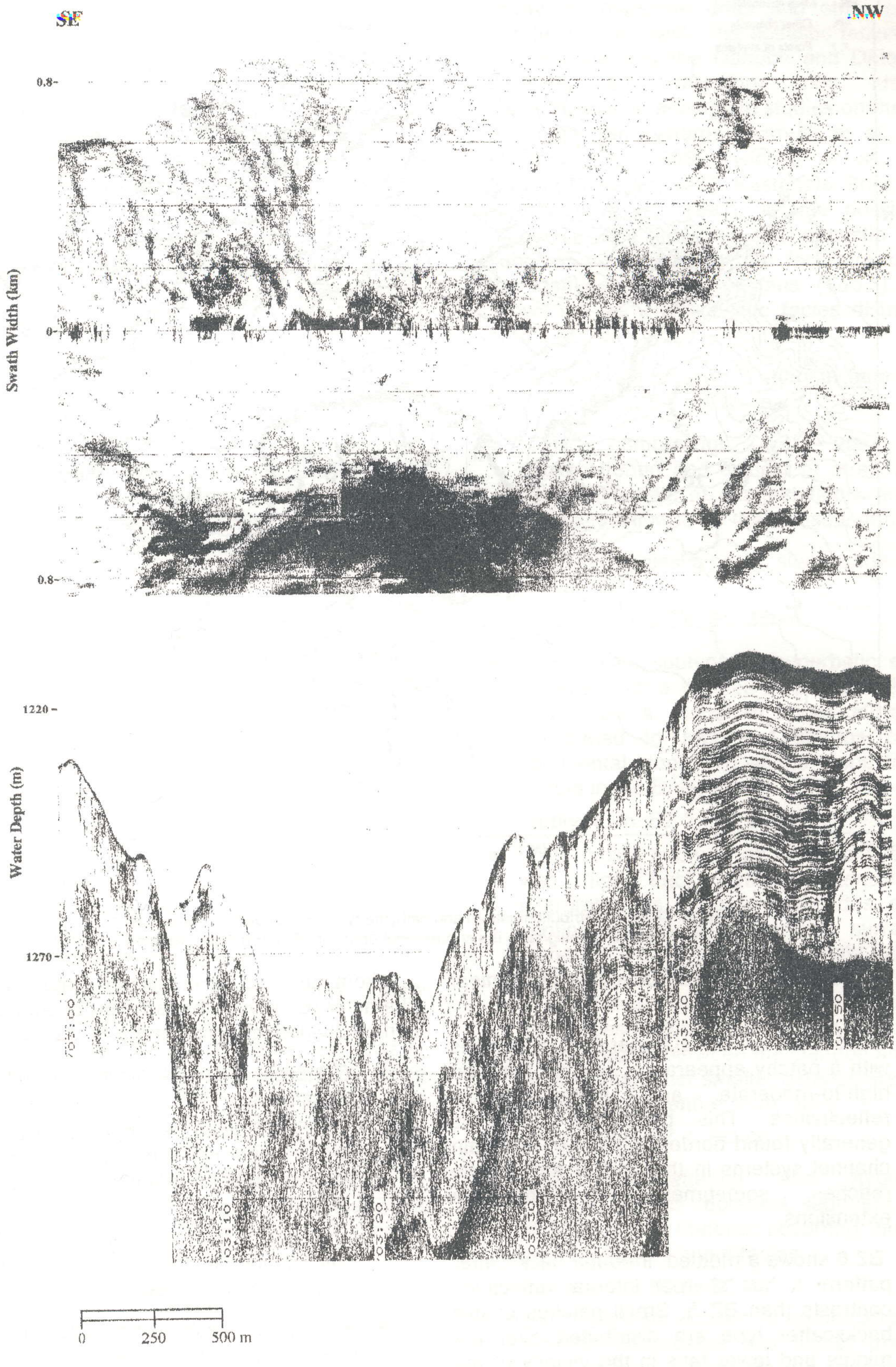

Fig.11 Part of MAK profile 294 (sidescan and pinger) showing stratified, cyclic levee sediments. See Fig.9 for profile location.

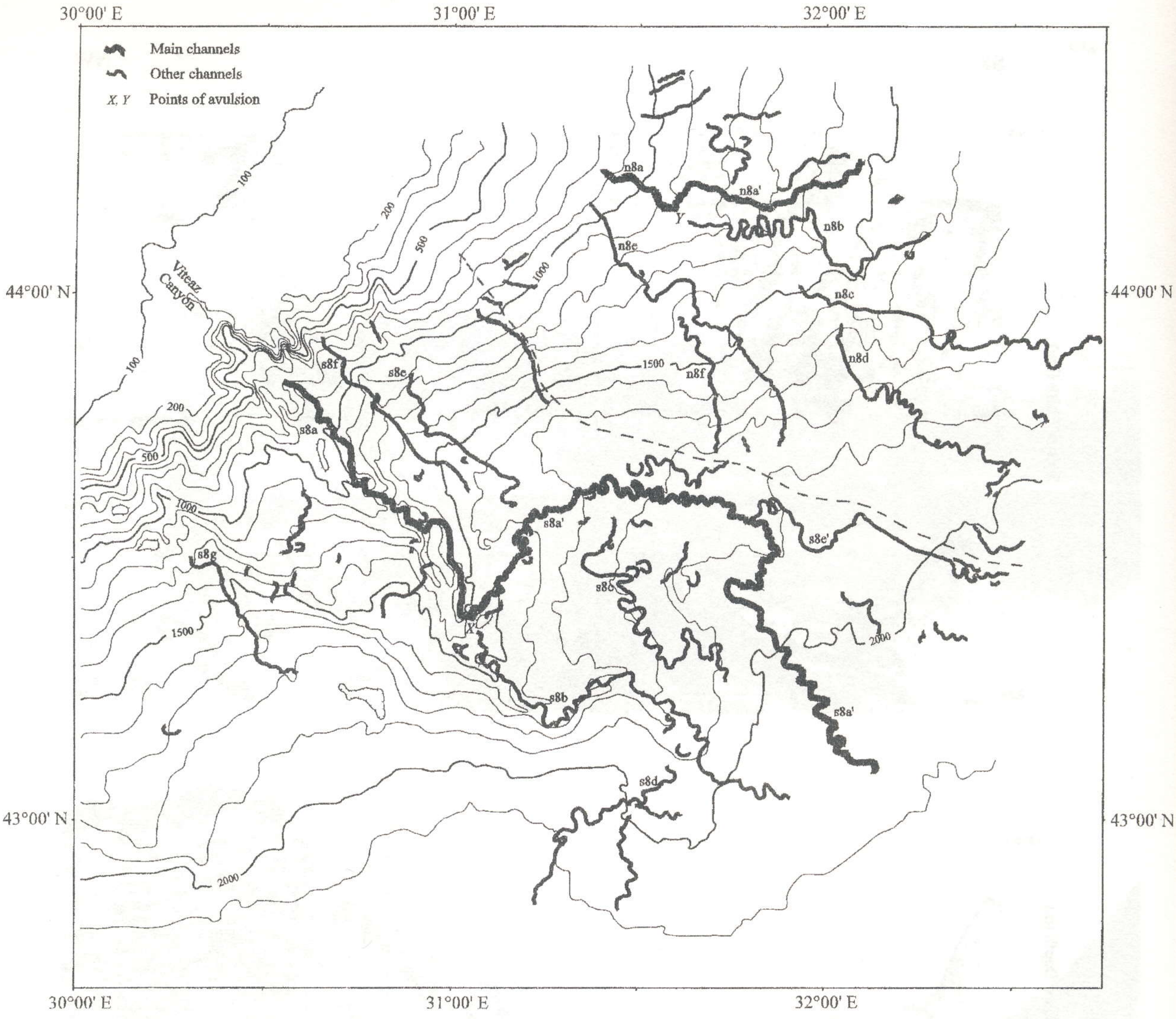

Fig.12 Channel distribution pattern and bathymetry of the Danube and Dniepr fans.
The dashed line designates the approximate boundary between these two fans.

systems of both the Danube and Dniepr fans.

- BZ 5 is a zone of heterogeneous reflections with a patchy appearance, varying between high-to-moderate and moderate-to-low reflectivities. This backscatter zone is generally found bordering parts of the main channel systems in their upper and middle reaches, sometimes with finger-like extensions.

- BZ 6 shows a mottled, irregular backscatter pattern. It has sharper internal reflectivity contrasts than BZ 5. Small patches of this backscatter type are distributed over the middle and lower fans in the vicinity of the main channel systems.

Echo character types (pinger data)

From the 3.5 kHz pinger data, five echo character (EC) types have been recognized. They can be divided into echo character subtypes:

- EC type 1 shows strong distinct bottom reflectors

  subtype a: with prolongation of the bottom echo, but no subbottom reflectors. It corresponds to channel floors without infill (Fig.7);

  subtype b: without echo prolongation, but with subbottom reflectors. It occurs in the inner channel slopes.

- EC type 2 consists of a bottom reflector, a semi-transparent zone and subbottom reflectors. This EC type generally accompanies the upper reaches of the channels of the Danube fan as well as the area between the Danube and Dniepr fans (Fig.7).

- EC type 3 consists of hyperbolic echos

  subtype a: of intermediate to large sizes, with subbotom reflectors beneath a transparent zone. This subtype is distributed in small patches over the Danube fan, often in the vicinity of meandering channels (Fig.7);

  subtype b: that are small. Subbottom reflectors are lacking and penetration is low. It occurs in small patches in the Dniepr fan and in the area between the Danube and Dniepr fans.

- EC type 4 is characterized by high penetration and very good resolution with numerous continuous, parallel to subparallel, subbottom reflectors:

  subtype a: the uppermost subbottom is sometimes transparent and the surface sometimes wavy. This EC subtype flanks the main channel system of the Dniepr fan and occurs within filled channels (Fig.7);

  subtype b: comprises a set of wavy reflectors over flat, parallel echoes. It occurs between the Danube and Dniepr fans; and

  subtype c: consists of hyperbolae with varying apex elevations, sometimes with a slightly diffuse appearance in the upper subbottom. It occurs between the Danube and Dniepr fans.

- EC type 5 is characterized by numerous high frequency, high amplitude, parallel reflectors conformal to the bottom (Fig.7). Penetration is about half of that of EC type 4. It is widespread in the lower fan.

Acoustic facies types and their interpretations

In a detailed study of the Zaire fan, Droz et al. (1996) combined their echo character types with the observed backscatter zones into acoustic facies groups and reconstructed the depositional environment of each facies. The Zaire fan, however, is still active despite the present sea level highstand; the Zaire submarine canyon extends landwards across the narrow continental shelf into the river estuary and serves as an immediate pathway to the deepsea for the sediments brought in by the Zaire River. In contrast, the Danube and Dniepr fans, like the Amazon, the Mississippi and numerous other fans (e.g., Damuth *et al.*, 1988; Flood *et al.*, 1995; Twichell *et al.*, 1992) is presently inactive. The fluvial sediments are trapped on the inner shelf or are transported away by longshore drifts and other currents parallel to the coast. The acoustic facies types of the Zaire and the Danube and Dniepr fan systems are therefore not identical. Nevertheless, in analogy to studies on the Zaire and other fan systems (Damuth *et al.*, 1988; Flood *et al.*, 1995; Twichell *et al.*, 1992; Damuth & Hayes, 1977; Kastens & Shor, 1985; O'Connell *et al.*, 1991), it was possible to recognize and interpret ten acoustic facies subtypes classified into four facies groups for the Danube and Dniepr fans (Tab.3). Fig.8 shows the surficial acoustic facies distribution of these fans.

- Acoustic facies type I: channel floor facies group BZ 1, EC 1a/1b/4a
- This combination of very high backscattering and distinct or stratified EC is characteristic of channel floors and can be easily followed on the sidescan mosaic.
- Acoustic facies type II: slump/slide facies group

⇒ subtype IIa: BZ 6, EC 3b/4c

- This facies subtype of hyperbolic echoes together with a mottled backscatter pattern and often a distorted upper surface is interpreted to represent slumps on the continental slope and at the slope front. It occurs in the Dniepr fan.

⇒ subtype IIb: BZ 2, EC 3a/3b/4c

- This facies subtype of hyperbolic echoes with high backscattering intensities is interpreted as slumps and slides on the continental slope where the surface is smoother than that of subtype IIa. Deposition takes place under the influence of a more-or-less constant surface gradient. The largest sediment deposits of this facies subtype occur between the Danube and Dniepr fans; other smaller patches are distributed over the entire study area.

⇒ subtype IIc: BZ 4, EC 4c

- Low backscattering and hyperbolic, stratified echoes represent sediment slides of fine-grained material occurring lateral to or overlying the levee facies.

⇒ subtype IId: BZ 5, EC 4c

Prolonged hyperbolic echoes in combination with heterogeneous backscatter and higher distortion than facies subtypes IIb and IIc are interpreted to represent sediment slides which occur as large bodies in the upper Dniepr fan.

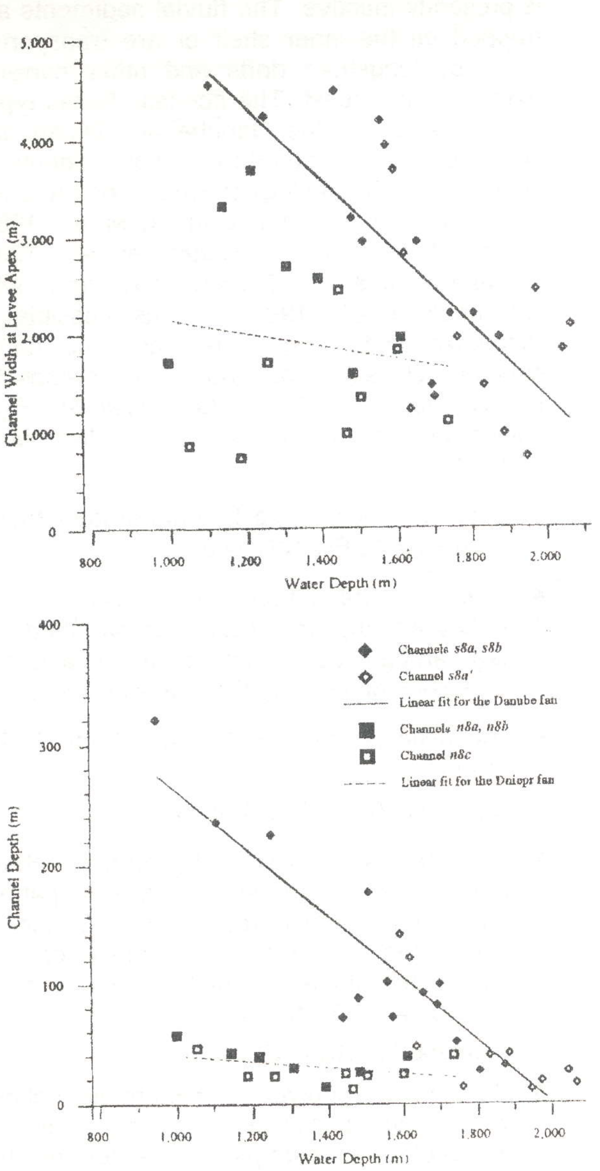

Fig.13 Channel width *vs.* water depth and channel depth *vs.* water depth, Danube and Dniepr fans.

- Acoustic facies type III: debris flow facies group

⇒ subtype IIIa: BZ 2/3, EC 2

- Acoustic transparency and high to intermediate backscattering strength generally characterize debris flows. These deposits occur as large bodies between the Danube and Dniepr fans and as smaller features adjacent to the proximal fan channels.

⇒ subtype IIIb: BZ 2/4/5, EC 4b

- Backscatter zones of varying intensities in combination with wavy parallel reflectors over flat-lying parallel reflectors are interpreted to represent small debris flows overlying levees or sediment slides over or adjacent to levees. The sediment waves probably resulted from compression that accompanied mass transport. This facies subtype is found adjacent to meandering channels in the middle and lower fans and at the distal ends of some channels.

- Acoustic facies type IV: levee/overbank facies group

⇒ subtype IVa: BZ 3, EC 4a/4c

- Moderate bottom reflectivity and numerous parallel, sometimes slightly hyperbolic echoes are indicative of coarser-grained levees, probably silts with sand intercalations, in the steep upper fans, or of downfan continuations of unchannelized debris flows.

⇒ subtype IVb: BZ 3, EC 4a/5

- This acoustic facies of intermediate backscattering strength and parallel, high frequency reflections occurs typically in the distal fans and consists probably of clayey sediments with interbedded silts.

⇒ subtype IVc: BZ 4, EC 4a/b

- This acoustic facies of numerous, even stratifications and low backscatter is interpreted to represent levee deposits and fine-grained channel overflows between channel-levee systems.

The interpretation of the acoustic facies types described above has been in part verified by sediment coring. The Holocene of all cores retrieved from the Danube and Dniepr fans is characterized by the deposition of dark sapropels and varves (coccolith ooze interbedded with diatomaceous clays). During the Pleistocene, however, turbidite sedimentation took place on the levees of the distal fan, while cyclic deposition of clay successions with thin silt/sand intercalations occurred on the middle and upper fans (Konyukhov *et al.*, 1988). Sediment samples from the central valley of the Danube fan yielded 177 cm of Holocene muds at 1,130 m water depth, probably from a sapropel slide from the steep channel walls, and thinner Holocene muds underlain by thin Pleistocene sands at 1,300 m depth (Konyukhov *et al.*, 1988).

We have retrieved cores from areas assignable to three of the acoustic facies types described above: (1) Core 1/1994 (43° 16.28' N, 31° 08.25' E), consisting of 111 cm of Holocene coccolith and sapropel varves overlying massive, layered, presumably Pleistocene, banded lutites (Wong *et al.*, 1995) corresponds to acoustic facies subtype

IIb. Sediment stratification is preserved in the sediment slide from which this core is retrieved.

(2) In core 2/1994 (43° 33.25' N, 30° 56.19' E), 38 cm of Holocene varves overlie 422 cm of turbidites (Wong *et al.*, 1995). It is retrieved from an area of acoustic facies subtype IVb and is lithologically consistent with its interpretation as medium to finer-grained (silty to clayey) levee or overbank deposits.

(3) Core S24/1992 (43° 38.00' N, 30° 56.12' E) is located in an area of acoustic facies subtype IVc. It is made up of 54 cm of microlaminated coccolith ooze and 104 cm of clay and seekreide overlying 233 cm of turbidites (Strecker, 1996). The poor backscattering strength is a result of the fine grain size of the Holocene deposits and the regularly layered reflectors are typical of a turbiditic sequence.

From the surficial acoustic facies distribution map (Fig.8), it can be seen that the most of the mass transport deposits (debris flows, slumps and slides) occur in the Dniepr fan while only minor occurrences are found in the Danube fan. We attribute this observation to differences in the material deposited and hence to their different sources: the Dniepr fan was fed by the Ukranian rivers, while the Danube fan was accreted by the Danube. Konyukhov *et al.* (1988) described the sediments which fill the paleo-morphologic lows within the Danube and Dniepr fans as flysch-like. This zone corresponds to the major area of mass transport deposits between the most recently active channels of the two fans in which the lateral compression that accompanied mass transport is expressed in the form of sediment waves.

Backscatter characteristics from deep-towed, high-resolution sidescan data

Two small neighbouring areas which include the avulsion point *X* of channel *s8a* into *s8a'* and *s8b* were surveyed using the deep-towed, combined sidescan-pinger (Mak) system in 1993 and 1994 (Fig.9). Immediately downstream of this point adjacent to channel *s8a'* are sediment slumps which have resulted from minor channel breaching (arrow on Fig.9). They lie within an area of BZ 5 (patchy, heterogeneous) in the Okean mosaic, and consist of compressively deformed but still stratified sediments. Channel *s8b* is largely sediment-filled (Fig.10) while the younger channel *s8a'* is almost devoid of sediments. The pronounced levees of channel *s8a* upstream of the avulsion point near a meander is an area of low backscatter (BZ 4, Fig.11). The levee deposits are cyclically stratified in such a way that high frequency, low amplitude reflectors are overlain by high amplitude reflectors, indicative of an upward

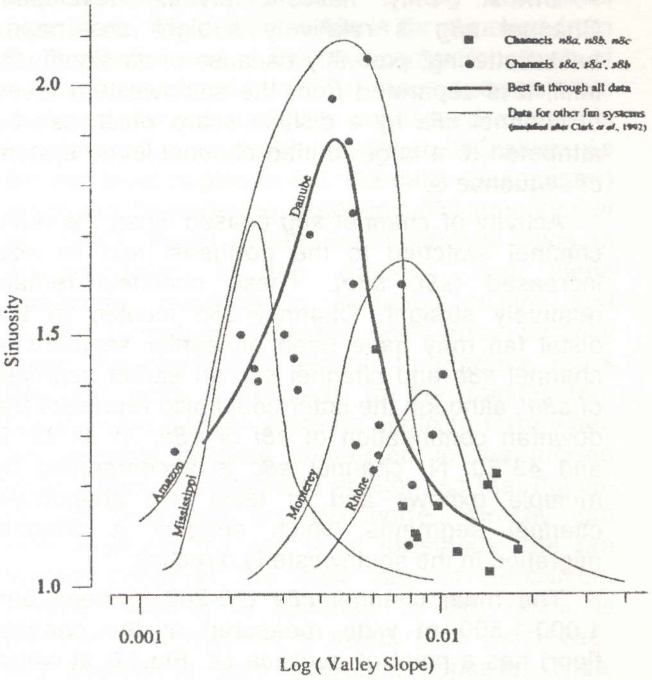

Fig.14 Sinuosity vs. log (valley slope), Danube and Dniepr fans.

coarsening sequence. Five cycles can be readily recognized and there is evidence for four additional cycles. The total thickness of these cyclic sediments is about 40 m, i.e., 4-5 m per cycle. They may be the result of turbidity events during the last sea level lowstand.

Distribution pattern of channels on the present-day fan surface and their age relationship

The channels of a deepsea fan system are produced and maintained by turbidity currents and represent the pathways for sediment transport into and within the fan area. Their shapes and positions are controlled by depositional processes (producing large levees and overbank wedges and decreasing the channel slope by channel meandering) as well as erosional processes (such as slumping, sliding and levee failure). The channel-levee systems are the most pronounced features within each seismic sequence; they consist of diverse, partly bifurcated channels with their levees, overbank sediments and other mass transport deposits.

Figure 12 shows the surficial channel distribution pattern of the Danube and Dniepr fans. The overlapping pattern of the mass transport deposits associated with these fans suggests a longer period of activity for the Danube fan. Within each fan, the relative channel chronology is established using the stacking pattern and degree of channel infill.

For the Danube fan, the first major channel activity within sequence 8 (channel *s8g*) was in the southwest. Only nascent levees developed. Channel *s8g* is relatively straight and poorly backscattering, probably because of its significant infill. It is separated from the southwestern levee of channel *s8a* by a distinct scarp which can be attributed to a large, buried channel-levee system of sequence 6.

Activity of channel *s8g* ceased when the main channel switched to the northeast and its size increased (*s8f*, *s8e*). These channels remain relatively straight. Channel *s8d* located in the distal fan may have been an earlier segment of channel *s8b* and channel *s8c* an earlier segment of *s8a'*, although the latter could also represent the downfan continuation of *s8f* or *s8e*. At 31°30' E and 43°30' N, channel *s8c* is accompanied by multiple oxbows and at least two abandoned channel segments which suggest a channel migration in the southwesterly direction.

The main channel *s8a* (20-200 m deep and 1,000-1,500 m wide measured at the channel floor) has a point of avulsion (*X*, Fig.12) at which the previous downfan continuation of *s8a* (channel *s8b*) was abandoned and filled with overbank deposits of a younger system. Channel *s8b* (sinuosity: 1.1-1.5) is less sinuous than *s8a'* (sinuosity: 1.4-1.9), *s8c*, *s8e'* and *s8d*. Channels *s8a/b* developed a large levee system (up to 40 km width and 400 m height) which dominates the Danube fan. In contrast, the levee system of *s8a'* is small (up to 10 km in width and 100 m in height); it overlies the large *s8a* levees.

The Dniepr fan probably developed from south to north, i.e., from *n8f* to *n8a*. Compared to the Danube fan, its main channel is smaller (60 m deep and 1,500 m wide at the thalweg) and more sediment-filled (another indicator that it may be older). It has also migrated to the north by channel avulsion (*n8b* to *n8a'*).

Quantitative analysis of the geometry of the fan channels and their distributaries

A morphometric analysis of the channels and their distributaries of the Danube and Dniepr fans (in analogy to the Amazon fan, Flood & Damuth, 1987) was carried out so that a quantitative comparison between their geometry and that of the known fan classes can be made and the processes that control their geometry estimated. The geometrical parameters used were selected in analogy to studies of subaerial river systems. These include:

- channel depth (from the channel axis to the levee crest);
- channel width (at the levee apex); and
- water depth (depth of channel axis below sea level).
- valley length (the straight-line distance between two crossings); and
- channel length (the distance measured along the channel between two crossings).

Apparent values for these parameters were obtained from profiles (especially echo-sounding lines) that cross a channel and from sidescan mosaics. The computed parameters are:

- valley slope (gradient along valley length);
- channel slope (gradient along channel axis);
- sinuosity (ratio of channel length to valley length); and
- width/depth ratio for each reach (i.e., channel segment between two successive crossings; Clark et al., 1992; Flood & Damuth, 1987).

The measured and calculated morphometric parameters show considerable scatter. Uncertainties in depth due to interference between channel floor reflections and side echoes from the channel walls may reach 10 m. Additional errors arise from uncertainties in the exact reflection pattern on the sidescan mosaic such as unrecognized meander abandonment. Only channels with more than five successive channel crossings (hence four reaches) and with a well-determined channel path were analyzed. These include two channels from the Danube fan (s8a/s8a' and s8b) and three from the Dniepr fan (n8a, n8b and n8c).

Channel width and depth and hence the channel cross-section decrease downfan (Fig.13). The decrease in channel depth with increasing water depth suggests a progressive downfan decrease in the maximum thickness of the turbidity currents, the decrease in channel cross-section a decrease in flow volume, in contrast to subaerial rivers for which the bedload and discharge increase (Flood & Damuth, 1987). This is because in submarine turbidite systems, channel overspilling which leads to a loss of transported material (especially at channel bends or crevasse splays) is common. The finest material can therefore be increasingly stripped from the channelized flow. The channel depth and width are greater for the Danube fan than the Dniepr fan, but since they decrease faster downfan for the former, they reach approximately the same values in the distal parts of the fans.

Fig.14 shows a plot of sinuosity versus the logarithm of valley slope. Compared with other fan systems, channels of the Danube and Dniepr fans are highly sinuous within a narrow valley slope interval, analogous to the Mississippi (Clark et al., 1992). At low valley gradients, the sinuosity increases with increasing valley slope (generally in a manner similar to that observed for subaerial rivers) to maintain a slope optimized for the accommodation of flow volume and sediment load (Flood & Damuth, 1987; Damuth et al., 1988; Weimer, 1991). After a peak sinuosity is reached, a further increase in valley slope results in a decrease in sinuosity. The most intricate and extensive meandering (i.e., the highest sinuosity) is observed in the middle fan, the least in the upper fan. Channel *s8a'* is the main contributor to the peak in sinuosity (2.05); the peak of the best fit curve through all data lies at sinuosity 1.9. The threshold valley slope beyond which the channel searches a more direct path downslope is a unique quantifiable parameter for each fan system (Clark et al., 1992). It varies with sediment type and quantity as well as with the general fan and basin geometries. The gradient which gives rise to the peak sinuosity for the Danube and Dniepr fans is 1:200. The Danube fan has generally a lower valley slope and a higher sinuosity than the Dniepr fan, suggesting that its source material is finer. Two reaches of channel *n8a* for which the sinuosity exceeds 3 have been excluded. These high values may result from cutoff meanders which were not recognized as such and were mistakenly included in the measurements.

Clark *et al.* (1992) distinguish between high-sinuosity/low-gradient (e.g., Indus) and low-sinuosity/high-gradient (e.g., Porcupine) submarine channel systems as two end-members of a wide spectrum. They contend that these quantitative parameters are more appropriate for deepsea fan classification than the conventional correlation of fan shape and sediment grain size because the fan shape is mainly influenced by the preexisting basin shape. Channel morphology, on the other hand, reflects the nature of depositional processes which were active during fan accretion. In comparison to other systems, the Danube and Dniepr fans form a highly sinuous system which reaches a peak sinuosity at relatively low gradients (like the Indus or the Mississippi). River studies suggest that the type of sediment transported plays an important role in shaping the channel morphology and valley slope, high sinuosity being an indicator for fine-grained transported material.

EVOLUTION OF THE DANUBE AND DNIEPR FANS

Depositional fan model

The schematic development of a typical sequence of the Danube and Dniepr fans can be described as a function of the relative sea level (Winguth *et al.*, this vol.). This suggests that the depositional model for deepsea fan systems proposed by Weimer (1990) is applicable to the Danube and Dniepr fans. During sea level highstands, the deltaic region is far removed from the shelfedge and is the depocenter for much of the fluvial sediment input. The slope and basin are sediment-starved so that a condensed section is laid down as a result of hemipelagic deposition. As the sea level begins to fall, the delta (depocenter) progrades towards the shelfedge (Posamentier *et al.*, 1991). Rapid deltaic sedimentation leads to overpressuring in the prodelta and slope sediments, resulting in sediment failure and canyon formation. Turbidity flows may partially erode the condensed section to produce mass transport units, particularly in the middle fan. Small channel-levee systems begin to form when the canyons become connected to the incised valleys through retrograde erosion, so that fluvial-derived sediments are transported directly into deeper waters. At sea level lowstands, the fan system becomes the main site of deposition. Coarse material is confined to the channels whereas finer material is swept onto the levees and beyond to form overbank deposits. Thus, channel-levee systems may coalesce to form composite systems. As sea level rises to a highstand, the deltaic system retreats towards the coast. The incised channels are filled with finer material and hemipelagic sedimentation prevails in the slope and basin.

Age of the Danube and Dniepr fans

Based on seismo-geological data, Khakhalev (1975) demonstrated that the structure of the Plio-Pleistocene boundary (his horizon B) precludes the existence of the Danube and Dniepr fans in pre-Quaternary times, a conclusion which is also consistent with the unusual thickness of the Quaternary deposits mapped there. Ianovici et al. (1960) and Banu (1967) suggested that the Danube penetrated into the Black Sea only in the Late Pleistocene, implying that this is the age of the Danube fan-delta complex.

By using the preliminary relative sea level curve developed for the northwestrern Black Sea (Winguth et al., this vol.), age assignments to the seismic sequences 3 to 8 of the Danube and Dniepr fans can be made (Tab.2): deposition of sequence 3 probably started ca. 480 ka BP and ended ca. 400 ka BP, sequence 4 was deposited from ca. 400 to 320 ka BP, sequence 5 from ca. 320 to 190 ka BP, sequence 6 from ca. 190 to 75 ka BP, sequence 7 from ca. 75 to 25 ka BP and sequence 8 from ca. 25 ka BP to today. The last sea level cycle is not yet complete.

We contend that the Danube and Dniepr fans are formed during the deposition of sequences 3 to 8 in the past 480 ka. Sequences 2 and 1 lack fan-typical channel-levee complexes and must therefore be deposited before fan construction started. Fan sedimentation was probably initiated as a result of a reorganization of the river course subsequent to tectonic or climatic events. One such possible event may be the major subsidence that started around 500 ka BP (Degens & Stoffers, 1980; Degens *et al.*, 1986). Evidence for the initiation of subsidence at about this time is found in the termination of a shallow water facies at approximately 0.5 ma BP (Degens & Stoffers, 1980) and in a rapid increase in the subsidence rate about 0.45 ma ago inferred from successive backstripping of the sedimentary layers (Degens *et al.*, 1986). However, other opinions on basin subsidence in the Black Sea exist. Hsü (1978) attributes the shallow water facies to desiccation of the Black Sea following a water deficit which resulted from drainage reorganization. Letouzey *et al.* (1977) postulate major subsidence in the Eocene/Oligocene and in the Pliocene/Pleistocene, while Zonenshain & Le Pichon (1986) suggest a linear increase of the subsidence rate since basin development 80 ma ago.

Estimated sedimentation and sediment accumulation rates

Based on the sequence age assignments and on interval velocities from Romanian industrial reflection profiles, average sedimentation rates in the Danube and Dniepr fans can be computed. They range between 2.4 and 7.2 m/ka (Tab.2). Sedimentation rates for the individual lowstand, transgressive and highstand systems tracts of a sea level cycle are still unknown, but it is likely that a large part of fan accretion takes place during sea level lowstands. The higher sedimentation rates of the upper sequences (especially sequence 8) may be due to the fact that sediment compaction has not been taken into account. Also, the computed sedimentation rate of sequence 8 is not an average over the entire sea level cycle as for the other sequences since deposition of its highstand systems tract is still continuing. Its very high value reflects in part the dominance of rapid lowstand sedimentation.

For the six upper sequences, the total volume of each sequence within our study area has been calculated and the mean annual sediment accumulation rates estimated (Tab.2). For this purpose, a density of 1.4 g/cm³ was assumed to transform the volumetric sediment accumulation into an accumulation rate in tons per year. The computed rates range between 88×106 t/a and 302×106 t/a. The sediment discharge rate of 83×106 t/a for the Danube before the Iron-Gate Dam was completed lies at the lower end of this computed range.

For the Plio-Pleistocene sequences in the Mississippi fan in the Gulf of Mexico, Mitchum & van Wagoner (1991) computed a sedimentation rate of 0.43 m/ka. Mean sedimentation rates are higher in the Danube and Dniepr fans. They are more comparable to the rates in the Amazon fan, where 1-3 m/ka for older levees, 10-25 m/ka for the last active levee and 2 m/ka for distal sandy lobes have been reported (Flood et al., 1995). In the Rhône deepsea fan, the average sedimentation rate is only 23 cm/ka, but this may be a result of low sediment input by the River Rhône (5.5×106t/a; Torres et al., 1995).

CONCLUSIONS

Two distinct but interfingering fans exist in the northwestern Black Sea: the Danube fan which is fed by the River Danube during fan accretion, and the Dniepr fan built up by the Ukranian rivers Dniepr, Dniestr and Bug. Eight seismic sequences have been identified within each of these fans. While the lowermost two consist mainly of mass transport-related deposits, the six upper sequences comprise fan-typical facies associations with pronounced channel-levee systems and levees which pass laterally into overbank deposits. The sequences are separated from each other by condensed sections interpreted to represent hemipelagic sediments of sea level highstands. In addition to the channelized turbidity currents which use the channels as pathways, mass transport processes which result in slumps, slides and debris flows played a major role in fan construction.

Channel displacement occurs within a sequence as well as from sequence to sequence. It is probably due to activation and/or clogging of the delta arms or to channel breaching. Despite these displacements, the major channels did not migrate significantly except the southwesternmost channel of sequence 5, which perhaps represents the paleo-channel of the Danube when it flowed through the Karasu valley south of its present-day delta. Only one channel is assumed to have been active at any given time within each sequence of a fan.

For the youngest sequence, ten acoustic facies subtypes classified into four groups have been identified. Channels filled to various extents, coarse- and fine-grained levees as well as various mass transport units could be distinguished. The distribution of mass transport deposits suggests that the associated processes must have been much more important in the Dniepr fan than in the Danube fan. Age relationships between the channels of a given sequence could be established using the degree of channel fill and the overlap pattern.

Quantitative analysis of various morphological parameters of the channels suggests that like other deepsea fans, the Danube and Dniepr fans adjust their channel slopes to accomodate the flow volume and sediment load of the turbidity input. These fans belong to the group of highly sinuous, mud-rich systems which also include the Mississippi and the Indus fans. The Danube fan has generally a lower valley slope and a higher sinuosity than the Dniepr fan, suggesting that its source material is finer.

The Danube and Dniepr fans were constructed during the past 480 ka (sequences 3 to 8). Average deposition rates for the fan sequences range from 2.4 and 7.2 m/ka and the volume of material deposited within a sea level cycle lies between 4,300 km^3 and 9,590 km^3.

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