Submarine canyons of the Black Sea basin with a focus on the Danube Canyon

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Abstract

The first part of the paper presents an overview of the Black Sea canyons which are evident in the present-day morphology of the marine basin. Two types of canyons are revealed – the active and the passive canyons. The study then concentrates on the analysis of the Danube Canyon. The canyon morphology is reviewed, in correlation with the Upper Quaternary paleo-Danube channels and the structure of the Danube Deep Sea Fan. Erosive flow along the canyon axis producing bottom down-cutting and instability of the walls is regarded as the process controlling the morphological evolution of the Danube Canyon. The lowstand-time morphology of the shelf is reconstructed, based on the filled-up paleo-channels and the wave-cut terrace extension. The buried channels clusters suggest two main directions of the paleo-Danube drainage systems, partly discharging in the Danube Canyon. The high paleo-Danube sedimentary influx appears to represent the major control on the canyon development. The age constraints for the canyon initiation are currently non-existent. It is conceivable that the youngest phase of evolution of the Danube Canyon corresponds to the last Black Sea lowstand.

1. Introduction

1.1 Objectives, methodology, study area

For the sediments discharged by rivers in marine basins, the canyons are the most important way to reach their final destination, the deep marine bottom. Due to the diversity of its surrounding terrestrial relief (Fig. 1), the Black Sea accommodates many canyons with multiple aspects. Ignored for a long time by scientists, the Black Sea canyons slowly begin to represent attractive themes of study. Beneficiary of several international research projects, the Danube Canyon is now at a relatively high level of knowledge, representing a reference point for other studies of this kind from the Black Sea area.

The present paper stands for a review of the information regarding the Black Sea canyons. Sparse literature data are the base for the Black Sea canyons overview. The focus of this study is on the Danube Canyon, covering a study area at the edge of the northwestern Black Sea shelf. The head of the Danube Canyon is located 130 km east of the town of Constanţa (Romania). The canyon is extended southeastward by the Danube Channel, through the Danube Deep Sea Fan (Fig. 1). Complex geological and geophysical investigations (swath bathymetry in the canyon area combined with sub-bottom profiling and different types of seismic profilings) were carried out in this area in the framework of national, French-Romanian and German-Romanian common projects (Winguth *et al.*, 1997, 2000; Wong *et al.*, 1994, 1997, 2002; Panin 1996, 2009; Popescu, 2002; Popescu and Lericolais, 2003; Popescu *et al.*, 2004, Lericolais, 2007), and these data are analysed.

Figure 1. Black Sea morphology. Detailed view of the northwestern Black Sea area. Earth satellite image.

1.2. Black Sea general features

The Black Sea is located almost at the boundary between Europe and Asia. The southeastern and northeastern Black Sea is constrained by the Pontic and Caucasus Mountains. The Crimean Mountainous Peninsula borders the sea basin to the north. Low relief terrain (lowstanding loess plateaux, the Danube delta and the Dobrogean geological units) surrounds the northwestern and western Black Sea. The south-western section of the sea is again mountainous – the Balkans Mountains flank the coastal zone.

Hydrology and hydrochemistry. The almost total isolation is one of Black Sea special characteristics. The Black Sea is connected to the Mediterranean Sea through the Bosporus-Dardanelles narrow system of straits (called also Turkish Straits). In this geographic isolation condition, due to the high fresh water runoff, the Black Sea salinity is quite low for a marine body (17 to 22 ‰).

The Black Sea temperature and salinity stratification restricts the vertical water mixing, and consequently the oxygen from atmosphere does not reach the deep water, which became anoxic. The decaying organic matter accumulated in time led to the present day hydrogen sulphide saturation of the deep, anoxic Black Sea water. The upper layer of oxic marine water (about 150 – 200 m thick) practically supports the entire biological life in the Black Sea ecosystem.

Coastline. The 4870 km long Black Sea coastline (Stanchev *et al.*, 2011) is shared by six states, Turkey, Georgia, Russian Federation, Ukraine, Romania and Bulgaria.

Three main Black Sea morphodynamic types of coasts are distinguished by Panin (2005): (1) low, accumulative coasts, in the areas of the main river mouth zones, mainly with sandy complex barrier beaches; (2) erosive coasts within which active cliffs in loess and loess-like deposits lowstanding plateaux and plains, sometimes with very narrow beaches in front of the cliffs; (3) mountainous coasts, with cliffs, marine terraces, landslides, with sandy or gravely beaches.

1.3 Physiography

The Black Sea shelf represents about 30% of the sea area (Ross *et al.*, 1974; Panin, Jipa, 1998). The largest shelf development is in the northwestern part of the Black Sea, between the Crimean peninsula and the Danube Delta, where the shelf can be more than 190 km wide (Fig. 2). In contrast the shelf width from the southern and eastern Black Sea is less than 20 km (Ross *et al.*, 1974). The shelf is mostly shallower than 100 m, but in the northwestern area the shelf break reaches -140 m to -170 m in water depth (Popescu, 2002).

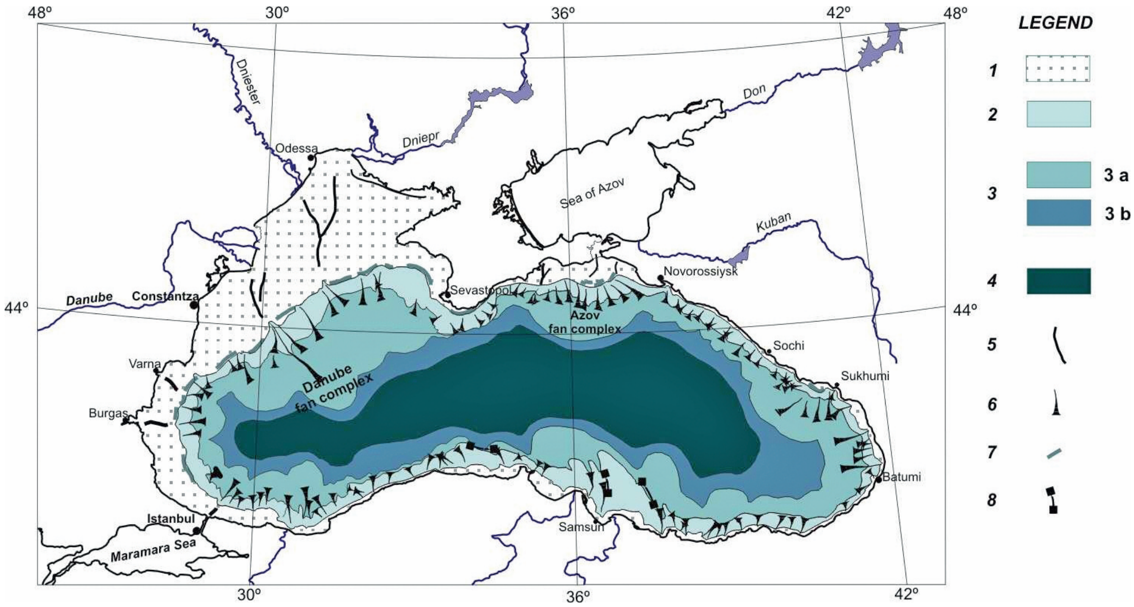

Figure 2. Geomorphologic zoning of the Black Sea (after Ross *et al.*, 1974, Panin, E and G. Ion, 1997). Legend: 1, continentals shelf; 2, continental slope; 3, basin apron: 3a - deep sea fan complexes; 3b - lower apron; 4, deep sea (abyssal) plain; 5, paleo-channels on the continental shelf filled up with Holocene and recent fine grained sediments; 6, main submarine valleys - canyons; 7, paleo-cliffs near the shelf break; 8, fracture zones expressed in the bottom morphology.

Along the high relief southern and north-eastern Black Sea coasts, the continental slope is steeper and crossed by numerous canyons. The slope area associated with the wide shelf from the northwestern Black Sea is smoother and its gradient is gentler.

In the deep Black Sea area, Ross *et al.* (1974) separated the basin apron and the abyssal plain physiographic units. Distinct features of the basin apron are deep sea fans of large tributaries and mainly of the Danube River. The Euxine Abyssal Plain, from the almost plane area in the central part of the Black Sea, represents only about 12% of the sea surface (Ross *et al.*, 1974).

The differences in the continental shelf width of western and north-western Black Sea, compared to the eastern and southern sections of the sea, control the dynamics of canyons located in the respective regions: in the mountainous eastern and southern coastal zones where the shelf is narrow the canyons are active even during the highstands and capture entirely or partially the sediment load brought by rivers into the sea, while in the area of very wide shelf the canyons are active only during lowstands.

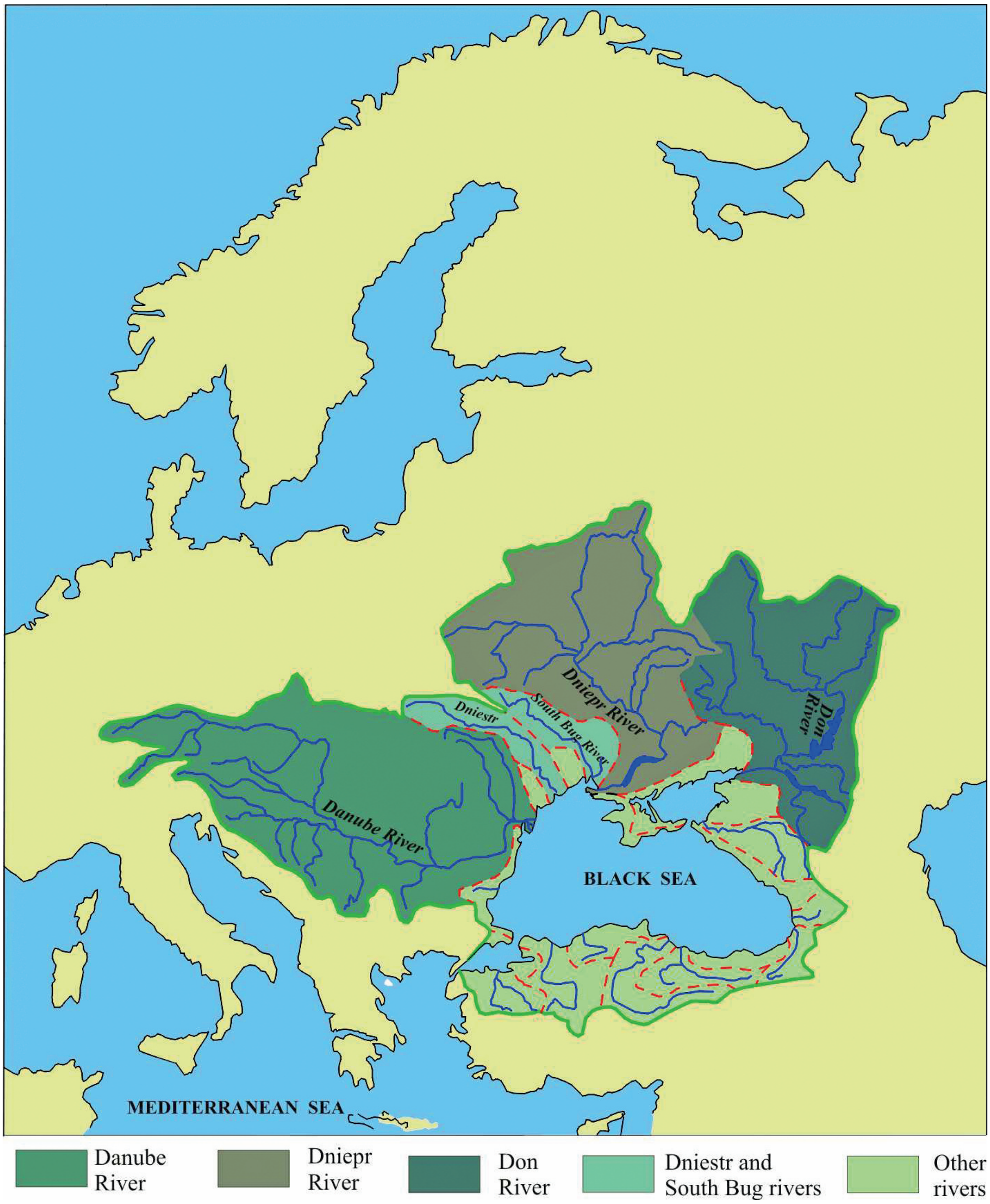

Figure 3. The Black Sea drainage basin (from Popescu, 2002).

1.4 Sediment input

The Black Sea drainage basin is very large, summing more than 2 million sq.km, and the water is collected from about one third of the Europe territory (Fig. 3). The largest rivers, with the greatest catchment basins and the larger water and sediment discharge are located in the northwestern

Black Sea. The Danube River has a mean water discharge of about 200 $km^3.yr^{-1}$ and the Ukrainian rivers Dnieper, Southern Bug and Dniester contribute with about 65 $km^3.yr^{-1}$.

The Danube River is the predominant sediment contributor. Its influence extends up to the Bosporus region, and down deep in the Black Sea basin. Dniester, Dnieper and Southern Bug rivers are presently discharging their sedimentary load into lagoons separated by beach barriers from the sea. During the lowstands all these rivers supplied sediments directly to the deep Black Sea.

After the Iron Gates I and II dams were built in 1970 and 1983 respectively, the Danube sediment discharge diminished by almost 40-45 % and the sediment load introduced by the Danube River into the Black Sea is not larger than 30-40 million t/yr. (Panin and Jipa, 1998, 2002). Out of this sediment stock the littoral zone in front of the Danube Delta receives only 10-12 % representing sandy material.

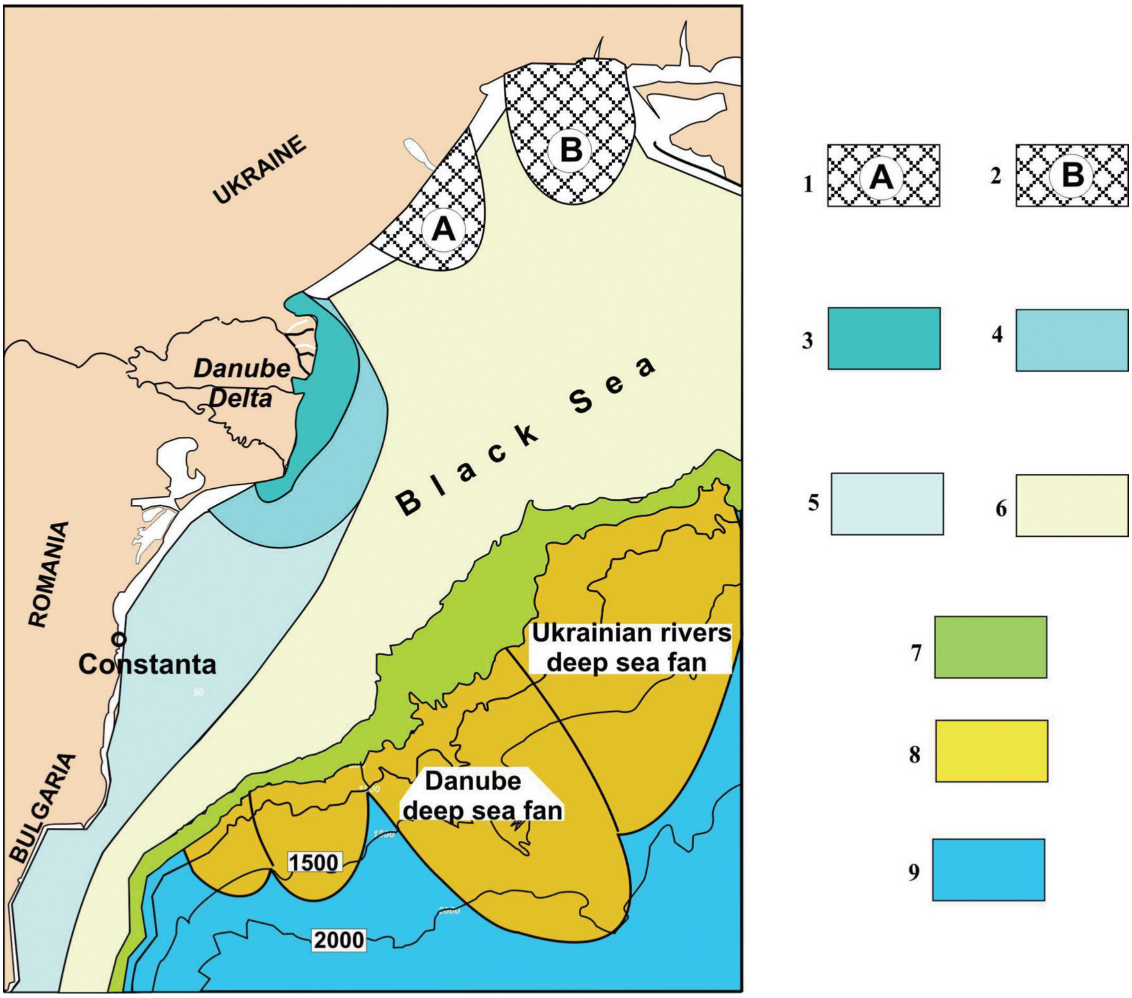

Figure 4. Main sedimentary environments in the north-western Black Sea (after Panin and Jipa, 1998, 2002). Legend: 1-2, Areas under the influence of Ukrainian rivers (A, Dniester; B, Dnieper) sediment discharge; 3, Danube Delta front area; 4, Danube prodelta area; 5-6, Western Black Sea continental shelf areas (5, area under the influence of the Danube-borne sediment drift; 6, sediment starved area); 7, Shelf break and the uppermost continental slope zone; 8, deep-sea fans area; 9, deep sea floor area.

1.5 Black Sea sediments distribution

Sandy sediments dominate in the coastline area. On the shelf besides shelly sediments, a variety of silty and muddy deposits are well developed. The distribution of the main sedimentary environments on the north-western Black Sea continental shelf is illustrated in Fig.4. The deep-water sediments are very fine grained, consisting of Coccolith muds with various carbonate content. Silty and sandy sediments were deposited by turbidity currents on the basin slope and in deeper areas (Shimkus and Trimonis, 1974).

1.6 Past Black Sea level and environmental changes in the Upper Quaternary - Holocene

Along the Black Sea geologic history large-scale sea level changes and consequently drastic reshaping of land morphology, strong erosions and large accumulation of sediments in the deep part of the sea have led to significant modifications of the environmental settings. The Quaternary was especially characterised by very spectacular changes, driven by global glaciation and deglaciation episodes.

During these changes the Black Sea level behaviour was influenced by the restricted connection with the Mediterranean Sea via the Bosporus – Dardanelles straits. When the general sea level lowered bellow the Bosporus sill, the further variations of the Black Sea level followed specific regional conditions, without being necessarily coupled to the Ocean level changes.

One of the main consequences of the lowstands was the interruption of the inflow of Mediterranean water into the Black Sea, which became a brackish or almost freshwater giant lake.

The main glacial periods of the Quaternary in Europe (Danube, Günz, Mindel, Riss and Würm) corresponded to regressive phases of the Black Sea as well, with lowstands down to –100 and even -120 m. As mentioned above, the regressions represent phases of isolation of the Black Sea from the Mediterranean Sea and the World Ocean. Only the connection with the Caspian Sea could sometimes continue through Manytch valley.

Correspondingly, during regressions, under brackish/fresh water conditions, the particularities of fauna assemblages had a pronounced Caspian character. On the contrary, during the interglacials, the water level rose to levels close to the present level; the Black Sea was reconnected to the Mediterranean Sea, and the environmental conditions as well as the fauna characteristics underwent marine Mediterranean influences.

We shall discuss mainly the upper part of the Pleistocene when the lowstands influenced the present-day Danube canyon morphology and evolution.

During the warm Riss-Würmian (Mikulinian) interglacial that corresponds to the Karangatian phase of the Black Sea (since 125 ka BP to ~ 65 ka BP), the water level exceeded the present-day level by few metres (8 to 12 m). The saline Mediterranean water penetrated through the Bosporus, and the Black Sea became saline (up to 30 even 37 ‰), with a steno- and euri-haline marine Mediterranean type fauna (Nevesskaya, 1970). The sea covered the lowlands in the coastal zone, including also the Danube river mouth zone (a large gulf was formed at that time).

The last Upper Würmian glaciation (Late Valdai, Ostashkovian) corresponds to the Neoeuxinian phase of the Black Sea. This is a very low-stand phase, down to -110 ÷ -120 m. The shoreline moved far away from the present-day position, especially in the northwestern part of the Black Sea, and large areas of the continental shelf were exposed. At depths between -100 m and -80 m, a drowned paleo-shoreline represented by wave cut terraces and fields of dune–like structures occurs (Popescu *et al.*, 2004; Ryan, 2007; Lericolais *et al.*, 2007). The hydrographic network, especially the large rivers as Paleo-Danube and Paleo-Dnieper, incised up to 90 m the exposed areas. The Neoeuxinian basin during the glacial maximum (~19 ÷ ~16 ka BP) was completely isolated from the Mediterranean Sea, and, correspondingly, the water became brackish to fresh (3÷7 ‰ and even less), well oxygenated, without H_2S contamination. The fauna was brackish to fresh water type with Caspian influence.

At about 16 ÷ 15 ka BP the postglacial warming and the ice caps melting started. As the supply of melting water from the glaciers through the Dnieper and the Dniester rivers, as well as the Danube River, to the Black Sea was very direct and important, the Neoeuxinian sea-level rose very quickly, reaching and overpassing at ~ 12 ka BP the Bosporus sill. Some researchers believe that in this phase a large fresh-water outflow through the Bosporus-Dardanelles straits towards the Mediterranean (Aegean) Sea occurred. Kvasov (1975) calculated that the fresh water outflow discharge was about 190 km^3/year.

At the beginning of the Holocene, some 9-7.5 ka BP, when the Mediterranean and the Black Seas reached the same level (close to the present day one), a two-way water exchange was established, and the process of transformation of the Black Sea in an anoxic brackish sea started. During the last 3 ka BP, a number of smaller oscillations of the water level took place ("Phanagorian regression", "Nymphaean" transgression, a lowering of 1÷2 m in the Xth century AD, with a slow rising continuing up-today).

The hypothesis formulated by Ryan *et al.* (1997) considers that during the Younger Dryas cooling (~11 ka BP until 9 ka BP), under more arid and windy climate, the Black Sea experienced a new lowering of the level (down to more than -100 m). At the same time, the Mediterranean Sea continued to rise, reaching by 7.5 ka BP the height of the Bosporus sill, and generating a massive inflow of salt water into the Black Sea basin.

More recent interpretations propose refined scenarios of reconnection of the Black Sea with the Mediterranean. Data seem to indicate a rapid transition from a fresh to brackish lake to the modern Black Sea around 9400 years ago (Ryan *et al.*, 2003; Major *et al.*, 2006; Hiscott *et al.*, 2007; Bahr *et al.*, 2008).

It seems that a highstand at about -20–30 m was reached during the deglacial to the earliest Holocene, but the timing and the temporal extent of this event is still under discussion (Ryan *et al.*, 2003; Hiscott *et al.*, 2007; Lericolais *et al.*, 2007a). The present-day Danube canyon is related to the last lowstands of the Black Sea – the Neoeuxinian one and, possibly, those of Younger Dryas.

2. Black Sea canyons – background

Information regarding Black Sea canyons is not very abundant. Aspects of the Black Sea canyons will be found in Algan *et al.* (2002), Wong *et al.*, (1994 and 1997), Lericolais *et al.*(2002), Dimitrov and Solakov (2002), Popescu and Lericolais (2003). Popescu *et al.* (2004), Dondurur and Çifçi (2007), Pasynkova (2013) and Gulin (2013).

Significant knowledge on canyon heads came through the investigation of the coastal zone morphodynamics carried out by Georgian scientists (Bilashvili, 2004; Papashvili *et al.*, 2010) while cruises focused on deep-water cold seeps or deep sea fans provided important data on the lower reaches of some Caucasian or west Crimean submarine canyons (Lüdman *et al.*, 2004; Akhmetzhanov *et al.*, 2005; Naudts *et al.*, 2006; Klaucke *et al.*, 2006; Bohrmann and Pape, 2007; Wagner-Friedrichs, 2007; Sipahioglu, 2013).

2.1 Black Sea canyons and the coastline morphodynamics

Black Sea canyons characteristics depend on the relief energy of the coasts they are associated with. From this viewpoint the Black Sea offers two different environments (see Fig. 1).

The southern and eastern Black Sea coastline is mountainous. The relief behind this coast is very high, with summits of almost 4000 m (3937m - Kaçkar Dağı in the North Anatolian Mountains) or close to 6000 m (5642 m - Mount Elburs in the Greater Caucasus Mountains). In the southern Crimean Peninsula the relief is also elevated, but the altitude is in the 600-1,545 m range.

From the Crimean Peninsula to the north of the Bosporous Strait the Black Sea coast shows a low relief, reaching a hilly morphology only southward of Varna (the easternmost extension of the Balkans) and northward of Constanţa (Northern Dobrogea Plateau). This is a low, accumulative coast (Panin, 2005).

In the Black Sea basin the shelf extension is well correlated with the shoreline morphodynamics, and this also influences canyons development. More frequent submarine canyons occur in the southern and eastern Black Sea area with mountainous shoreline, very narrow shelf (Fig. 1) and coarse-grained sediments. In areas with low-relief shoreline, the shelf is wide and have fine-grained (sandy and silty) sediments (like in the northwestern Black Sea area) and the submarine canyons are scarcer and less closely spaced.

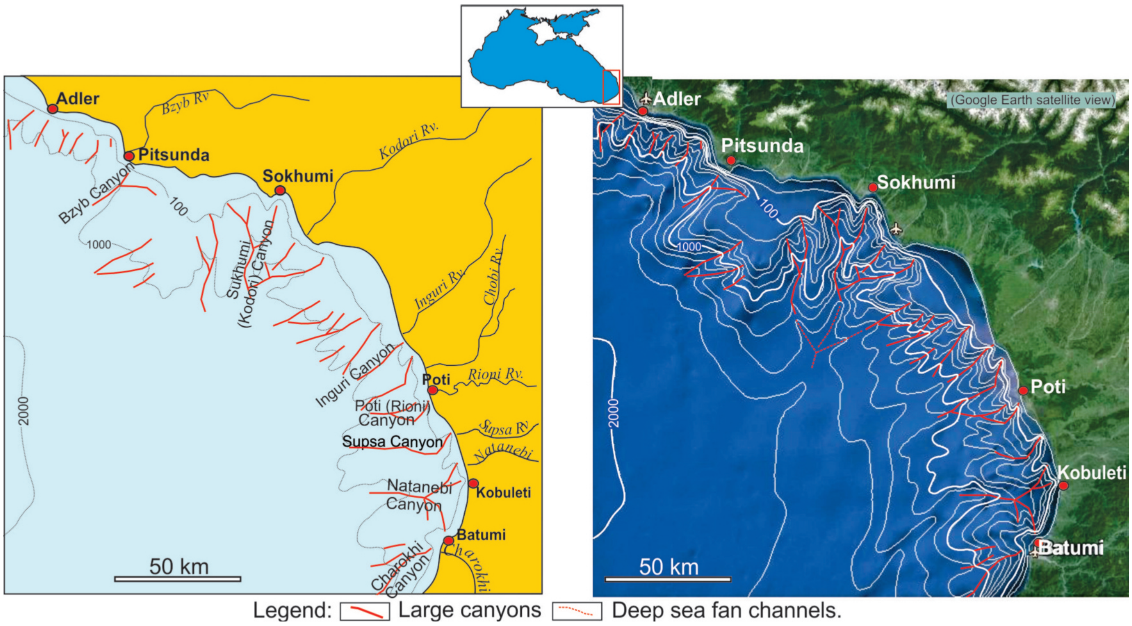

Figure 5. Major submarine canyons from the Caucasian, eastern Black Sea. Google Earth satellite view used as background image. Bathymetry in meters.

2.2 Submarine canyons in the eastern, Caucasian Black Sea area

The submarine canyons located close to the Caucasian coast are the most renowned in the Black Sea area. In this area a close relationship appears to exist between the canyon and the rivers. The major canyons of this area (Bzyb, Kodori, Inguri, Rioni, Supsa, and Chorokhi/Çoruh) are all associated with rivers (Jaoshvili, 2002).

The Caucasian coast is associated with very narrow shelf areas. In the Batumi-Kobuleti, SE of Sokhumi and Adler-Pitsunda zones (Fig.5) the shelf is less than 5 km wide. In these areas the canyon's heads incise the narrow shelf, and are located at close vicinity of the rivers mouth. The Chorokhi canyon head appears at 70-140 m from the Chorokhi (Çoruh) river mouth, at 7-8 m water depth (Bilashvili, 2004). Before harbor and river management works were carried out, the Poti submarine canyon head was surveyed at the 10 m isobath and at about 600 meters from the shoreline and from one of the Rioni river mouths (Papashvili *et al.*, 2010). The head of the southern branch of the Natanebi Canyon occurs at the Batumi harbor entrance, at about 10 m water depth (Bilashvili, 2007).

The shelf is wider and the continental slope gentler slope in the Pitsunda – Sokhumi marine area and between Kodori and Inguri canyons. This is why the canyons from these areas occur 25-35 km offshore.

Seismic sections (Akhmetzhanov *et al.*, 2007) point out the concave-upward profile in the canyons lower reach parts, at water depth of 1400-1600 m. On the bottom of the Sokhumi and Natanebi canyons there are gravels with large current ripples and also very large scours.

The seismic investigations carried out by Sipahioglu (2013) revealed the presence of several older, buried channels in the canyons sedimentary structure from the marine area westward of the Chorokhi (Çoruh) river mouth. The arrangement of these erosion surfaces reveals limited lateral migration of the submarine valley and in other cases the longtime persistence of the canyon.

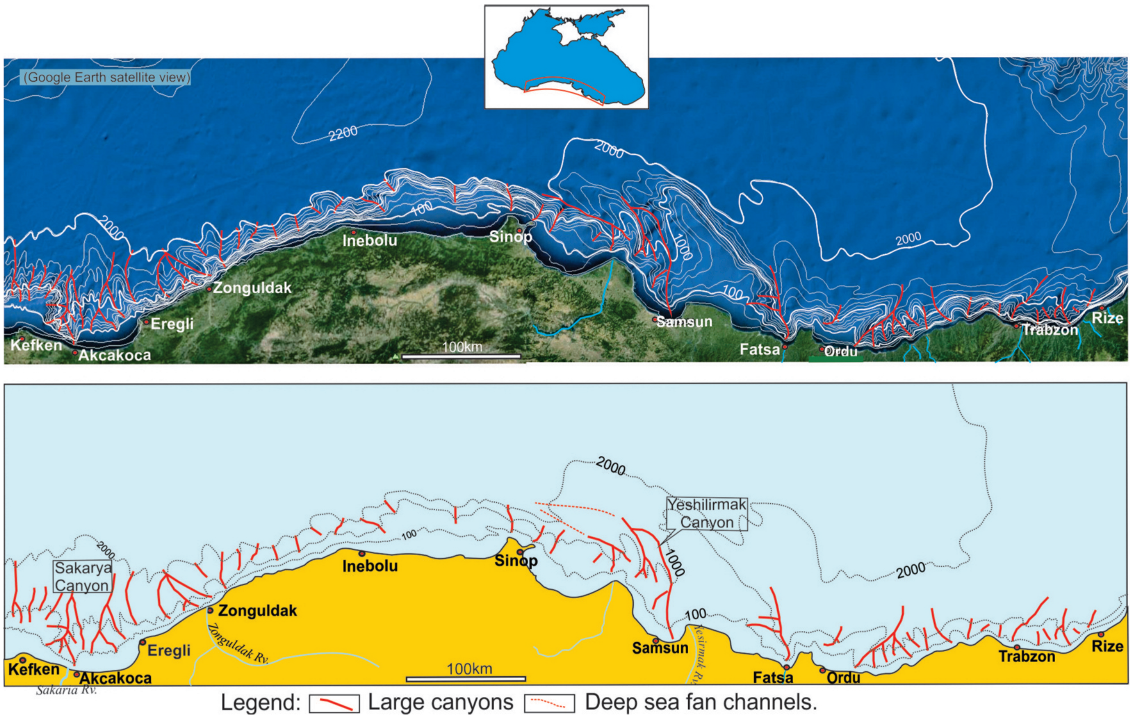

Figure 6. Large canyons from the southern Black Sea, the Anatolian area. Google Earth satellite view used as the background image. Bathymetry in meters.

2.3 Submarine canyons of the Anatolian, southern Black Sea area

The Anatolian zone is the largest Black Sea mountainous coast, with a 900 km east-west extension (Fig. 6). Steep slope and shelf areas (Eregli-Inabolu and Fatsa-Rize) of 2-4 km width alternates with less extensive areas of larger shelf (7-10 km width in Fatsa-Sinop and Eregli-Kefken marine zones) and gentler slope, associated with deep sea fan build up. The main canyons (Sakarya and Yeshilirmak) appear in the milder slope areas. They have a higher dendritic trend, showing a system with a main channel thalweg and several limbs.

On the large scale bathymetric maps, some of the Anatolian canyons appear to cross or reach the 100 m bathymetric curve and could be considered as shelf-incising. This is the case of the Sakarya Canyon. As Algan *et al.* (2002) specified the Sakarya Canyon displays two heads, occuring at about -50m and respectively -10m water depth.

Mapping the continental slope in the area of the Yeshilirmak River mouth Dondurur and Çifçi (2007) have been able to accurately trace the canyons axes. In this way they revealed a very dense, dendritic system of canyons. The canyons heads are 3 to 9 km away from the shelf break, at 500 to 800 m water depth, which is a good example of slope-confined canyons.

2.4 Black Sea canyons of the Crimean area

The submarine canyons from the Crimean area occur within two physiographic zones: the gentle slope of the Don-Kuban deep sea fan and the steep slope of the Sevastopol-Yalta (Crimean escarpment) and Anapa-Gelendzik areas (Fig. 7). The Don-Kuban (Kumani) Canyon, the best known from the area, is well indenting the shelf south of the Kerch Strait.

Legend: Large canyons Main deep sea fan channels.

Figure 7. Large canyons from the northern Black Sea basin, the Crimean area. Satellite picture from Google Earth. Bathymetry in meters.

2.5 Black Sea canyons of the Bosporous area

Completing the previous data by Di Iorio *et al.* (1999), Okay *et al.* (2011) mapped the eastern Bosporous outlet area and identified a shallow marine fan and a canyon system. The canyons appear as a bunch of submarine valleys oriented transversally to the coast alignment (Fig. 8). The main Bosporous canyons are 50-55 km long. Within this system at least 12 canyons are distributed in an about 115 km wide area, northeast of the Bosporous Strait. They are quite closely spaced, with a 7-8 km distance between adjacent canyons. The dendritic aspect of the Bosporous canyons is minimal, the main canyons showing no more than one limb.

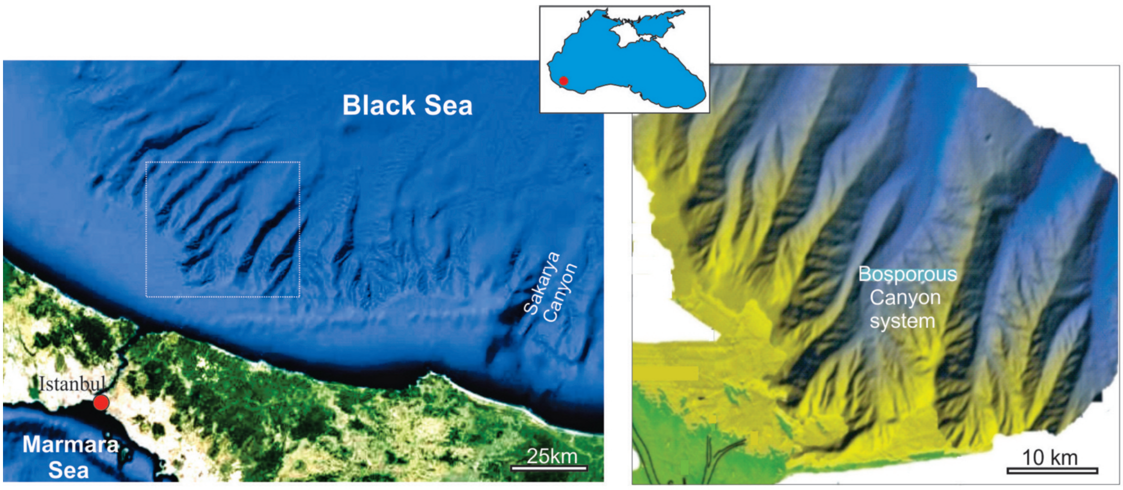

Figure 8. Bosporous submarine canyon system. Left-side image (from Google Earth) shows the general distribution of the Bosporous canyons. Detail of the central canyon system (modified from Okay *et al.,* 2011) in the right-side image.

2.6 Submarine canyons of the western Black Sea basin

Unlike all other Black Sea canyons, the canyons in the western part of the basin occur far away from the coastline, at the edge of a wide shelf (Fig. 9). Presently they have no connection with rivers, and are not functional.

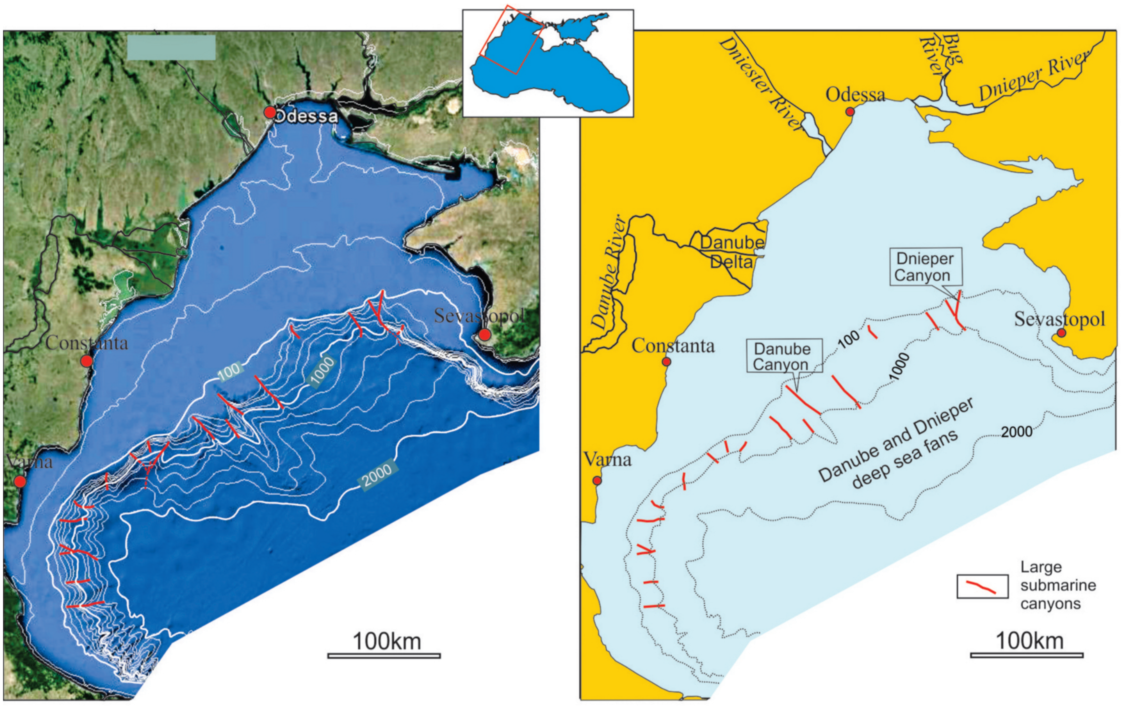

Figure 9. Large submarine canyons from the western and northwestern Black Sea basin. Satellite picture from Google Earth. Bathymetry in meters.

The most important canyons from the western and northwestern Black Sea basin are the Danube Canyon and the Dnieper Canyon (Fig. 9). They are both shelf-indented, but the smaller canyons close by are not incising the shelf. The larger development of the Danube and Dnieper canyons was facilitated by the longer and milder slope connected with the extensive Danube and Dnieper deep sea fans.

The submarine canyons distributed on the edge of the Bulgarian shelf, where the continental slope is steeper, are shorter and seem to be slope-enclosed.

3. The Danube river canyon – a case study

3.1 Morphology

The Danube Canyon (also called the Viteaz Canyon) is part of a 60 km long submarine trough with a NW to SE course (Fig.10).

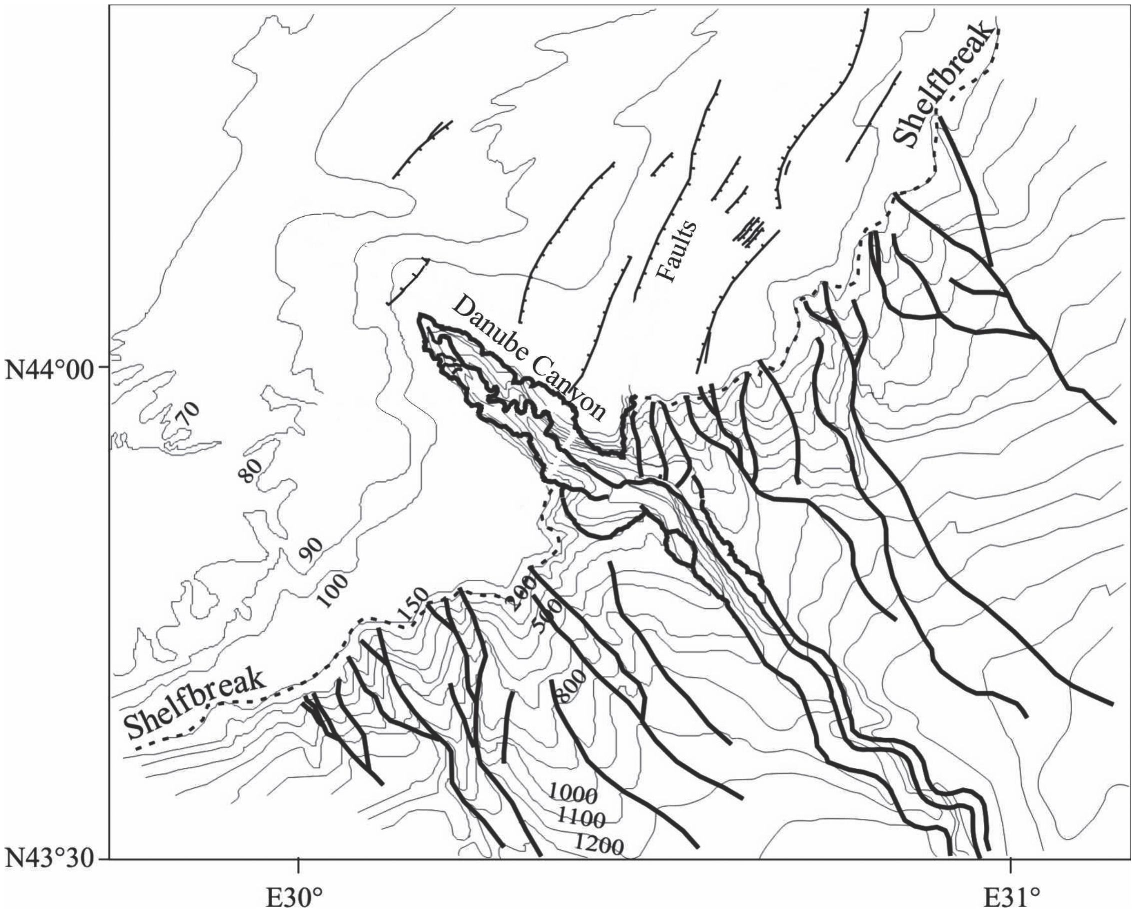

Figure 10. Morphology of the north-western Black Sea margin (after Popescu *et al.,* 2004). The Danube canyon is deeply incised into the shelf.

The 26 km shelf-indented segment of the trough, northwestward from the shelfbreak, is the Danube Canyon. At the shelfbreak level the canyon is about 6 km wide, and landward is getting narrower (Fig. 11). The canyon flanks are steep, with up to 30° declivity. They are part of an older erosional surface, infilled by sediments with a chaotic seismic facies, overlain by well bedded sediments (Fig. 12). The modern thalweg, 400 to 600 m wide and up to 400 m deep, is cut into these stratified sediments. The canyon shows significant longitudinal changes in morphology, direction and gradient. In the southeastern part of the canyon (segments C, D and E in Fig. 11), close to the shelf-break, there is a single entrenched axial thalweg, downstream progressively becoming more stable, straighter and deeper.

Strong meandering of the thalweg line, including meanders, is visible in the sector C of the canyon (Fig. 11). The canyon shows significant longitudinal changes in morphology, direction and gradient. In the southeastern part of the canyon (segments C, D and E in Fig. 11), close to the shelf-break, there is a single entrenched axial thalweg, downstream becoming progressively more stable, straighter and deeper. Strong meandering of the thalweg line, including abandoned meanders, is visible in the sector C of the canyon (Fig. 11).

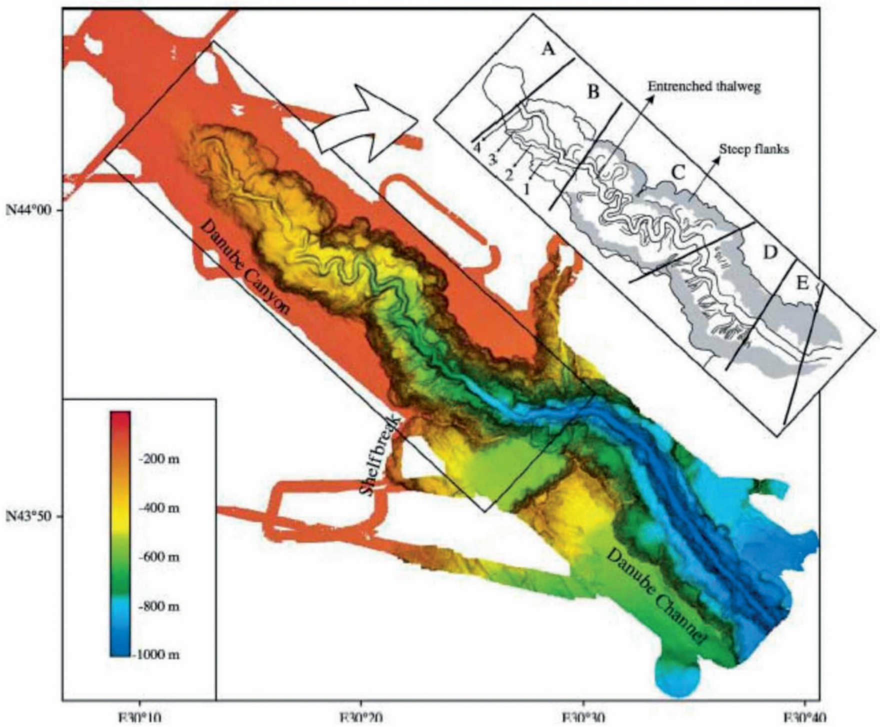

Figure 11. Bathymetric 3D map of the Danube Canyon (EM 1000 multibeam data) (from Popescu *et al.,* 2004). The inset box shows a schematic representation of the canyon morphology, and the segments A to E separated along the canyon. Distinct paths of the thalweg in segment B are numbered 1 to 4. Shaded areas mark the steep canyon flanks.

Close to the landward end of the canyon, the segment B (Fig. 11) is a trough with several converging small channels (1 to 4 in Fig. 11) and with gentler walls. At the landward extremity (segment A in Fig. 11) the canyon bed is concave, with no thalweg line and its walls are even less inclined.

Downstream of the shelfbreak the submarine valley becomes a channel, with smooth, concave-up profile. A knickpoint marks the boundary between the canyon and the channel.

The canyon longitudinal profile points to the strong entrenching of the valley, from less than 40m in segment A to about 230m in segment B, approximately 400 m corresponding to the segment C and 600 m close to the shelf break (segments D and E) (Fig. 13). Along with the continuous axial entrenchment, the canyon walls become steeper and steeper and wider and wider downstream (from 5° to 20° – 30° steep and from 2 km to 6 km wide).

3.2 Genesis and evolution

The transversal seismic reflection profiles reveal the presence of an erosion surface at about 240 m under the present-day thalweg (Fig. 12). This surface reflects the erosion process which initiated the first submarine valley stage. This morphologic inherited feature was subsequently developed by the erosional and depositional activities of the Danube Canyon. Thalweg downcutting caused instability of the flanks, probably triggering headward erosion of the canyon as in the apparently immature segment B (Fig. 11). Erosion in the axial thalweg also resulted in failures enlarging the major valley in the mature segments D and E (Fig. 11), directly (on the northern flank) or through a system of lateral gullies (on the southern flank). Segment C is a zone affected by erosion as well: perched terraces were created by failures inside the major valley, while abandoned meanders nearby the canyon walls determined the instability and widening of the canyon. The sediments with two different seismic facies are the result of the repeated stages of partial sedimentary infilling of the canyon trough. As revealed by the study of other submarine canyons (Shepard, 1981), the Danube Canyon evolved through a succession of erosion and deposition events.

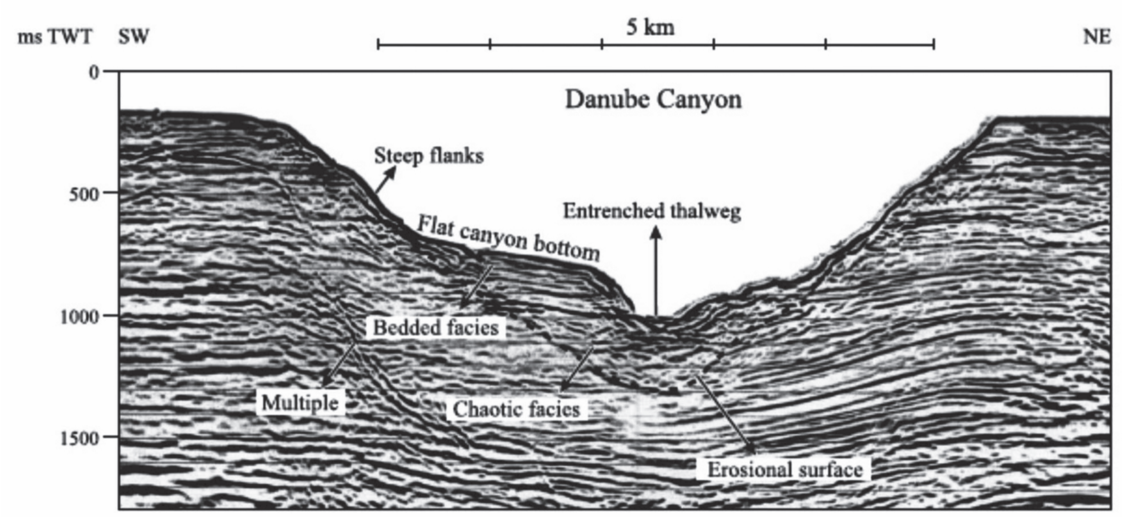

Figure 12. Sedimentary structure of the Danube Canyon (part of seismic industrial profile P941S-44) (from Popescu *et al.*, 2004). The line is situated across segment D. Canyon steep flanks are in prolongation of an ancient erosional surface (marked in dashed line), documenting a previous phase of canyon development. The infill consists of a chaotic seismic facies overlain by a high amplitude bedded facies, and is incised by the modern thalweg.

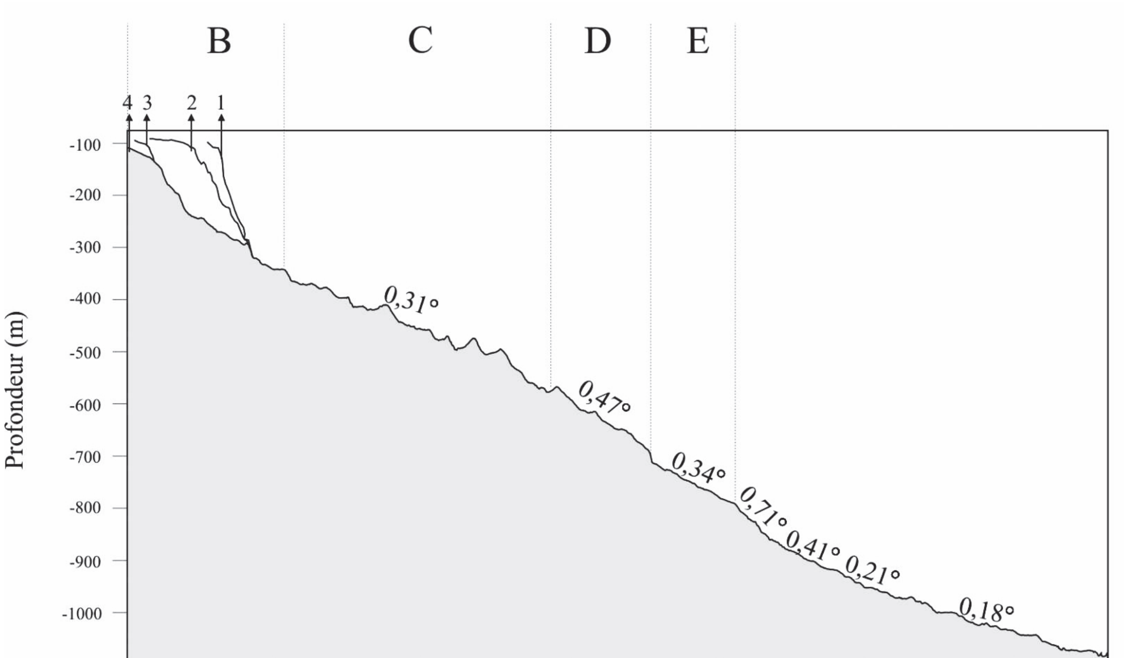

Figure 13. Longitudinal depth profile along the axial thalweg of the Danube Canyon/Channel (from EM 1000 multibeam data) (from Popescu, 2002).

The five segments of the canyon (Fig. 11), showing distinct features of morphology, orientation and gradient, are interpreted as zones of canyon advancement towards the coast. They also represent different maturity stages developed along the Danube Canyon valley.

Wong *et al.* (1994) consider that the Danube Canyon originated by processes of mass slumping produced on the continental slope and in time developed by subsequent retrograde slumping, during the following sea level rise episodes. The results of our studies indicate that canyon evolution was mainly due to erosion by heavily loaded bottom currents and/or by sediment flow generated during low sea levels stages. This idea is in agreement with the mechanism previously suggested by Shepard (1981), Pratson *et al.* (1994) and Pratson and Coakeley (1996).

There are significant morphology and structure features pointing out that the erosion processes generated the morphological features of the Danube Canyon. The axial thalweg is the erosional active zone of the canyon, where the canyon bottom downcutting resulted in trough entrenching. Sediment failures developed on the canyon lateral walls and headwalls due to the advancing entrenchment. These processes resulted in the canyon widening and promoted further landward shelf penetration by canyon headward erosion, along the sediment flow path and toward the source of the flow. Instability due to the presence of shallow gas in sediments and fault-controlled instability possibly contributed as additional mechanisms to cause sediment failures inside the Danube Canyon and its tributaries.

During the last Black Sea water-level lowstand the paleo-Danube River discharged close to the Danube Canyon head, maybe through a deltaic build-up (Fig. 14). During this most recent active stage of the canyon water, salinity was very low in the freshwater domain, which could have determined the initiation of hyperpycnal flows. In our opinion, the sediment-loaded flows related to the paleo-Danube River system stand for the main control factor of the Danube Canyon evolution.

3.3 Danube Canyon dating

The big unknown of the canyon evolution remains the age of this system. Currently, there is no independent age information either on the Danube Canyon incision and infill or on the fluvial buried channels we identified on the shelf. We can only assume that:

(1) The Danube Canyon is the most recent canyon related to the Danube River that developed in this part of the margin and its relief is preserved in the sea-floor morphology covered only by the Holocene deposits; therefore it was functioning during the last lowstand level of the Black Sea.

As a general rule, sea-level lowstands in the Black Sea do not necessarily correspond to global lowstands. The last sea-level lowstand in the Black Sea in particular, known as the “Neoeuxinian”, was generally considered as matching the marine isotope stage 2 (Chepalyga, 1985 and references therein), but this correspondence was recently questioned (Major, 2002). The canyon was thus active during the last lowstand, but the age of this period is still uncertain.

(2) Buried fluvial incisions on the shelf are sealed only by the thin Holocene blanket, so that they formed during the last sea-level lowstand. Consequently, they are coeval to the youngest phase of canyon evolution.

(3) The evolution of the canyon is related to the evolution of the Danube Channel, since they are parts of a unique canyon-channel system that acted as a whole. Previous estimates of the age of the Danube Channel (Popescu *et al.*, 2001) were based on the correlation of the fan sequences with the sea-level curve (Wong *et al.*, 1994; Winguth *et al.*, 2000). The Danube Channel was active during the last lowstand but also during earlier glaciations low-stands (Wong *et al.*, 1994; Winguth *et al.*, 2000), as indicated by the succession of sediment bodies evidenced in the deep-sea fan system and by ^{14}C datations in the distal part of this system (Strechie-Sliwinski, 2007).

Consequently, it is conceivable that the youngest phase of evolution of the Danube Canyon corresponded to the last lowstand of the Black Sea, but canyon formation has also undergone previous stages. Unfortunately, age constraints for the canyon initiation are currently non-existent, and further investigation is necessary to solve this problem.

3.4 Control factors

Sediment input. It has long been observed that many submarine canyons were spatially connected to rivers on the continent (Twichell *et al.*, 1977; Fulthorpe *et al.*, 1999). Modelling also indicated that canyon evolution should be most active when sediment influx to the slope is greatest (Pratson and Coakeley, 1996).

The Danube Canyon is presently situated more than 100 km from the Danube mouths. As river sediment is trapped by southward currents along the coast and on the inner shelf, the present-day supply to the canyon is interrupted (Panin, 1996). This was not the case during lowstand times when part of the shelf was exposed, allowing direct fluvial sediment delivery to the shelf edge and to the Danube Canyon (Panin, 1989).

In order to clarify the spatial relationship between the river and the canyon, we attempted to recognize (1) the location of the paleo-Danube river and (2) the location of the paleo-shoreline during the last lowstand period in the Black Sea, which was implicitly the last active period of the canyon. We investigated seafloor morphology and shallow stratigraphy of the continental shelf in front of the Danube mouths with the purpose of tracking buried fluvial channels - as a diagnostic feature of ancient drainage systems, and wave-cut terraces – generally considered as indicating the proximity of the coastline.

Paleo-rivers. We identified numerous completely filled channels on the continental shelf down to –90 m water depth (Fig. 14). They reach 400-1500 m in width and 20-30 m in depth. Channels are sealed only by a thin mud drape parallel to the sea bottom. There is no independent indication of the age of these incisions. However, their stratigraphic position lying directly under the discontinuity at the base of the Holocene strongly suggests that they formed during the last lowstand.

The distribution of the buried channels clusters around two main directions that seem to correspond to two distinct drainage systems (Fig. 14).

The southern system points straight towards the Danube mouths and most probably represents the paleo-Danube River. On the outer shelf the river apparently splits into several arms similar to a deltaic structure comparable in size to the modern Danube Delta, and lies close to the Danube Canyon.

The origin of the northern system is so far uncertain.

Paleo-coastline. A submerged wave-cut terrace was mapped for about 100 km on the outer shelf, below water depths varying between –90 m and –98 m (Fig. 14). The variable depth of the terrace seems to be related to the presence of the canyon since the terrace is obviously shallowest around the canyon head. This could be the effect of the redistribution of wave energy when approaching the shoreline, as energy is focused on promontories and dispersed in gulfs.

The last lowstand paleo-coastline should thus have been situated between this submerged terrace and the deepest buried fluvial channels (Fig. 14).

Our data show (1) a great number of buried fluvial channels on the shelf that suddenly disappear below –90 m depth, and (2) a wave-cut terrace on the outer shelf, with an upper surface varying between –90 and –98 m. This is consistent with a major lowstand level situated somewhere around –90 m depth.

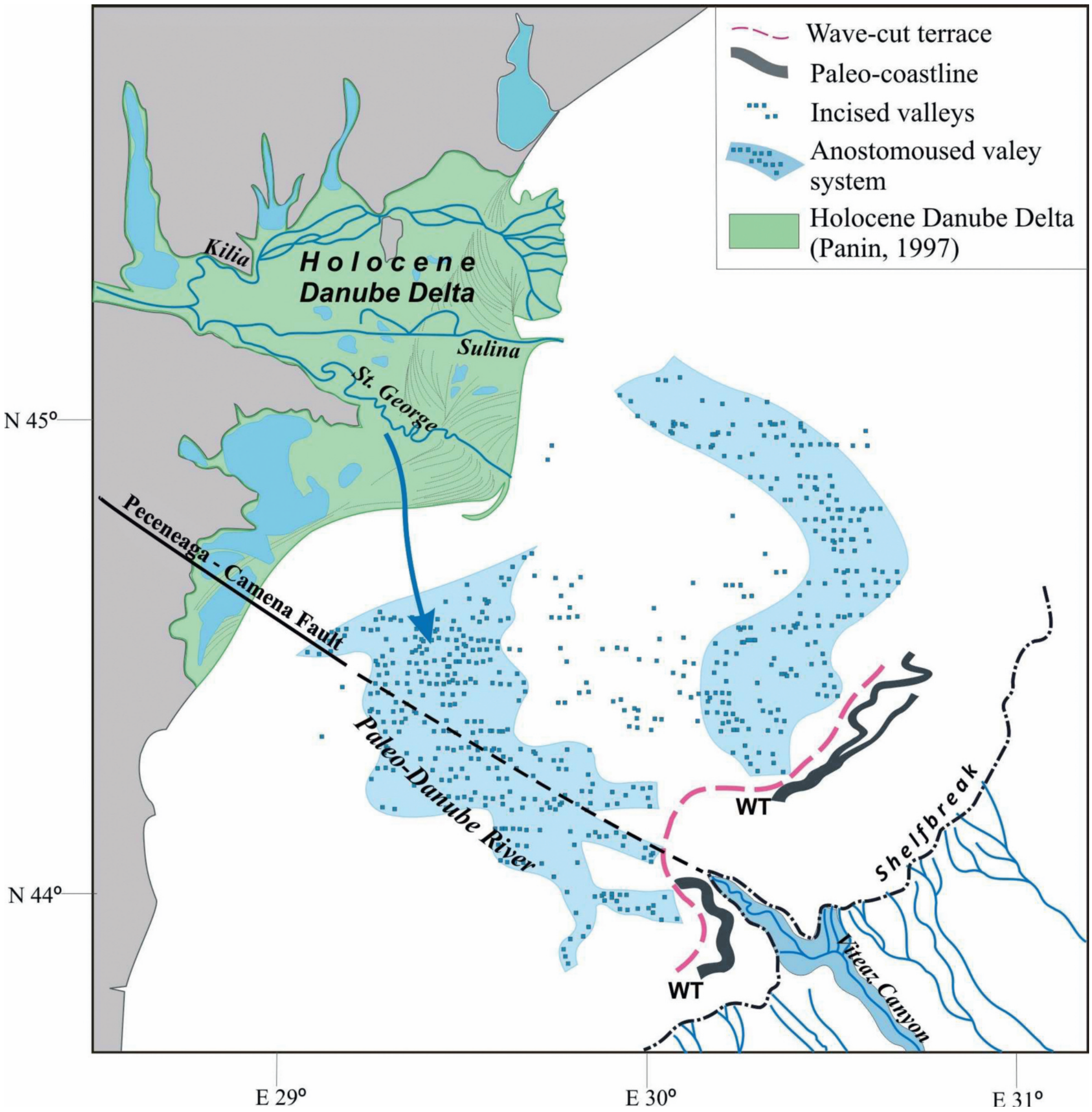

Figure 14. The hypothetical Paleo-Danube course on the exposed shelf area during the lowstands and the coastline location close to the shelf-break during the Last Glacial (from Popescu *et al.*, 2004).

Consequently, during the last water lowstand the Danube Canyon evolved in a shallow environment affected by high sediment supply. The paleo-coastline was forming a wide gulf in which it seems that two branches of the river were flowing. The canyon was entirely submerged and situated in the southern part of this gulf, in front of the paleo-Danube mouths and below the base of the wave-action zone, as attested by the position of the wave-cut terrace.

Meanwhile, it should be noted that the canyon developed under freshwater conditions that characterized the Black Sea during lowstands. The short distance between the river mouths and the canyon head, under environmental conditions that particularly favour the formation of hyperpycnal currents, suggests that the high sedimentary influx via the paleo-Danube was a major control on the canyon development.

Gas. The shelf edge of the north-western margin of the Black Sea contains evidence of abundant shallow gas and represents a zone of high fluid discharge (Vassilev and Dimitrov, 2000). Numerous gas seeps have been identified in this area (Egorov *et al.*, 1998). Most of them are located inside the Danube Canyon and along the landward prolongation of the canyon (Fig. 15). Gas seeps were also identified along the shelf break, on sub-recent faults north of the canyon, on the upper slope and in the upper Danube channel, usually related to failure areas.

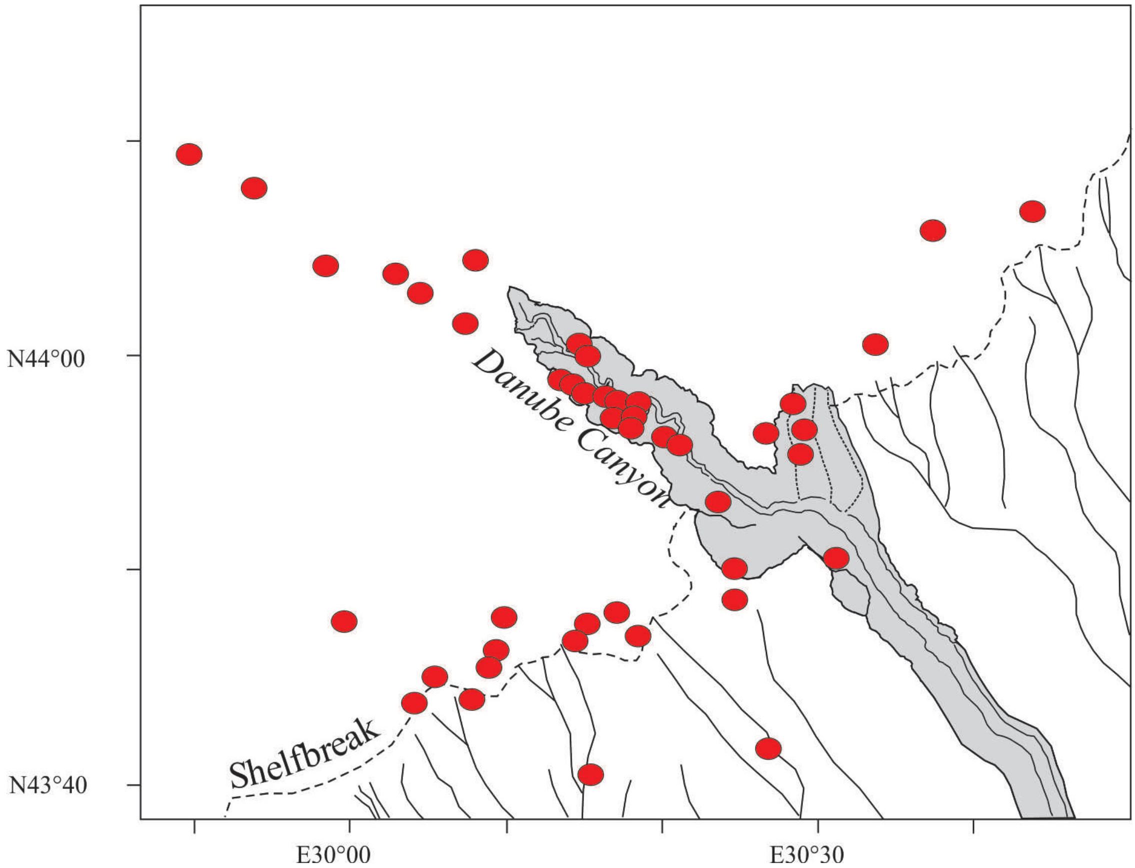

Figure 15. Location of gas seeps in relation to the morphology of the canyon area (from Popescu *et al.,* 2004, re-drawn after Egorov *et al.,* 1998).

Our seismic profiles show gas-related acoustic turbidity beneath the canyon, but also along its prolongation, commonly corresponding to the spatial distribution of the gas seeps. The gas area along the canyon has a limited lateral extent, so that the presence of the gas escape zones inside the Danube canyon is not due to exposure of a widespread shallow gas zone to the seafloor through erosion. In addition, the alignment of the gas seeps follows the same direction landward of the canyon (Fig. 15), which could be in relation with compression along a regional fault and thus a possible indication for a deep fault under the canyon. Moreover, profiles across major buried paleocanyons show acoustic turbidity clustering preferentially in the canyon areas (Popescu and Lericolais, 2003). It seems probable that the location of the gassy facies could have favored instability in the canyon area and possibly triggered sediment failures.

4. Conclusions

The Black Sea canyons characteristics depend on the relief energy of the coasts they are associated with. Considering their present-day dynamic characteristics, there are two main categories of canyons in the Black Sea: active canyons and inactive (inoperative) ones.

The active canyons are located in front of the mountainous Black Sea coasts (Caucasian and Pontic mountains), in zones with narrow shelf; they deeply cut this shelf, have steep walls and high gradient thalwegs and receive coarse-grained sedimentary load from closely discharging rivers or their deltaic built-up.

The northwestern and western part of the Black Sea, characterized by low, accumulative coasts and extensive shelf, is the region where the largest canyons (Danube and Dnieper canyons) are located. Only during the sea lowstands the paleo-rivers Danube and Dnieper extended across the shelf and fed the respective submarine canyons. The canyons formed in front of large shelf areas with low relief energy coast are generally supplied with finer-grained sediments and their deep-sea fan systems differ from the systems of mountainous coasts.

The Danube Canyon is a major erosional feature, deeply indenting into the shelf edge. The canyon consists of a main trough with steep flanks and a flat bottom incised by an entrenched thalweg. The sedimentary structure of the canyon shows evidence of previous cycles of erosion, followed by partial infilling and subsequently reincised by the modern canyon. Thus the canyon has not undergone a single-phase catastrophic formation, but a cyclic evolution with several erosion cycles of different magnitude.

On the basis of the geomorphological analysis, it appears that the main mechanism for canyon development was the sediment-flow-driven retrogressive erosion and even canyon-head wall failure. Sediment flows were most probably generated as high-density currents at the mouths of the paleo-Danube River, favoured by the low salinity conditions of the Black Sea basin during its lowstand phases. The high sediment influx in this part of the margin was therefore a major control on the canyon development, but other complementary controls (gas-related instability, deep fault control) could have contributed as well.

The Danube Canyon is connected to the Danube Channel and to channel-levee system on the Danube fan that extends to the abyssal plain down to 2200 m depth. The canyon represents the upper end of this system and acted as a gateway for transferring sediments between the shelf and the deep basin. High river discharge in the vicinity of the canyon, with probable hyperpycnal flow at the river mouths, suggests that a quasi-continuous river-canyon-fan channel system functioned in this part of the margin, ensuring highly effective transfer of the terrigenous sediments towards the deep sea.

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