BLACK SEA SUBMARINE VALLEYS – PATTERNS, SYSTEMS, NETWORKS

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Abstract. The article presents a detailed analysis of the underwater morphology of the entire Black Sea basin beyond the shelf break. The focus is on submarine valley systems on continental slope and rise zones, and partially in the abyssal plain area. The present research is among the very few studies that have undertaken a morphological analysis on a regional scale, for an entire marine basin. This achievement was possible by using the publicly available EMODnet bathymetric map of the Black Sea. The Black Sea submarine valleys networks are presented in a map-sketch. It includes 25 valley systems, 5 groups of simple first order channels, and other number of simple, not associated channels. The 25 valley systems are adding up more than 110 main channels and tributaries. Morphological description and analysis of each of the mapped systems is given – shape and plan view morphology, dimensions (length and surface) and slope gradient. Some considerations about the amount of sediments supplied by the valleys from the shelf to the basin floor, forming the deep-sea fans, are presented.

For a more detailed and precise image of the Black Sea network of submarine valleys additional work would be necessary to cover the entire basin with a minimum standard network of modern bathymetric mapping and of high resolution seismic survey lines. To take into account the composition and geological structure of different sectors, as factors that influence significantly the morphology of the seabed, would be also particularly useful.

Key words: Black Sea, canyon, deep sea fan, fan valley, submarine valley system

1. INTRODUCTION

As in any marine basin bordered by varying relief terrain, on the Black Sea continental slope there are multiple submarine valleys (Fig. 1). The canyon systems of the entire basin were presented (Panin *et al.*, 1997) at a time when the knowledge on the Black Sea bathymetry was in the initial stage (Ross *et al.*, 1974). Important progress has been made in the study of the Black Sea submarine bathymetry, and the EMODnet Bathymetry chart is the highest resolution dataset available (Miguez *et al.*, 2019; Thierry *et al.*, 2019).

The main objective of this paper is to present a closer view on the Black Sea submarine valley systems and networks, at the resolution corresponding to the current, publicly available EMODnet Bathymetry chart. This includes mapping valley systems and differentiating between canyon and fan valley (upper and lower) types of submarine valley channels (Fig. 1).

The main morphological characters of the submarine valleys and the distribution of sedimentary accumulations associated with the formation and evolution of these valleys are also important concerns of the study. The networks of Black Sea submarine valleys have been analysed in six perimeters, covering the Black Sea basin (Fig. 1). However, due to insufficient information, the Black Sea submarine escarpments were only briefly discussed.

2. MATERIALS AND METHOD

Method. The necessity to build up a more detailed picture of the Black Sea submarine valleys networks become obvious during recent years when research in the area intensified. The opportunity to carry out this project became feasible when the recently made Black Sea bathymetry map became public domain. This is the digital high-resolution EMODnet Bathymetry chart, part of the EMODnet digital model (European Marine Observation and Data Network). GEBCO_2019 (NOAA) DTM was also used (Amante and Eakins, 2009).

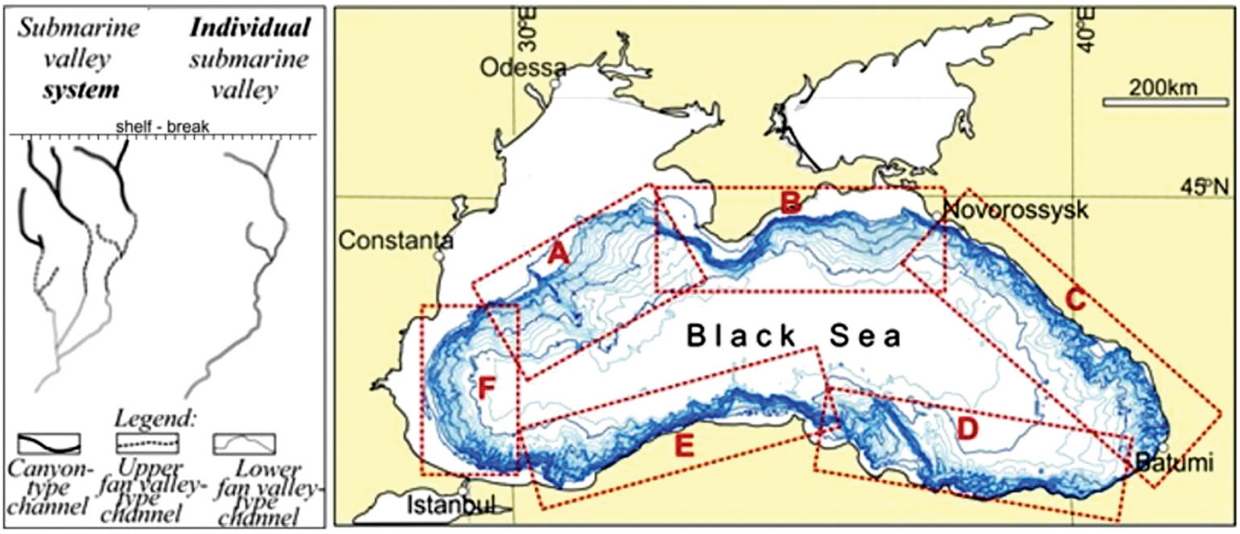

Fig. 1. Black Sea submarine valleys. Objective (left side) and study area (right side). See text for further discussion

The submarine mapping in this project focused on systems of valleys rather than on individual valleys. The term *valley system* used in this paper refers to a submarine valley entity consisting of main (trunk) channel and its flowing in (*tributaries*) or flowing out (*distributaries*) associated channels (Fig. 1). The submarine valley systems are commonly recognized in the slope area and analysed separately in a distinct submarine region, or the analysis is reported for the entire Black Sea basin.

The Black Sea submarine valley network map relied on the use of sea bottom relief chart presented by EMODnet Bathymetry. The thalweg of the valleys identified on the chart was drawn according to their morphologic significance. To present a more informative picture of the Black Sea submarine valleys, we separated the valleys into the upper course, *canyon-type,* and the lower course, *fan valley*, channels (Fig. 1). In most cases, it was also significant to distinguish on the fan area *the upper fan valley* versus *the lower fan valley* channels. The canyon and fan valley constituents of a submarine valley were marked differently according to three morphologic characteristic: bottom relief, axial gradient of the channel and shape of the channel transversal profile. Reflecting these connotations, the terms canyon and fan valley are used in this paper with the following meanings:

- *canyon (canyon-type channel)* is the relatively narrow submarine channel from areas of the slope that have higher gradient and irregular surfaces, typical of basin margin slope areas;
- *fan valley* term refers to the lower course of a submarine valley that is crossing lower relief sea bottom, in the continental rise area, that has gradients lower than on the slope, and wide and relative shallow channels. The fan valley generally can be subdivided into:
    - *upper fan valley* that shows intermediary morphologic features between the canyon-type and lower fan valley-type channels. The upper fan valleys are commonly located in the upper part of the continental rise;
    - *lower fan valley* is the downstream end section of a submarine valley crossing the smooth and very low declivity at the base of the continental rise, while extending toward the abyssal plain.

The canyon and fan valley channels are two morphologic aspects of the same, continuous submarine valley (Shepard and Buffington, 1967) (Fig. 1). The boundaries between the above-mentioned submarine channel types are transitional and in some cases subjective to establish. This is because there are no very clear criteria for accurately mark the boundary between the canyon-type and the fan valley-type channels when they gradually change morphology. Moreover, the distant extension of the lower fan valley channels to the abyssal plain is evaluated on lower resolution sea bottom bathymetry data. Consequently, the separation between the upper and lower fan and the morphology parameters are based on partly subjective evaluations. The bathymetry data have been significantly improved but not enough to create maps with exact and indisputable valley segments on the figures.

The name of submarine valleys and their systems. This study maintained the Black Sea submarine canyons names known from the literature. In some cases, the Black Sea canyons mentioned in the literature have names after the coastal location of one of their canyon heads. In more than one instance, the map of the Black Sea submarine valley prepared in this study highlighted valley systems, individual channels or important valley branches not previously evidenced and mentioned in the literature. In view of their description, new features are named according to rivers or localities located close to the canyon head.

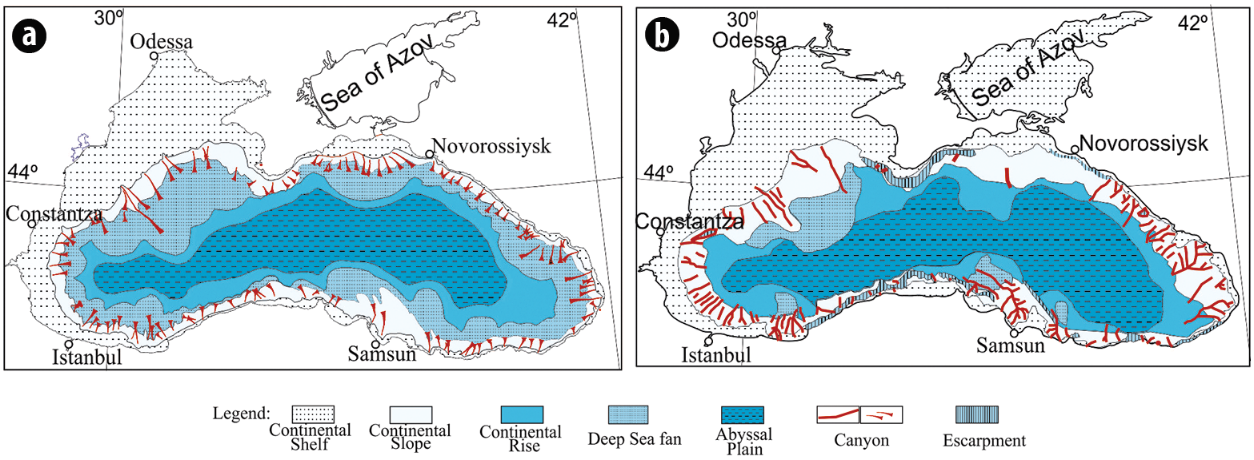

Fig. 2. Black Sea submarine valley network presented by (**a**) Panin *et al.*, 1997 and (**b**) Harris *et al.*, 2014.

3. SUBMARINE VALLEYS IN THE BLACK SEA LITERATURE

3.1 Previous data on Black Sea submarine valley network

Panin *et al.* (1997) made the first submarine valley network map of the entire Black Sea basin. The 112 valleys/ canyons marked by Panin *et al.* (1997) are irregularly distributed on the geomorphological map of the Black Sea (Fig. 2a). Panin et al (1997) map shows 18 valleys/ canyons in the west, 12 in the north-western Danube-Dnieper submarine area, 20 in the northern Black Sea (7 south of Crimea and 13 within the Azov Fan), 31 in the eastern Black Sea (offshore Caucasus), and 42 in the southern Black Sea and 6 in the area offshore Western Turkey and Bulgaria.

Black Sea submarine canyons are also marked on the global seafloor geomorphic map published by Harris *et al.* (2014). The Harris *et al.* (2014) study focused on the large Black Sea canyons, *with a depth range of at least 1000 m and incised at least 100 m into the slope,* as defined by Harris and Whiteway (2011) (Fig. 2b). The Harris *et al.* (2014) map shows the branched pattern of some Black Sea canyon systems from the eastern and southern Black Sea (North of Turkey). Harris *et al.* (2014) study points out that large canyons are almost absent in the escarpment areas, and no large canyons are shown on their map in the Black Sea area south of the Sea of Azov.

3.2. Previous data on specific submarine valley networks

The study of the northwest Black Sea area was initiated in the 1990s by the new seismic data collected (Wong *et al.,* 1994; Popescu *et al.,* 2004) and continued until recently (Constantinescu *et al.,* 2018). These early investigations focused on the north-western Black Sea submarine valley networks detailing mainly the morphology and evolution of the Danube submarine valley. A comparison between the north-western (Danube-Dnieper area) and the eastern Black Sea (submarine Caucasian area) regional canyons and fan-valleys network emphasized morphological differences between the two areas (Jipa and Panin, 2020).

3.3. Previous data on Black Sea submarine valley systems

Complementary to the interest in the Black Sea basin-wide canyons, the study of the local canyon networks is long overdue in the Black Sea literature. Until recently, many Black Sea canyons were known only through the effects on water circulation and sedimentation produced in their canyon head area (Zenkovich V.P., 1960, 1962; Buachidze J.M. and Djandjgava C.I., 1977; Zenkovich V.P. *et al.*, 1987, 1988; Kiknadze A.G., 1995; Bilashvili K. *et al.*, 2007).

In the submarine area in front of the Danube, detailed bathymetric and seismic mapping of the slope revealed the morphology of the large-scale system of the Danube Submarine Canyon. The investigation of the Danube Canyon and its extension into the deep sea area was the main objective of the detailed studies undertaken through German-Romanian (Wong *et al.*, 1994, 1997) and Romanian-French collaboration (Lericolais *et al.,* 1998; Panin *et al.,* 2001, Lericolais *et al.,* 2002; Popescu, 2002; Popescu *et al.,* 2004; Panin and Popescu, 2007; Popescu *et al.,* 2015; Constantinescu *et al.,* 2015).

In addition to the Danube deep-sea valley system, only in a few other cases bathymetric data highlighted individual Black Sea submarine systems in detail. Published Black Sea submarine bottom relief data detail parts of the systems such as the canyon head area (Billashvili, 2007; Algan *et al.*, 2002), individual sectors of the deep water submarine valleys (Shimkus *et al.*, 1997; Khrischev K., *et al.*, 1980; Krastev, T.I. *et al.*, 1984; Sipahioglu *et al.*, 2013; Klaucke *et al.*, 2006; Kannon *et al.*, 2007; Bohrmann and Pape, 2007; Bohrmann and Ohling, 2011), or a particular tributary branch of the valley system (Naudts *et al.*, 2006; Gulin *et al.*, 2013).

4. PRESENTATION OF DATA

4.1. Submarine valley systems of the north-western Black Sea

In the north-western Black Sea, the relief of the sea bottom evolves from the shoreline to more than -2 000 m in the deep sea. Compared to other areas, the north-western Black Sea is individualized by a very wide shelf (North-western Black Sea Shelf) and an important deep sea fan (Danube-Dnieper Fan) (Fig. 3a).

4.1.1. Danube deep-sea submarine area

The Danube Canyon and its down-slope deep-sea extension is one of the largest Black Sea submarine valley system. Marine geology studies conducted in the north-western Black Sea revealed several main components of the Danube submarine valley system: Paleo-Danube River network on the shelf, shelf-incising Danube Canyon, Danube Channel on the continental slope and channel levee distributaries system on the continental rise as part of the Danube Fan. The Danube Canyon, the largest submarine valley in the Black Sea, was discovered in 1950, during an echo sounder cruise, being initially named Vityaz Canyon, after the name of the cruise vessel (Dimitrov and Solakov, 2002). The submarine morphological units have been described in detail in more than one paper (Wong *et al.*, 1994 and 1997, Popescu *et al.*, 2001 and 2004, Panin *et al.* 2007 and 2011, Lericolais *et al.*, 2008 and 2012), in a PhD thesis (Popescu, 2002) and in a book (Popescu, 2008).

The *Danube Canyon* name is given to the 26 km shelf-incising submarine channel (Popescu *et al.*, 2004) (Fig. 3b). The canyon is practically without tributary channels, the small inflowing channels noticeable in the canyon pattern appearing as part of its internal morphology structure.

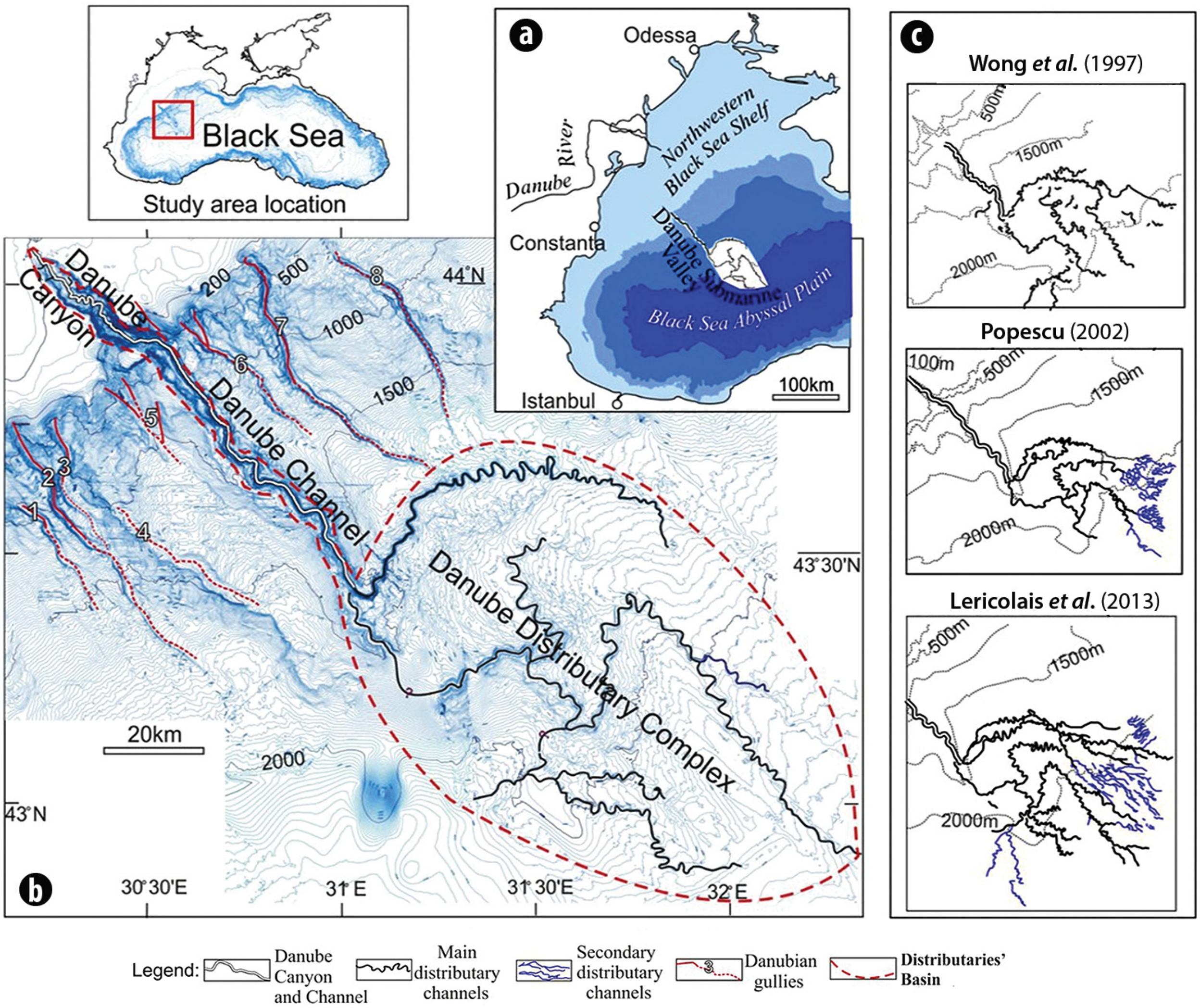

Fig. 3. Danube submarine valley system. Legend: (**a**) General location; (**b**) Only the submarine valleys identified on the EMODnet Bathymetry chart are drown in this figure; (**c**) The shallow, intricate distributary channels of the lower Danube submarine valley system have been highlighted by detailed maps (modified after Wong *et al.*, 1997, Popescu, 2002, Lericolais *et al.*, 2013).

The 2.4 km wide, 270 m deep (Lericolais *et al.*, 2013) and about 100 km long extension of the Danube Canyon along the continental slope, has canyon morpho-structure (deep and narrow), except it also has definite levee features. This is why it received a special name, the *Danube Channel* (Popescu *et al.*, 2004) (Fig. 3a).

Wong *et al.* (1997) used the name "main channel" that includes the Danube Channel and one of its extensions in the area of the channel-levee system. The Danube Canyon is presented as mostly erosive and the Danube Channel as mostly depositional according to Popescu *et al.* (2004). There are no clear tributaries to the Danube Channel that is a direct extension of the shelf to upper slope canyon.

The Danube Deep Sea Distributary Complex or System, a large and intricate network of channel-levee channels (Fig. 3b), continues the Danube deep-sea channel downstream. The size of the area covered by the distributary channels exceeds 6,000 sq. km. With more than one avulsion points, the distributary channels have high sinuosity and channels have wide levees with, in certain areas, up-slope migrating sediment waves (Lericolais *et al.*, 2015). Popescu *et al.* (2001) distinguished six channel-levee systems which together form Danube Deep Sea Distributary Complex. The levee-channel mapping, including the minor ones, has been a long-standing concern for the studies conducted in the Danube submarine area between 1997 and 2013 (Fig. 3c). Some of the shallow and variable morphology small channel-levees were not identified on the EMODnet Bathymetry chart.

Close to the Danube Canyon and Danube Channel, to the north-east and south-west of it, there are several small submarine valleys presented here as gullies. Only few of these channels are longer than 60 km (like submarine gully 7 in Fig. 3b). The downslope end of some of the submarine valleys, which are in the vicinity of the Danube Canyon, appears to be very close to the Danube's main channel (gullies 7 and 8 on Fig. 3). In Figure 3b, the upstream segments of the upper continental slope gullies have been represented as submarine canyons (Fig. 3a), but they are much shallower compared to the channel of the Danube Canyon. These gullies become very shallow and difficult to map in a downslope direction (Fig. 3b).

4.1.2. Dnieper deep-sea submarine area

Although a large Dnieper paleo-fluvial shelf-incising channel was discovered by Lericolais *et al.* (1998), in the deep-sea area only few Dnieper submarine valleys have been identified on the bathymetry chart or seismic investigations (Wong *et al.*, 1997) (Fig. 4).

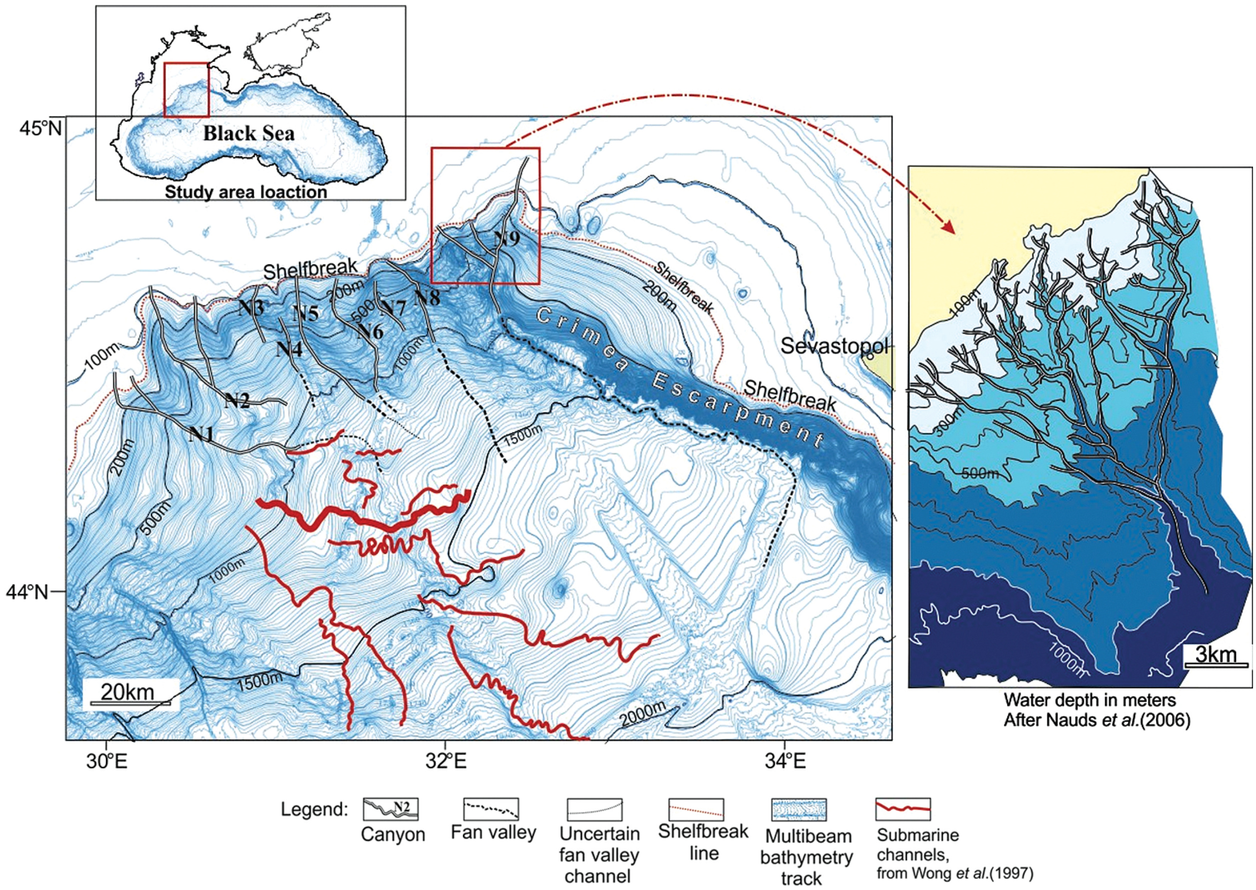

Fig. 4. Submarine valleys of the Dnieper Fan revealed on the EMODnet Bathymetry chart. The channel system mapped by Wong *et al.* (1997) was transferred on the map. Right side: detailed swath bathymetry of the north-eastern Dnieper Fan N9 submarine canyon; modified from Naudts *et al.* (2006).

Nine submarine valleys noticeable on the EMODnet map are located in a narrow, north-western area of the Dnieper Fan, near the shelf-break. The bathymetry map indicates the steep sea bottom gradients in this area of the slope, and based on this observation, the channels mapped are regarded as canyons (Fig. 4). Three of these small canyons (N3, N4 and N7) are about 15 km long. The canyons N1, N2, N5, N6 and N9 are the longest, up to 40 km length. The N1 and N8 canyons extend for additional 30-40 km with shallow valleys (Fig. 4). The N9 canyon is the only one in the Dniepr area that has two main upstream tributaries. In fact, the submarine valley model in the Dnieper deep-sea fan area is much more complex. The fan complexity is shown by the swath bathymetry map carried out by Naudts *et al.* (2006) (Fig. 4). A long fan valley extends downstream from the N9 canyon (Gulin *et al.*, 2013) (Fig. 4). For about 90 km, this fan valley can be followed along the base of the Crimean Escarpment.

4.2. Submarine valley systems of the northern Black Sea

4.2.1. Crimea Submarine Escarpment area

The Crimea Escarpment is one of the steepest zones of the Black Sea continental slope. With more than 300 km length, the escarpment extends westward and eastward offshore Crimea (Fig. 5a).

Numerous submarine valleys appear on the EMODnet Bathymetry map, in the western Crimea Escarpment area. The length of the submarine valley extends the entire width of the escarpment. More than half of these valleys have a single channel, straight or slightly curved, without tributaries. Other valleys are branched, with two or three arms. In the eastern part of the Crimea Escarpment, eastward of Yalta, the escarpment slope is gentler than in the west and it is wider (30-40 km).

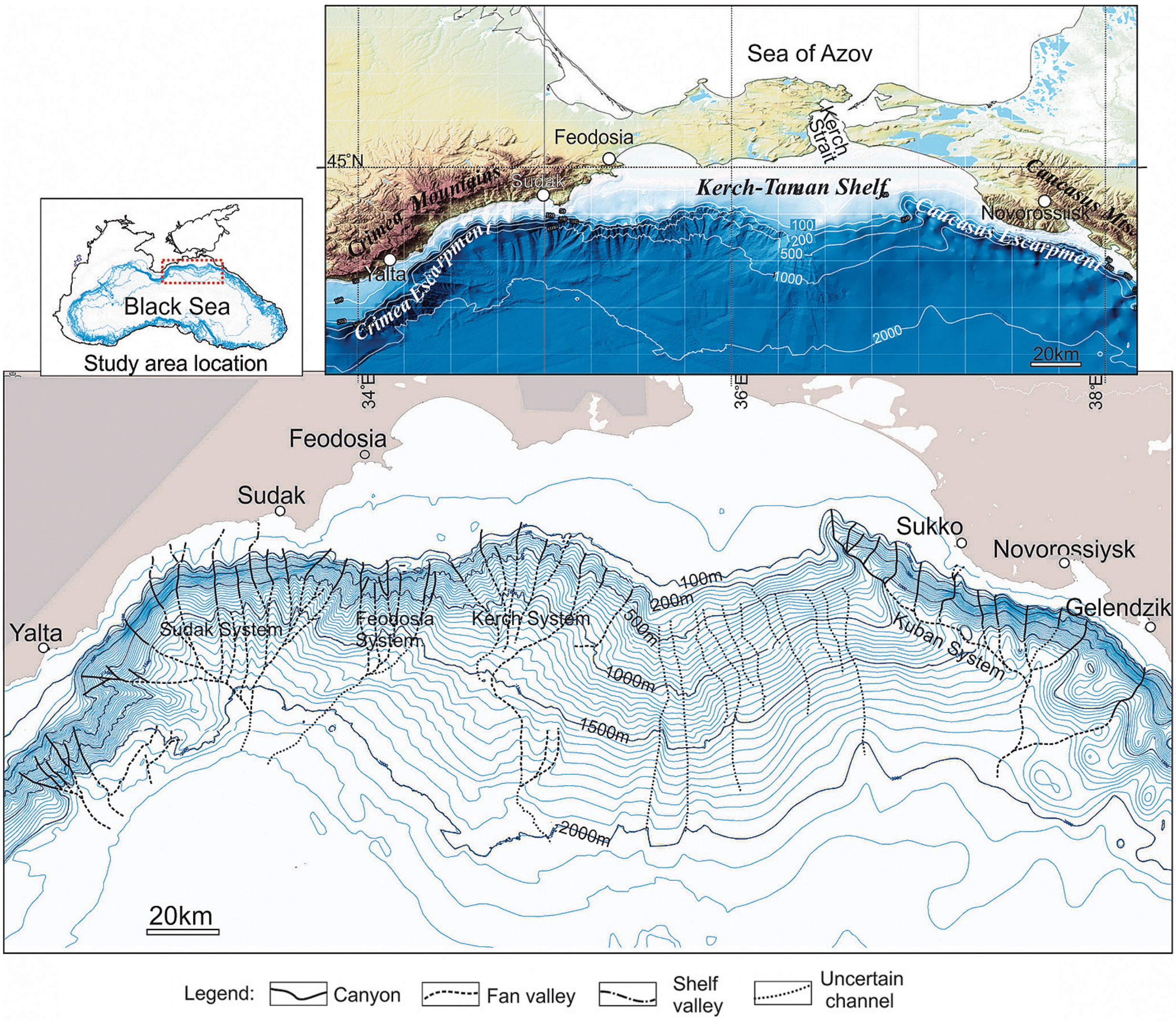

Fig. 5. Submarine valley systems in the northern Black Sea. (**a**) Physical-geography setting - EMODnet Digital Terrain Model (DTM). (**b**) Submarine valleys offshore Yalta-Kerch area. EMODnet Bathymetry Chart.

4.2.2. Northern Black Sea

The northern Black Sea area has a moderate shelf width and is connected to Sea of Azov through Kerch Strait, and according to our division, is well defined by several important physical-geography features (Fig. 5a). Its shoreline area describes a wide arcuate boundary between the Crimean Mountains in the west and the northern Caucasus Mountains in the east, and between the Crimean Submarine Escarpment and the Caucasus Escarpment.

Submarine valleys offshore Yalta - Kerch zone. Immediately south of the shelf-break, in the deep-sea area southwest of the Azov Sea, several submarine valley systems with similar characters have been identified. They have been *ad-hoc* named from west to east, Sudak, Feodosia and Kerch (Figure 5b and c). The above-mentioned submarine valleys can be traced downslope to below the 2,000 m water depth, and among the three valleys the western Sudak Valley System is the best defined.

An important feature of the three submarine valley systems identified is their multi-tributary, tree-branching-like drainage pattern. (Fig. 5b and c). For each system, a long single-channel fan valley extends from the confluence point of the dendritic submarine channels to the abyssal plain.

On the EMODnet Bathymetry chart, several canyons in Sudak-Yalta offshore area, belonging to submarine systems Sudak and Feodosia, are visible on the external self. The heads of these canyons are located at 90 m to 60 m water depth (Fig. 5b).

The drainage areas of the three dendritic valley systems in the Kerch Strait-Yalta offshore area are of various extensions. The Sudak System, the best defined and the most extensive, drains a submarine bottom surface of more than 2,000 sq. km.

Submarine valleys southward of the Kerch Strait. Eastwards, the Kerch Submarine Valley System (Fig. 5), where the EMODnet map is without high-resolution bathymetric data, a vague fan-like sea bottom pattern emerge on the EMODnet data (Fig. 5a), but the bathymetry chart is insufficiently detailed to reveal the submarine valley talwegs. Eastward of this feature Glebov and Shelting (2008) study highlights a complex of shallow, largely sinuous submarine valleys. With the NNV-SSE dominant direction, the valleys extend below the -2,000 m contour line.

4.3. Submarine valley systems of the eastern (Caucasian) Black Sea

One of the most significant characteristic of the eastern Black Sea area is the proximity of the Caucasus Mountains to the shoreline. Numerous rivers have springs in this mountain range and flow into the eastern part of the Black Sea (Jaoshvili, 2002). The Eastern Black Sea continental self is very narrow and divided in three parts (Jipa and Panin, 2020). Many submarine canyon heads in the eastern part of the Black Sea are only a short distance from the shoreline (Bukhidze and Djandjgava, 1977; Zenkovich *et al.*, 1981; Zenkovich and Schwartz, 1987; Zenkovich and Shuysky, 1988). The configuration of the canyon and fan-valley network from the eastern Black Sea, Caucasian area, was recently reviewed in a publication by Jipa and Panin (2020).

4.3.1. Kuban Submarine Valley System

Located in the north-eastern Black Sea, offshore Anapa and Novorossiysk (Fig. 6a), the Kuban Canyon is large and was imaged on old regional, low resolution bathymetric maps (Kara, 1979, Melnik, 1982-2001, Evsyukov *et al.*, 1986, Yevsyukov, Kara, 1989,1990).

The Kuban Submarine Valley has the distinctive character of being roughly parallel, in the upstream part, with the Caucasus Escarpment (Fig. 6b). Along the main channel of the Kuban Submarine Valley, there are three types of channels with specific morpho-structural features: canyon, upper fan valley and lower fan valley (Fig. 6). The upper course of the valley extends from 60 m to almost 1,000 m water depth and has the highest axial slope gradient forming the Kuban Canyon (Fig. 6a and b). Further downstream, the main channel crosses through an area with increasingly flat bottom relief, in water depths that extends - 2,000 m, passing into the Kuban Fan Valley. The upper part of the fan-valley has channel slope and bottom morphology gradually changing from those of the canyon. The Lower Fan Valley is located entirely on the flat relief area of the continental rise (Fig. 6b).

Evolving near the Caucasus Escarpment, with the high and steep relief of the escarpment on the left side of the valley, the Kuban Canyon and Kuban Upper Fan Valley show a significant asymmetry of the transverse profile. The Caucasus Escarpment slope extends to the proximity of the Kuban Canyon axis, affecting only the upper part of the Upper Fan Valley tributaries. The Lower Fan Valley is completely out of the escarpment area, passing through a very low sea-bottom relief area (Fig. 6b).

The Canyon and Upper Fan Valley is oriented northwest to southeast while, the Lower Fan Valley extends from north to south, changing abruptly its direction (Fig. 6b).

Several canyons of the Kuban Submarine Valley system, tributaries to the main valley, incise the shelf for small distances, notably the Sukko Canyon head (Fig. 6b).

4.3.2. Krinitsa, Tuapse and Sochi Submarine Valley Systems

Three submarine valley systems have been identified in the Gelendzhik-Sochi offshore area: Krinitsa, Tuapse and Sochi (Fig. 7a). The bathymetric map of the area is not supported by modern, high resolution data, and the plan-view identification of the stream channels is sometimes less accurate. The drainage patterns of these three systems are similar, consisting of two or three main branches, with tributaries. The complexity of the drainage model increases from the Krinitsa system, in the northwest, to the Sochi

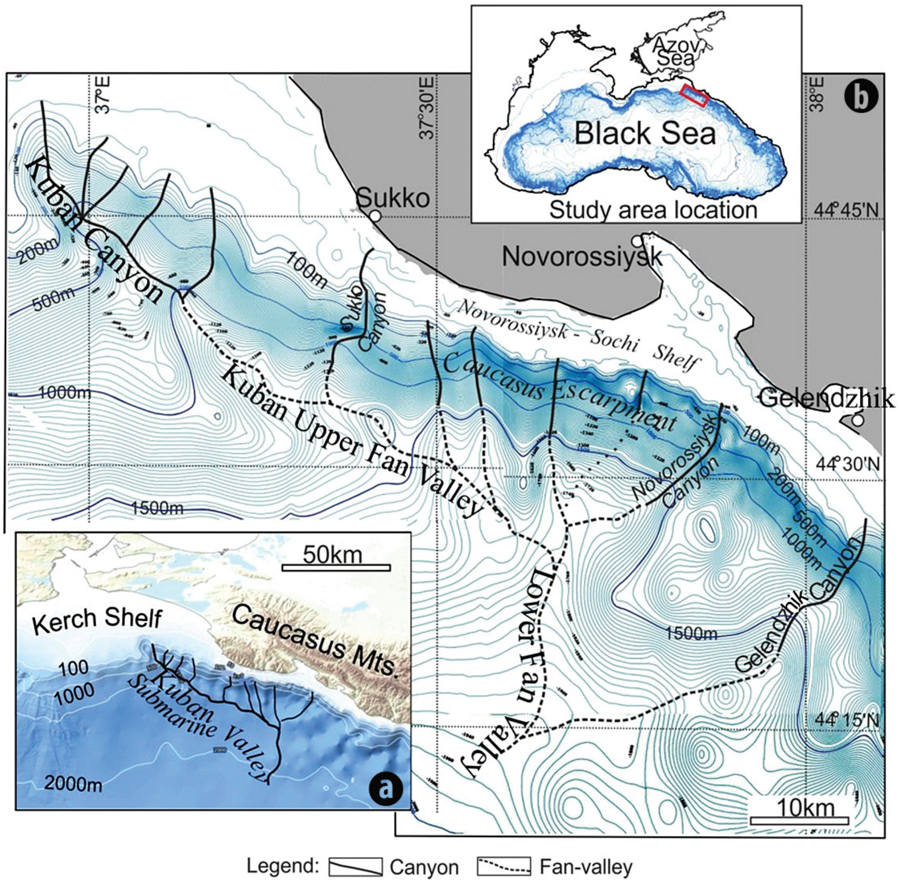

Fig. 6. Kuban Submarine Valley. (**a**) General geographic setting of the northern Caucasus area. EMODnet Bathymetry. (**b**) Kuban Submarine Valley system on EMODnet Bathymetry chart.

system, in the southeast. Between the three systems, there are also several simple, single-channel submarine valleys.

The main branches of the Krinitsa, Tuapse and Sochi submarine systems are 25 to 35 km long with confluences at different water depths: Krinitsa at about 2,040 m, Tuaspse at nearly 2,100 m and Sochi at about 1,940 m (Fig. 7b, c, d). From the water depth of approximately 1,000 m (continental slope lower part) the canyon channels of each system are passing down-slope into fan-valleys, and confluence at about 1,500 m water depth.

As revealed by the bathymetric map, the canyon head course of the main Krinitsa System channel incises the shelf, extending to about two kilometres close to the shoreline. The other canyon heads of the systems are located at the edge of the 2 to 10 km wide shelf.

Downslope of the last confluence of the lower fan valley channel extends 15 to 30 km to the abyssal plain.

4.3.3. Bzyb-Mzymta Submarine Valley System.

A short distance south-east of the Sochi System, the Bzyb (Bzipi)-Mzymta Submarine Valley System occurs offshore Gagra. The area of this system is constrained within a space where the shelf is extremely narrow, almost absent, situated between the Novorossiysk-Sochi shelf to the north-west and the Gudauta Bank shelf to the south-east (Jipa and Panin, 2020) (Fig.8a).

The Bzyb-Mzymta tree-like drainage pattern displays four main branches (Fig. 8b). The channels of the upper course submarine valley system, extending between the shelf edge and the continental-slope base (at around 1,500 m water depth), are regarded in this paper as canyon-type channels. Corresponding to the main branches of the system, in the upper course of the Bzyb-Mzymta Valley there are four main canyons: Mzymta, Psou, Gagra (with a no-name western canyon arm) and Bzyb-Pitsunda (Fig. 8b).

Each of these main canyons has several tributary channels, with canyon-type channels. Within the system, more than 15 main canyon heads have been identified with multiple smaller ones still yet to be recognized. Located on the edge of a very narrow shelf, these canyon heads are close to the shoreline, and implicitly to the foot of the Caucasus Mountains slopes (Fig. 8a). Zenkovich (1960, 1962) and Zenkovich *et al.* (1981) located a canyon head called Akula (Shark) at about 30-40 m distance from the beach line at 10 m water depth.

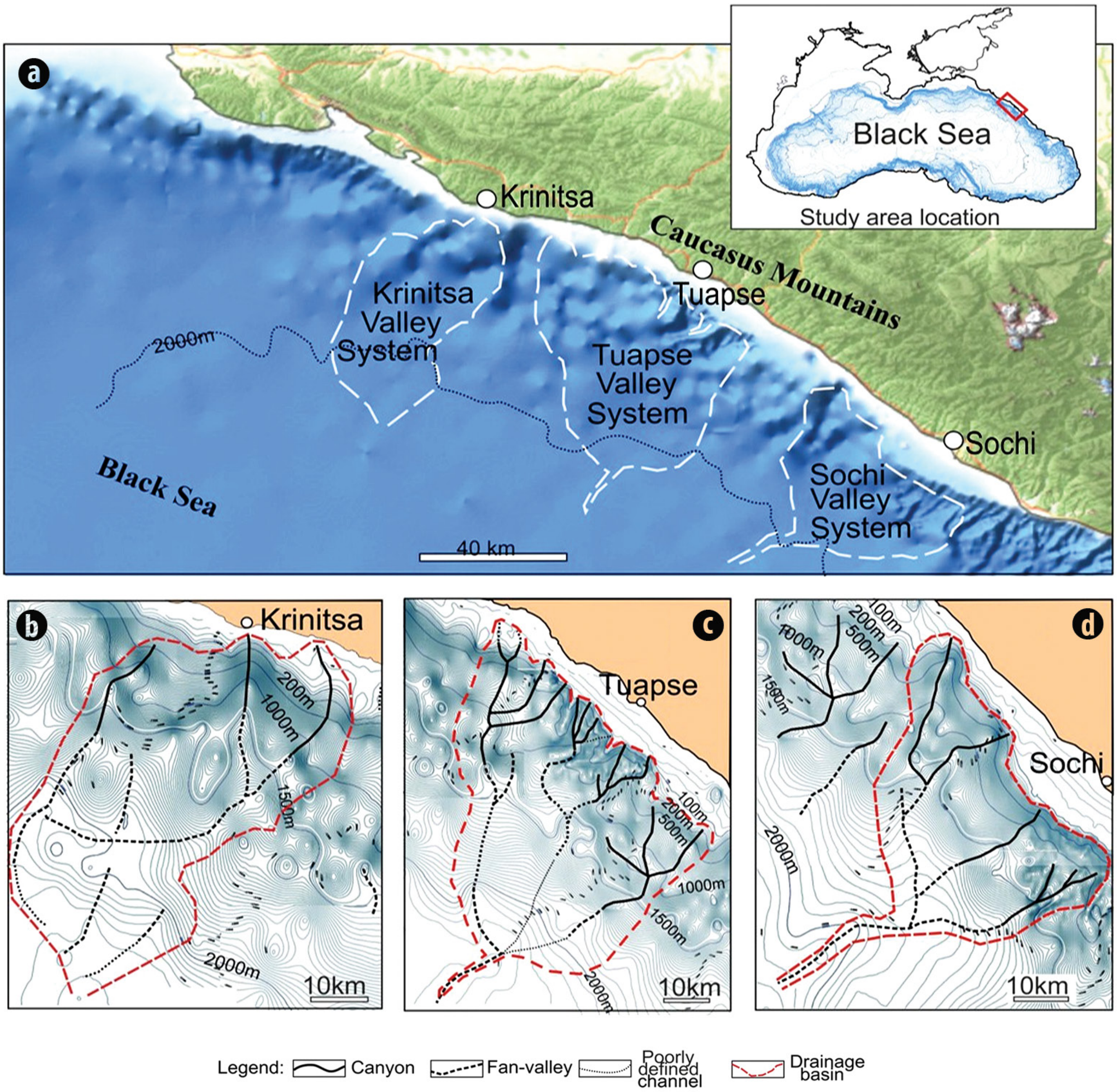

Fig. 7. Submarine valleys offshore Tuapse – Sochi, north-western Black Sea. (**a**) General geographic setting - EMODnet DTM; (**b**), (**c**) and (**d**) Krinitsa, Tuapse and Sochi submarine valley systems. EMODnet Bathymetry chart.

In the lower relief continental rise area, the Bzyb-Mzimta canyons continue down-slope into shallower, fan valley-type channels. The upstream dendritic drainage pattern channel complex is replaced and extended toward the abyssal plain by the single-channel Bzyb-Mzymta fan valley (Fig. 8b).

In the upper part of the continental slope, the drainage area of the Bzyb-Mzymta System is approximately 60 km wide. The length of the main canyon and upper fan valley channels, before coalescing at about 1,800 m water depth, ranges from 45 to 60 km. The lower fan valley, downslope the main channel coalescence point, was followed on the EMODnet bathymetric map over a distance of about 30 km.

South-eastward of Bzyb-Mzymta, a small drainage area, named Gudauta Submarine System in this paper, formed on the Gudauta Bank slope (Fig. 8). The irregularity of the channels and the location at the base of the slope suggest this might be formed as a result of a submarine landslide.

4.3.4. Gumista-Kodori-Enguri Submarine Valley System

Located offshore the Sukhumi–Ankalia area, the Gumista-Kodori-Enguri submarine valley system (Fig. 9) is situated within a large marine space where the shelf is extremely narrow, almost non-existent, resembling the Bzyb-Mzymta geographic setting (Fig. 8a).

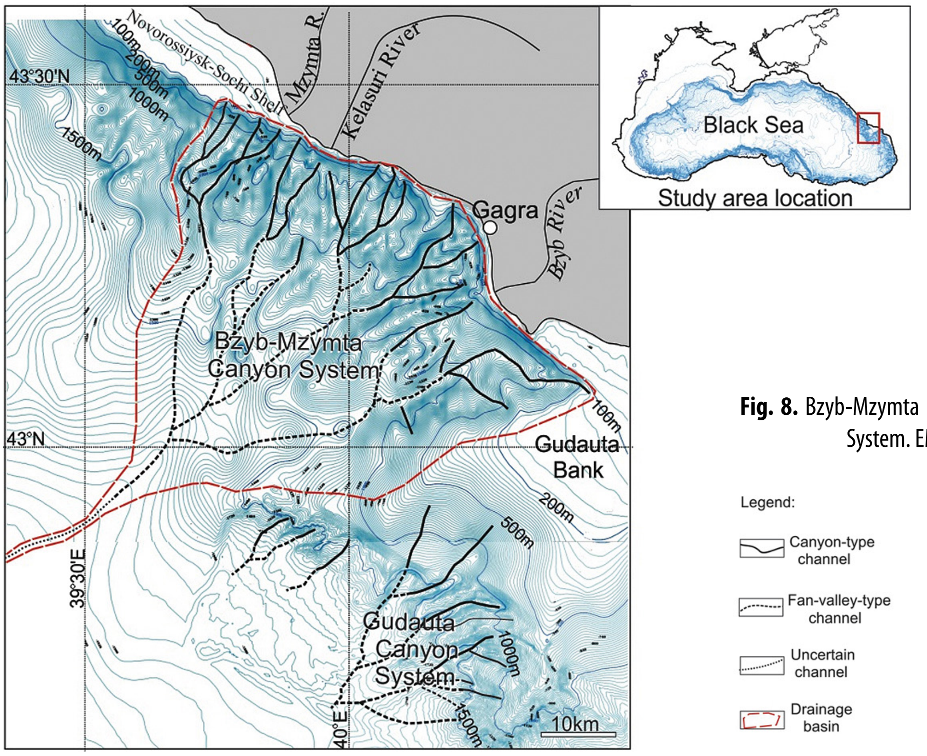

Fig. 8. Bzyb-Mzymta Submarine Valley System and Gudauta System. EMODnet Bathymetry chart.

Two subsystems are noticeable in the plan-view morphology pattern of this system: Gumista–Kodori and Enguri. The main channel of the Gumista–Kodori sub-system, with two upper course canyon-type arms (Gumista Canyon and Kodori Canyon), is joined by two, western and eastern, partly parallel, large channels. Further down-slope, the joined tributaries of the submarine sub-system extends as a long first order channel (Gumista-Kodori Fan Valley), through a shallow and exceptionally large channel (Fig. 9a).

In the upstream higher relief and steeper zone, the main submarine channels of this subsystem are canyon-type. They display more than one tributary canyon channels, outlining a dendritic pattern. Part of the subsystem canyon heads, especially of the Gumista and Kodori canyons, are close to the shoreline (Fig. 9a), in particular at offshore Sukhumi (Fig. 9b).

Within the lower relief continental rise area, with diminishing axial slope gradient, each main channel extends to the abyssal plain with fan valley-like, shallow and very wide channels.

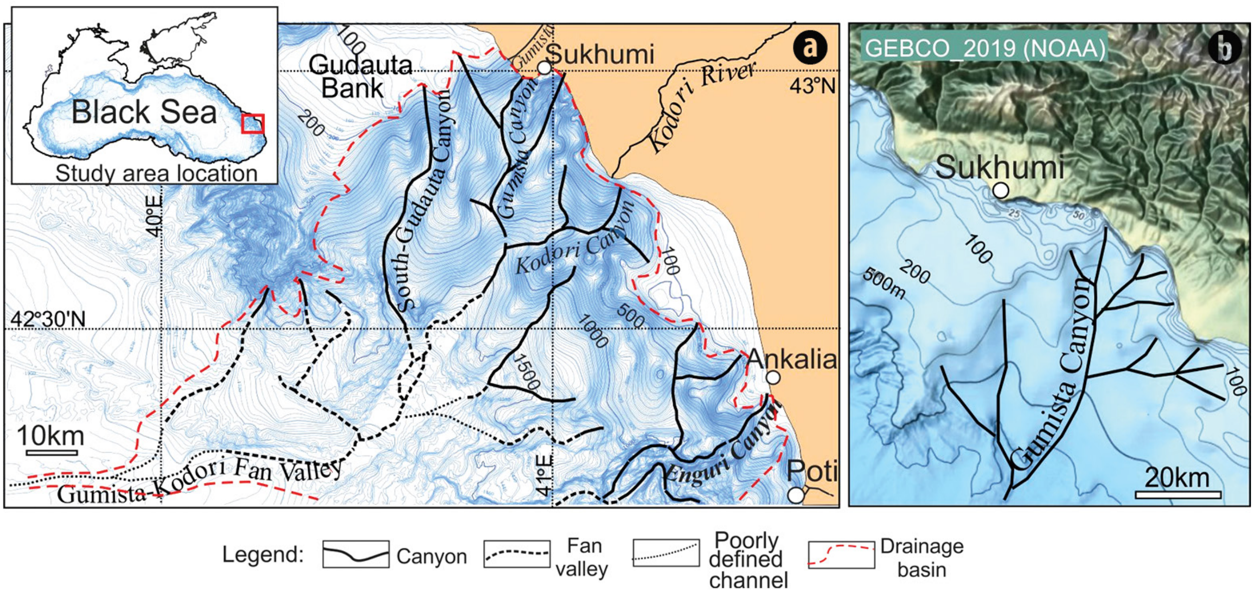

Fig. 9. Gumista-Kodori-Enguri Canyon System. (**a**) Submarine valley system on the EMODnet Bathymetry map. (**b**) Detail view of Gumista canyon head. GEBCO_2019 (NOAA) Bathymetry map.

The southern sub-system is that of the Enguri Canyon (see lower part of Fig. 9). In contrast to the Gumista-Kodori subsystem, the submarine valley model of the Enguri subsystem has a simple morphology. It consists of two relatively small tributaries in the upstream area of the subsystem and a long fan-valley directed from east to west. The Black Sea EMODnet bathymetric chart shows that the upstream part of the Enguri trunk channel is deeply incised, typical for canyon-type morphologies (Figure 10).

The length of the Gumista-Kodori subsystem, measured along the Gumista Canyon upstream the confluence with the Enguri Canyon, is approximately 120 km. The Enguri Canyon is of similar length. The drainage surface of the Gumista-Kodori-Enguri system is large, about 5,300 sq. km.

4.3.5. Khobi - Rioni Submarine Valley System

Located south of the Enguri Canyon, offshore the Ankalia-Poti-Grigoleti area, the Kobi-Rioni Submarine Valley System has, in the upper course, three branches: Khobi - Ankalia, Rioni and Grigoleti (Fig. 10). Their upper reach channels are steep-walled, canyon-type. Beyond the continental slope base (1,000 to 1,200 m water depth), the canyons pass into shallower channels, interpreted as upper fan valleys.

After successive confluences, at 1,600 m water depth, the three tributaries join into a single channel (the lower fan valley), 30 km long, that heads downslope to the abyssal plain (Fig. 10). A number of important channel bends distinguishes the northern branch of the system, the Khobi-Ankalia Canyon. The southern tributary including the Grigoleti Canyon are slightly sinuous. In accordance with Papashvili *et al.* (2010), a 1937 bathymetry study indicated that Rioni Canyon head location was close to the Poti Harbor and river mouth. However, in 1939 when the Rioni River mouth was artificially shifted the canyon head started to accumulate sediments.

4.3.6. Supsa-Batumi Submarine Valley System

The offshore area between Poti to Batumi, where the Supsa-Batumi Submarine Valley System is located, is the most extensively investigated sector of the eastern Black Sea margin. The Supsa-Batumi System deep-sea area is covered by multibeam mapping (Klauke *et al.*, 2006; Kenyon *et al.*, 2007; Bohrmann and Pape, 2007; Wagner-Friedrichs, 2007; Bohrmann and Ohling, 2011; Sipahioglu *et al.*, 2013), and most part of this dataset is included in the Black Sea EMODnet Batymetry chart. The studies of Bilashvilli *et al.* (2007) and Papashvilli *et al.* (2010) focused on the shallow water area. The NE to SW- trending main channel of the Supsa-Batumi Submarine Valley system, receives several important eastern tributaries: North-Batumi, South Batumi and Chorocki (Fig. 11a).

In the upper reach of the Supsa Valley System, there are multiple canyon-type channels. Within this system, 13 canyon head channels have been distinguished on the EMODnet Bathymetry chart. About ten canyon heads belong to the dendritic North Batumi canyon (Fig. 11a). Several canyon heads are close to the shore, while the main North Batumi canyon is located within the Batumi harbour (Bilashvili *et al.*, 2007).

Downstream an important confluence, the North Batumi Canyon runs along a wide, straight and flat-bottomed channel, with high and steep walls (Fig. 11a)

The Supsa Canyon is 70 km long, from the Supsa River mouth down to the confluence with the South Batumi branch (at 1,460 m water depth) (Fig. 11a). The North Batumi and South Batumi branches of the system can be followed 50km, respectively 40 km, before joining the Supsa Canyon.

Considering the large-scale pattern, it appears the Chorocki Valley might also be a tributary of the Supsa-Batumi System (Fig. 11b). The reconstruction of the general pattern of the system is not supported by high definition bathymetry, and is partly a presumption.

The Supsa Canyon and its Batumi tributaries represent the upstream dendritic drainage pattern of the Supsa-Batumi Submarine Valley System. Downstream, after the supposed junction with Chorocki Canyon, the trunk of the system extends westward over 100 km through a shallow channel (fan valley type), to the abyssal plain (Fig. 11b).

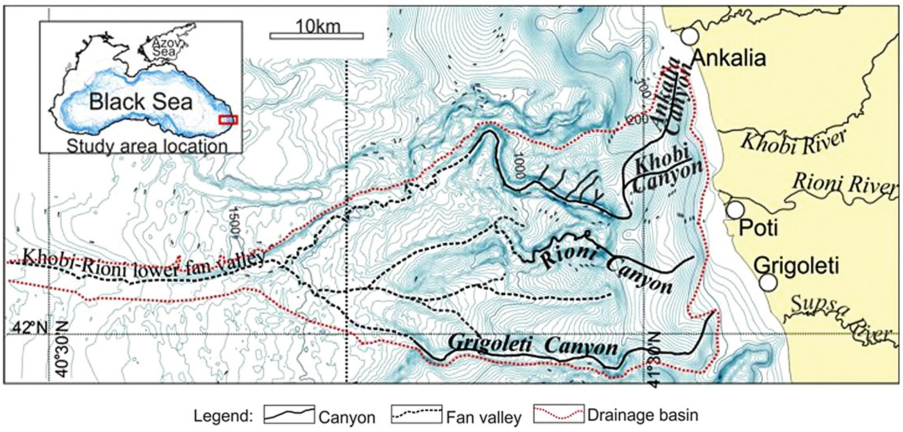

Fig. 10. Khobi-Rioni Submarine Valley System – EMODnet Bathymetry chart.

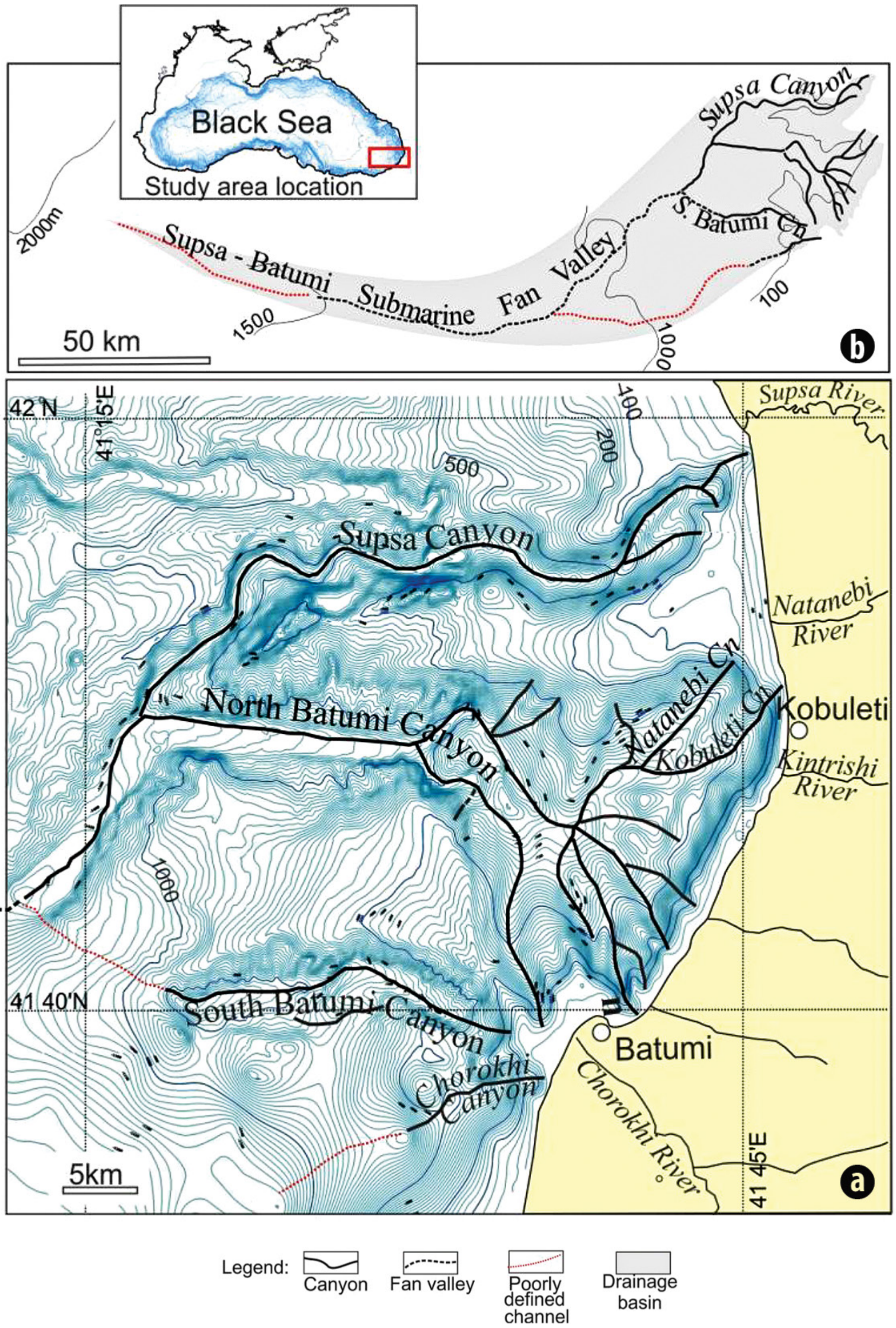

Fig. 11. Supsa – Batumi Canyon System. (**a**) Upstream valley system on EMODnet Bathymetry chart. (**b**) General view of the Supsa-Batumi Submarine Valley system.

4.4. Submarine valley systems of the south-eastern Black Sea

On the southern margin of the Black Sea, along the Turkish coast, the sea bottom shows various large-scale morphologies. Küre and Carik Escarpments, two of the steepest Black Sea scarps, mark the western and eastern limits of this area (Fig.12a) where multiple submarine valley systems have been identified. The morphological submarine expression of the tectonic Archangelsky (Samsun) Ridge oriented oblique to the coast is also located in this zone (Fig. 12a).

4.4.1. Submarine valley systems offshore Batumi-Rize

The Batumi-Rize is the offshore area where the Carik Escarpment occurs (Fig. 12a). The submarine valleys in this area are rare spaced and relative short (up to 40 km). Some of them have tributaries in the upper part of the network.

4.4.2. Giresun-Fatsa valley systems

Westward Giresun (Fig. 12a), where the slope gradient is lower, the submarine bottom is crossed by at least five valleys. The largest of them, Giresun, Ordu and Fatsa systems

(Fig 12b), have been named in this paper according to the locallities near their main channel heads. On the continental slope, the three valleys have canyon morphology with simple radial dendritic pattern in the upper part with two to four tributaries. The continental shelf is narrow in this zone and multiple canyon heads are close to the shoreline at Fatsa and Giresun localities (Fig. 12b).

From the base of the continental slope (between 1,300 to 1,500 m water depth) the valley systems extends toward 2,000 m water depts through single fan valley-type channels without forming distributaries. The direct lengths of the Giresun-Fatsa submarine valley systems, from the shelf edge to their outlet, varies from 60 km (Giresun and Ordu Systems) to 100 km (Fatsa System).

4.4.3. Samsun offshore zone

Two important submarine valley systems, Yeshilirmak and Kizilirmak, are located in the Samsun offshore area, confined between the Archangelsky Ridge and the eastern edge of the Küre Escarpment (Fig. 13a). The two submarine valleys are a continuation of the rivers with the same name.

Dondurur and Çifçi (2007) conducted detailed studies in the south-eastern upstream area of the Yeshilimak System and on the south-west slope of the Archangelsky Ridge. Their bathymetric map highlights a dense assemblage of submarine canyons.

The upper course of the Yeshilirmak system has a dendritic drainage model in the Samsun Bay area (Fig. 13b). Several canyon heads located at the shelf edge mark this sector of the system between 100 to 1,500 m water depth. In the lower part, when crossing the low-relief continental rise, the winding main channel fan valley-type channel, with only two tributaries evidenced on the EMODnet Bathymetry chart, is extending to at least 2,000 m water depth. The length of the Yeshilirmak submarine system is over 120 km, the

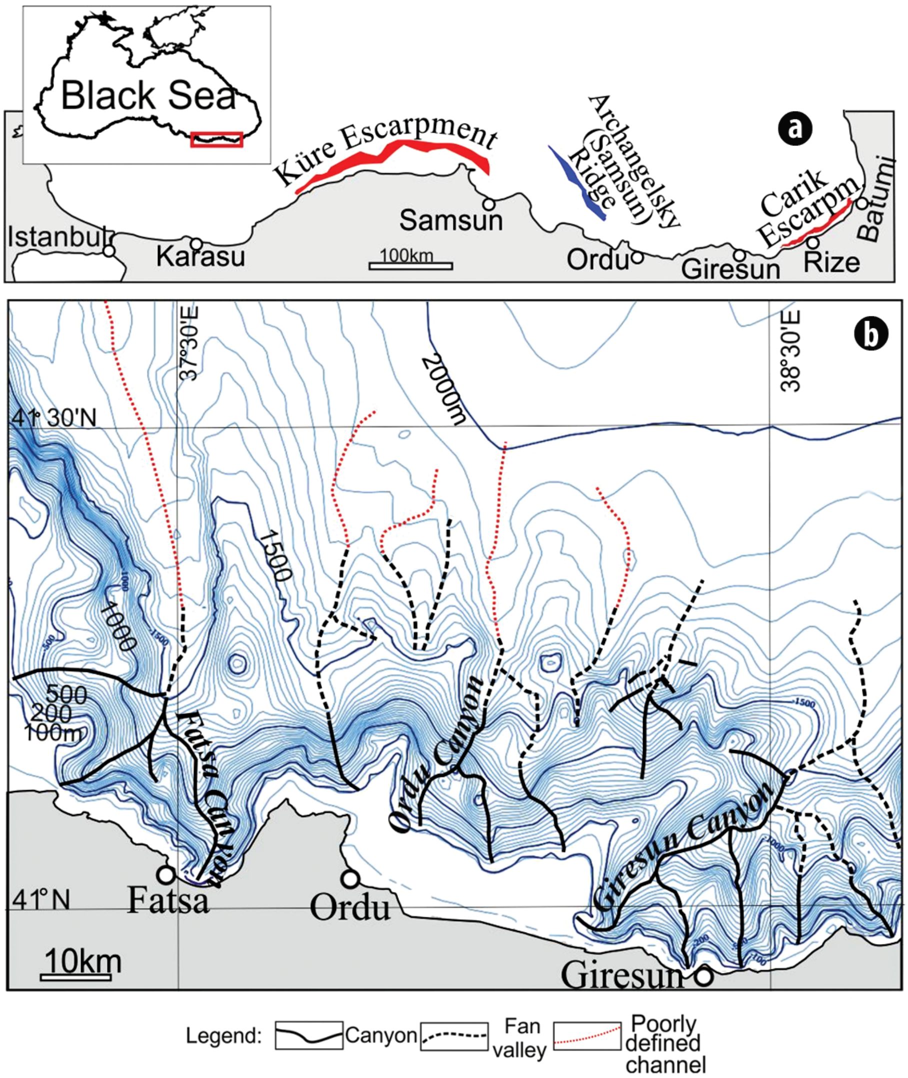

Fig. 12. (**a**) Bottom morphology features in the south-eastern Black Sea. General setting. (**b**) Submarine valleys offshore Giresun-Fatsa zone. EMODnet Bathymetry Chart.

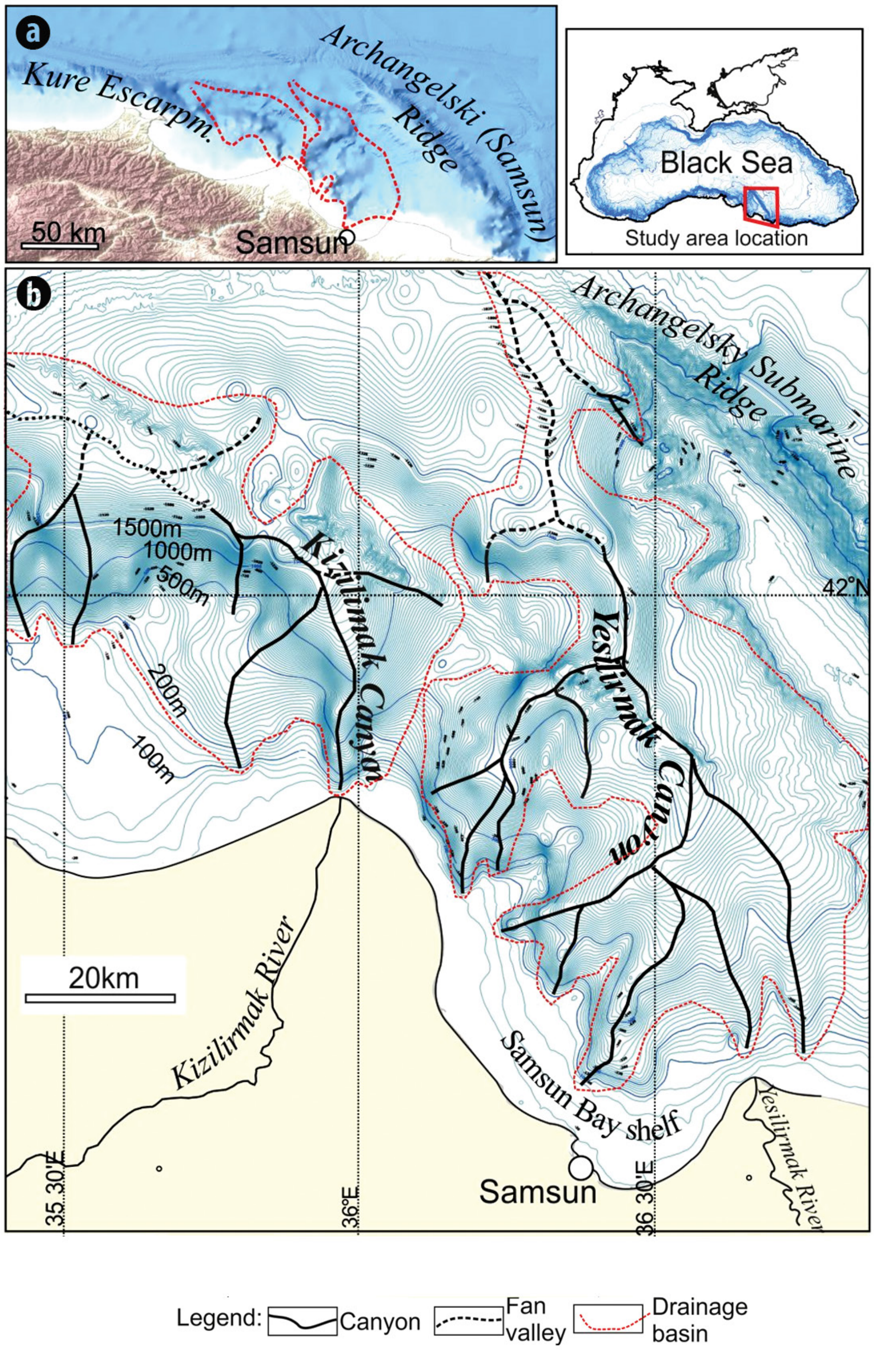

Fig. 13. Submarine valleys in the area between the Archangelsky Ridge and the Küre Escarpment. General setting - EMODnet DTM. B. Yeshilirmak and Kizilirmak submarine valley systems on the EMODnet Bathymetry chart.

dendritic part representing approximately 60 km (Fig. 13). The Yeshilirmak system has a drainage network surface exceeding 3,600 sq. km.

The Kizilirmak System with a length of over 90 km is slightly smaller than the Yeshilirmak System. Its drainage pattern is similar to the Yeshilirmak, with a smaller number of tributaries and a simpler dendritic model (Fig. 13b). The main Kizilirmak canyon head is very close (less than 1 km) to the mouth of the river with the same name.

Like the neighbouring Yeshilirmak Submarine System, the direction of the Kizilirmak main channel is from SSE to NNW. In the lower, fan valley section, the Kizilirmak Valley gradually turns westward, extending along the foot of the Küre Escarpament.

4.5. Submarine canyon systems of the south-western Black Sea

4.5.1. Sinop -Eregli offshore zone

The Western Turkish, Küre Escarpment extends from Sinop offshore area to the west (Fig. 12a). Along the Küre Escarpment, the steep slope of the Sinop area is becoming gentler to the west and starting from offshore Bartin the escarpment is replaced by a normal-gradient continental slope.

In the Sinop-Eregli offshore area are a few relatively short (up to 30 km) submarine canyons and only a few have tributaries. In the sector with a steep and long slope (up to the depth of 2,000m) of the Western Turkish Escarpment, about 100 km west of Sinop, on the EMODnet Bathymetry chart only 3 short (20km) canyons without tributaries can be identified. Further westwards, in the Zonguldak offshore area, submarine valleys are more common. They show a canyon-type channel in the upper part and become fan-valley in the lower part, with the entire submarine valley up to 40 km long.

4.5.2. Eregli-Karasu offshore zone.

Westward of the Kure Escarpment (Western Turkish Escarpment), in the area offshore the Eregli and Karasu localities, two major submarine valleys are present (Fig. 14a). Sakaria Canyon, the upstream sector of the most important of these submarine valleys, was investigated by Erinc (1958) and Algan *et al.* (2002). The authors revealed a submarine canyon pattern with two heads and several tributaries, significantly incising into the shelf, and affected by faults.

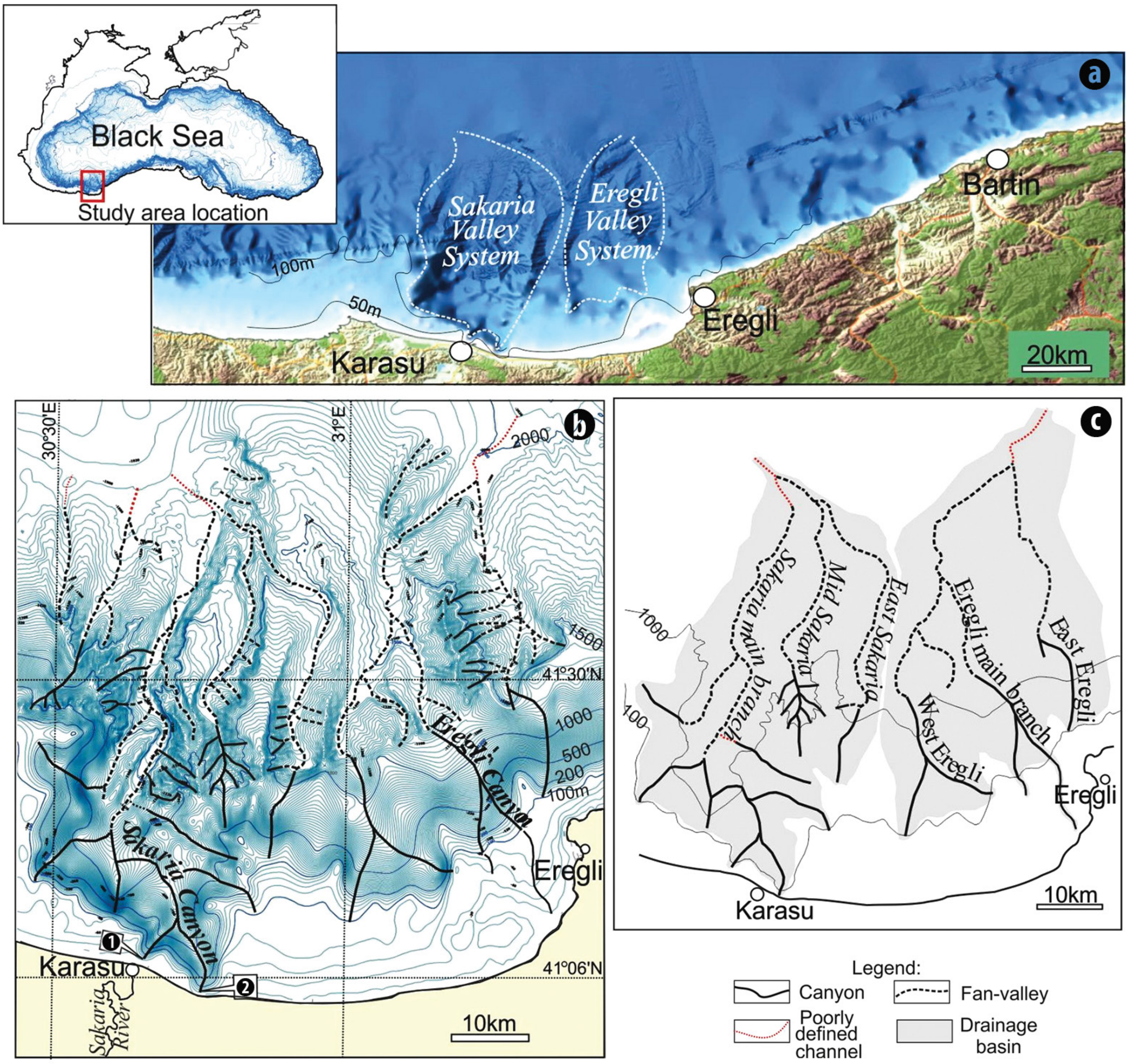

Fig. 14. Submarine valleys offshore Karasu-Eregli. (**a**) Larger-scale setting on EMODnet DTM. (**b**) Sakaria and Eregli submarine valley on EMODnet Bathymetry chart. (**1**) and (**2**) – canyon heads in very shallow water (after Algan *et al.*, 2002). (**c**) Drainage basin and pattern of the Sakaria and Eregli submarine valley systems.

According to Algan *et al.* (2002), the two Sakaria frontal canyon heads are very shallow at 50 m and 10 m water depth (Fig. 14a and b).

The Sakaria Submarine Valley system displays three major long branches with a south to north trend (Fig. 14b). The tributaries outline an elongated dendritic drainage pattern. As it is crossing rough bottom relief, the upstream 30 km long mainstream segment is regarded as running through a canyon-type channel. The heads of the five tributaries of the main Sakaria channel are located at different water depths, from 10 m to 300 m.

At about 1,350 m water depth, the channel is considerably widening, and the Sakaria main submarine channel becomes a fan-valley, that extends downstream toward the abyssal plain. With a width between 1.5 km to over 3.5 km, the fan valley channel is slightly winding and in the upper and central part receives three tributaries (Fig. 14b). The other two, middle and eastern tributaries of the system (Fig. 14c), each of them 45 to 50 km in length, join the main channel at water depth between 1,700 to 1,800 m. The S-N elongated, 150 km long (from the 10 m depth canyon head to the abyssal plain) drainage area of the Sakaria System covers over 1,700 sq. km (Fig. 14c).

Several kilometres eastward of the Sakaria drainage basin, another important underwater valley occurs, named in this paper the Eregli Submarine Valley (Fig. 14). The three tributaries of the Eregli drainage basin are elongated, in a similar way to the Sakaria pattern (including its direct length and surface area) (Fig. 14c). Following the confluence of the tributaries, a single channel extends to the water depth of nearly 2,000 m. The five Eregli canyon heads recognized on the bathymetry map are located at the shelf edge. The main Eregli canyon channel incises the shelf, reaching the several tens of metres water depth westward of the Eregli locality (Fig. 14b).

4.6. Submarine canyon systems of the south-western Black Sea

4.6.1. Bosporus and Şile submarine valley systems

A large number of submarine canyons are cutting into the continental slope of the western Turkey. Many of them are part of two submarine valley systems, Bosporus and Şile, located on the continental margin East of the Bosporus Strait. Eastward, offshore Şile and Karasu localities, the submarine valleys are smaller and more spaced into an area that extends to the Sakaria Canyon (Fig. 15a). Şile Submarine Valley is a name, given according with the closest Turkish locality (Fig. 15b).

These two submarine valley systems are next to each other and morphologically very similar. Each of the Bosporus and Şile valley system has two main branches with several tributaries. The confluence of the main tributaries is at water depth of around 2,000 m, close to the down slope end of the valley system. The two main branches of both systems are 45 to 50 km long each. On the continental slope, down to around 1,300 m water depth, the tributaries are short, numerous and canyon-type (Fig. 15b and c). Down-slope, in the continental rise area there are fewer and longer tributaries, extending to the abyssal plain through shallow, fan valley-type channels. In case of the two submarine valleys in discussion the distinction between canyon and fan valley channels is sometimes difficult, as the bathymetric map points out that wide channels begin even from the rough relief, canyon type areas (Fig. 15b).

Their drainage pattern systems are elongated, dendritic shaped (Fig. 15b and c). The Bosporus drainage basin surface (1,400 sq. km) is smaller than the surface of the Şile submarine valley drainage basin (1,700 sq. km) (Fig. 15b).

The numerous canyon heads of the Bosporus and Şile submarine systems are located by the shelf edge, without significant shelf incisions.

The *Bosporus single channel* is a submarine valley located north-westward of and parallel to the left branch of the Bosporus System (Fig. 15b and c). The Bosporus channel extends basinward toward the abyssal plain and is not joining the Bosporus Valley System.

A 30 to 40 km wide shelf separates the Bosporus and Şile submarine valleys from the shoreline (Fig. 15a). On this shelf, Di Iorio *et al.* (1999), Lericolais *et al.* (2002) and Okay *et al.* (2011) outlined a submarine fan with its apex in the eastern end of the Bosporus Strait (Fig. 15b). From the Bosporus Strait, several shelf channels form a distributive pattern spreading northward. The reconstructed route of some of these channels (Flood *et al.*, 2009) were mapped toward the Bosporus submarine canyon heads (Okay *et al.*, 2011; Ryan *et al.*, 2014) (Fig. 15b).

4.6.2. Offshore Bulgaria Submarine Valleys

The submarine valleys of the Bulgarian shelf occur in two areas with different morphological characters: offshore Burgas area (Fig. 16a) and offshore Cape Kaliakra area (Fig. 16b).

Offshore Burgas area. On the continental slope and the continental rise east of Burgas, six submarine valleys have been identified on the EMODnet Bathymetry chart (Fig. 16a). The upper part of these valleys crosses the continental slope with a length of 10 to 15 km (Fig. 16 A1-A2) as canyon-type channels. The canyons extend on the continental rise through 10 to 25 km long, very shallow channels. There are small areas where some of these channels are shallow, close to data resolution. At the downstream edge of the shallow channel area, a slope break occurs, and some valleys are incisional with canyon-type characteristics (Fig. 16a).

In the offshore Burgas area, the submarine valley drainage pattern is simple, with a single channel, or with two shorter or longer tributaries. The valleys are almost parallel and slightly curved.

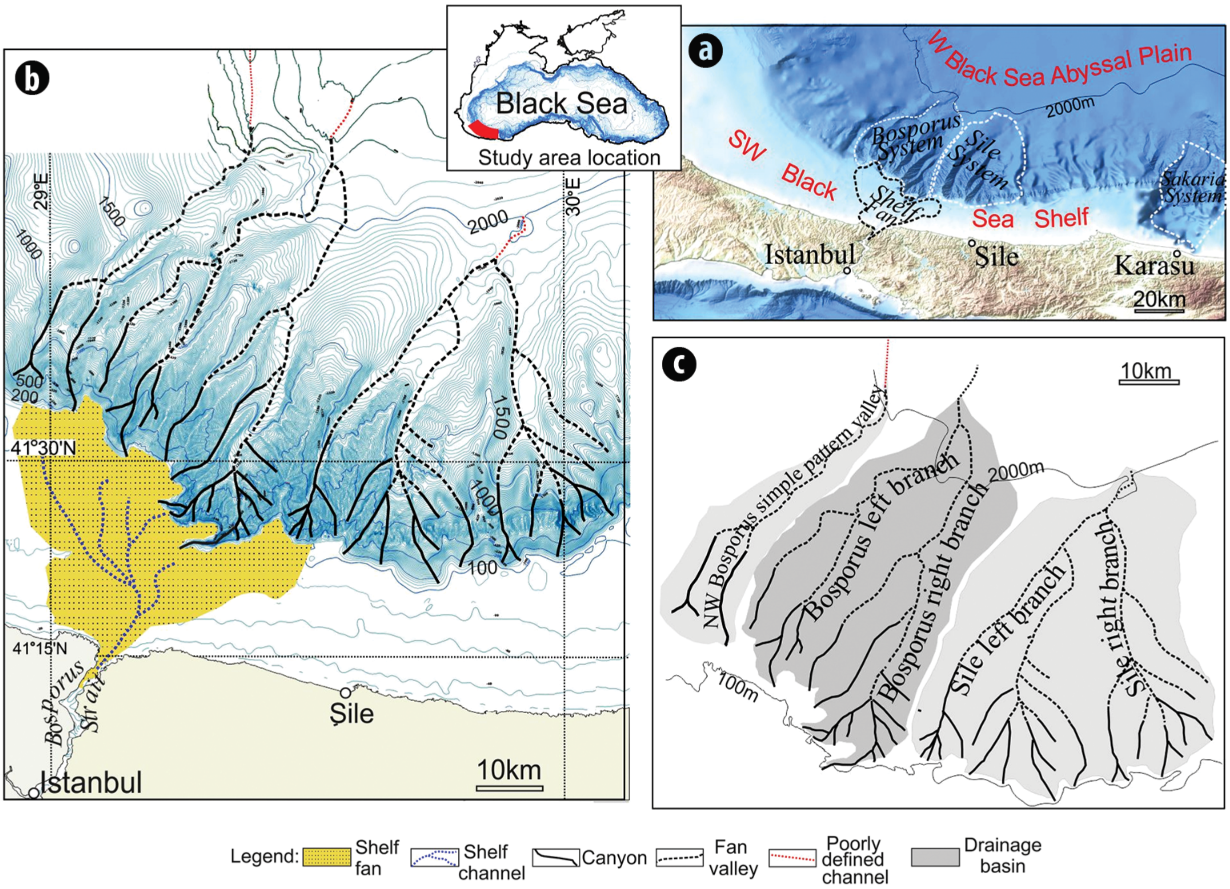

Fig. 15. Western Turkey submarine valley systems. (**a**) General setting - EMODnet DTM. (**b**) Bosporus and Şile submarine valley systems, on EMODnet Bathymetry chart. Bosporus Shelf Fan modified from Okay *et al* (2011). Bosporus shelf channels after Okay *et al.* (2011) and Ryan *et al.* (2014). (**c**) Bosporus and Şile drainage basin and pattern

Offshore Cape Kaliakra area. Several kilometres north of Burgas, the submarine relief changes, the continental slope from the east of Cape Kaliakra becoming significantly steeper (Fig. 16b and B1-B2). This change of morphology extends along the shelf-break line over a distance of about 125 km. The submarine valleys in the Cape Kaliakra offshore area are generally shorter than the offshore Burgas valleys and have higher sinuosity.

At the northern edge of the Cape Kaliakra offshore area, an elongated erosional morphology is named Manganary Canyon on GEBCO Gazeteer of Undersea Feature Names (Fig. 16m). The Manganary Canyon is located on the continental rise, in the area with a water depth of about 800 m down to about 1,700 m. On the EMODnet Bathymetry chart, this feature is visible as a 45 to 50 km straight and continuous line, which marks the western slope of a relatively flat submarine ridge. This submarine morphological erosional feature does not look like a submarine valley but is rather tectonically formed.

5. INTERPRETATION OF DATA

5.1. Black Sea submarine valley network

Using the Black Sea EMODnet Bathymetry chart, the work carried out in this study led to the elaboration of the Black Sea submarine valleys sketch-map (Fig. 17). The submarine valleys of the Black Sea have been studied as valley systems, i.e. genetically related, distinct ensembles, which include one or more main channels with its tributary and / or distributary patterns (Fig. 1). These data refer to the submarine valleys of the entire Black Sea basin that have been identified on the EMODnet Bathymetry chart. The Black Sea submarine valleys network includes 25 valley systems, 5 groups of simple, first order channels (2a, 2b, 9, 29 and 30 in Fig. 17) and other simple, not associated channels (Fig. 17). The 25 valley systems are summing up more than 110 main channel/channels and tributaries. The Black Sea submarine canyons mentioned in the literature are only components of these valley systems. The submarine valleys in the escarpment areas, which require a special analysis, are not included in the sketch-map of the Black Sea submarine valleys presented in this article.

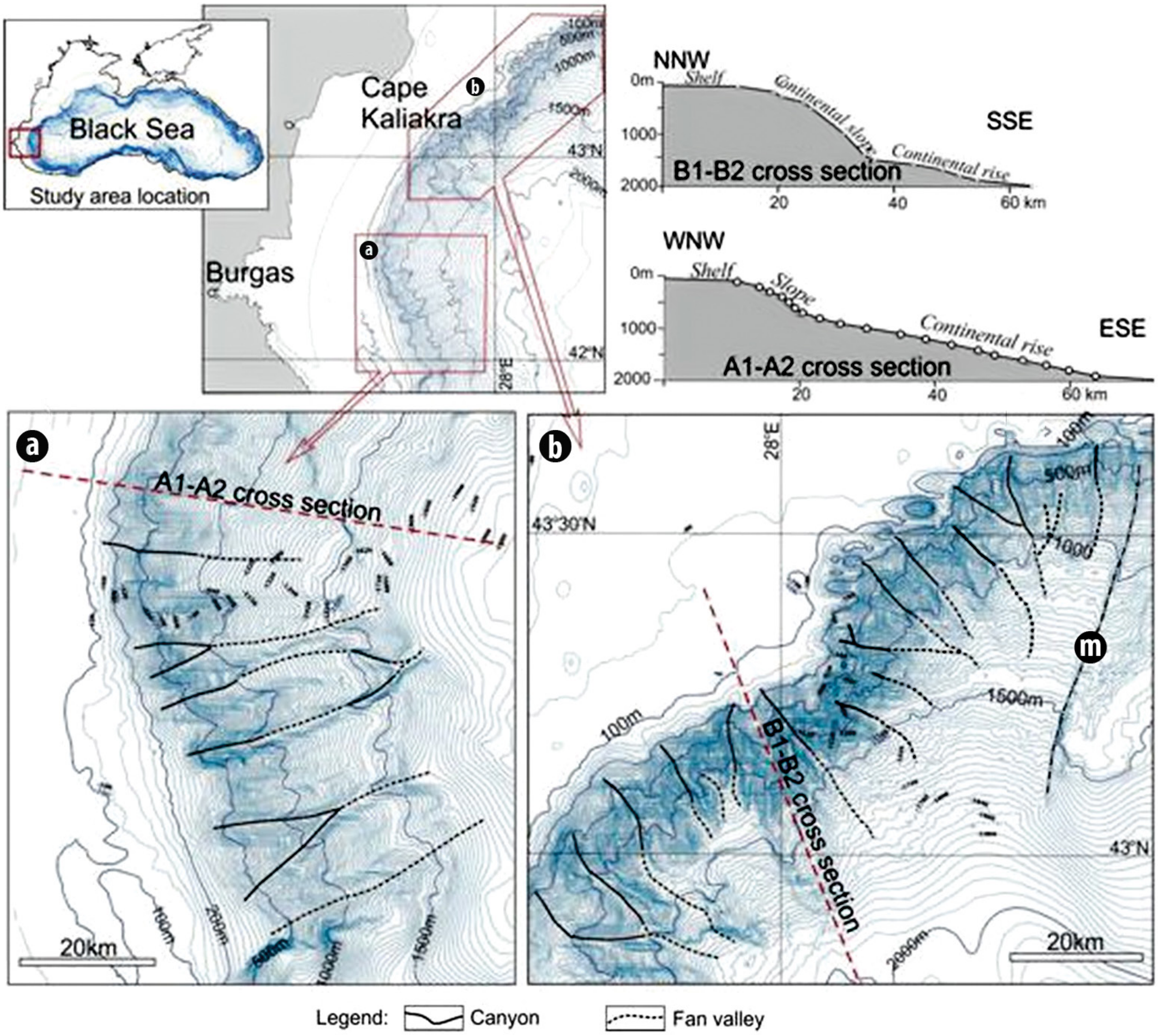

Fig. 16. Western Black Sea submarine valleys. (**a**) Burgas offshore area. (**b**) Cape Kaliakra offshore area. (**m**) Manganary seabed morphology feature. EMODnet Bathymetry chart.

Another new element highlighted by the map of the Black Sea submarine valleys, is the differential marking of the canyon-type channels versus the fan valley-type channels, within a distinct valley system. As already stated, *canyon-type* are considered the channels running through higher sea bottom relief (continental slope) as evidenced by the bathymetry map, with higher axial slope gradient. The *fan valley-type channels*, cross lower sea bottom relief (continental rise), with lower axial slope gradient, as resulting through the examination of the Black Sea EMODnet Bathymetry chart. Moreover, distinction is made between *upper fan valleys* (upstream fan valleys segments, making the transition to canyons), and *lower fan valley*. The last ones are represented by the very shallow channels, extending to the abyssal plain area.

Several regional submarine valley networks can be separated within the all-basin Black Sea network. The regional network in the eastern Black Sea, Caucasus offshore area, involves nine closely spaced valley systems (10 to 18 in Fig. 17). On the western Black Sea, the second large regional network of submarine valleys occurs, including valleys of the Danube and Dnieper area (3 and 4 in Fig. 17), the offshore Bulgaria valleys (29 and 30 in Fig. 17) and the valleys of the western Turkey network (25 to 28 in Fig. 17).

The submarine escarpments set the limits of the areal development of the submarine valley systems, in the northern and southern Black Sea basin. The network south of the Sea of Azov (5 to 9 in Fig. 17) is constrained between the Crimean Escarpment and the Caucasus Escarpment. The Giresun-Samsun submarine valleys (19 to 24 in Fig. 17) extends between the Küre and Carik escarpments, on the southern, Turkish, margin of the Black Sea.

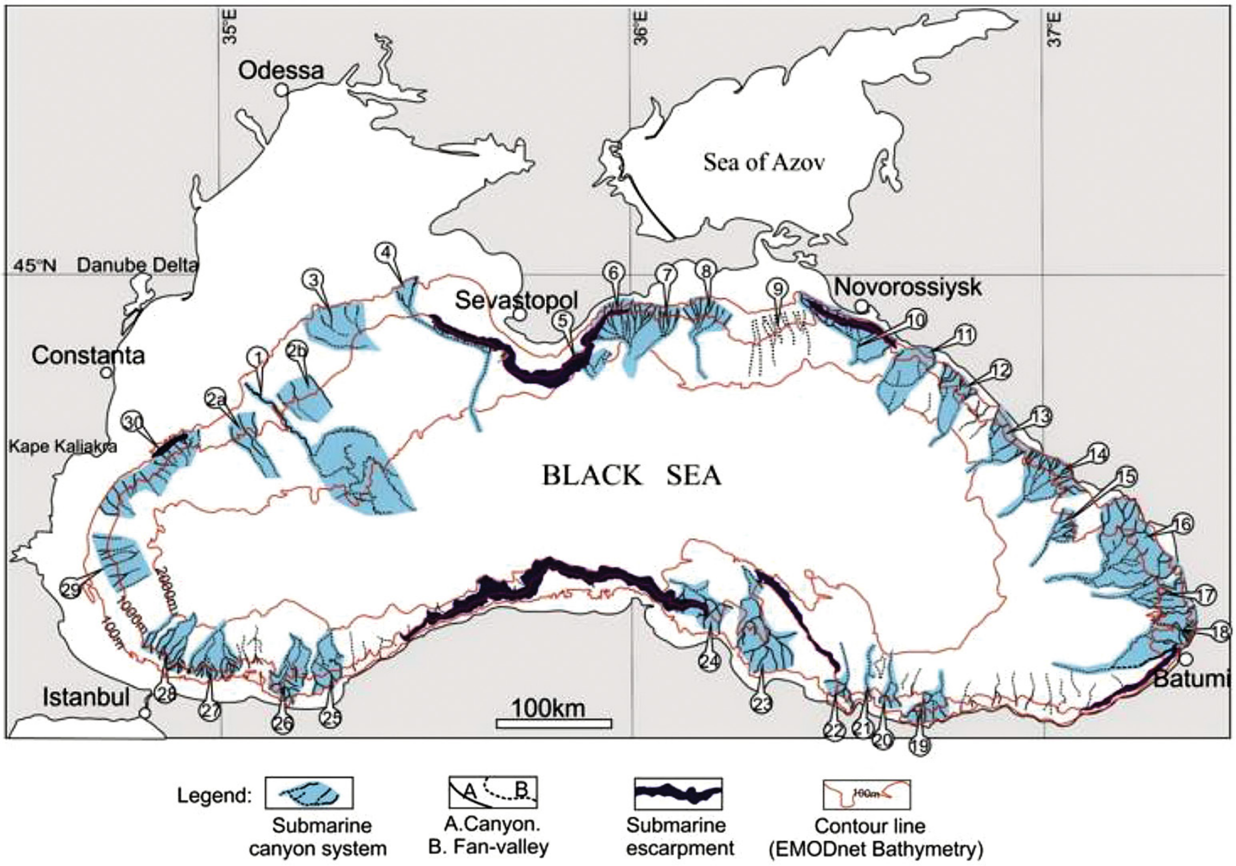

Fig. 17. Sketch-map of the Black Sea submarine valley network. **1**. Danube. **2a**. North-eastern Danubian Gullies. **2b**. South-western Danubian Gullies. **3**. Western Dnieper. **4**. Eastern Dnieper. **5**. Yalta. **6**. Sudak. **7**. Feodosia. **8**. Kerch. **9**. South Kerch Strait. **10**. Kuban. **11**. Krinitsa. **12**. Tuapse. **13**. Sochi. **14**. Kodori-Gumista. **15**. Gudauta. **16**. Bzyb-Mzimta. **17**. Khobi-Rioni. **18**. Supsa-Batumi. **19**. Giresun. **20**. Ordu. **21**. Aziziye. **22**. Fatsa. **23**. Yeshilirmak. **24**. Kizilirmak. **25**. Eregli. **26**. Sakaria. **27**. Şile. **28**. Bosporus. **29**. Offshore Burgas **30**. Offshore Cape Kaliakra

Within the Black Sea submarine network, several valley systems extend significantly more than others towards the abyssal plain. These are the Danube Submarine Valley System (3 in Fig. 17), and the Bzyb-Mzymta and Supsa-Batumi submarine valley systems (16 and 17 in Fig. 17) from the offshore area in front of the highest altitude Caucasus Mountains.

5.2. Morphologic features of the Black Sea submarine valley systems

5.2.1. Shape and structure of the submarine valleys systems drainage basin

Two main morphologic categories of submarine valleys occur in the Black Sea (Fig. 18). The first category is characterised by *complex drainage pattern valley systems*. The second group brings together *simple drainage pattern valley systems*.

Complex drainage pattern valley systems. Two drainage models occur in the Black Sea complex valley system category: tree-root-like when channel network is distributary or tree-branching-like pattern when channel network is tributary. The tree-root-like submarine valley systems drainage pattern is defined by two main features: a single-channel in the upper and middle course, and a network of distributary channels in the lower course (Fig. 18a). Within the Black Sea network, the tree-root-like drainage model is displayed only by the Danube Submarine Valley System (Fig. 3b). Although unique in the Black Sea, this pattern is important because a major participant of the Black Sea submarine valley network highlights it. The submarine Danube single-channel, extending from 100 m to 1,500 m water depth, is represented by the Danube Canyon and the Danube Channel (Popescu, 2002) (Fig. 3b). In the lower part of the Danube Submarine System, at the continental slope base, a large distributary-channel network occurs. From the first avulsion centre, marked by Lericolais *et al.* (2012) at 1,525 m water depth, new channels are separating as channel-levee distributaries (Figs. 3b, c and 18a). In this way, a large tree-roots-like pattern is formed, that can be followed downslope beyond the 2,000 m water depth line (Fig. 3b). Lericolais *et al.* (2012) identified five major avulsion points in the Danube submarine system distributary-channel network.

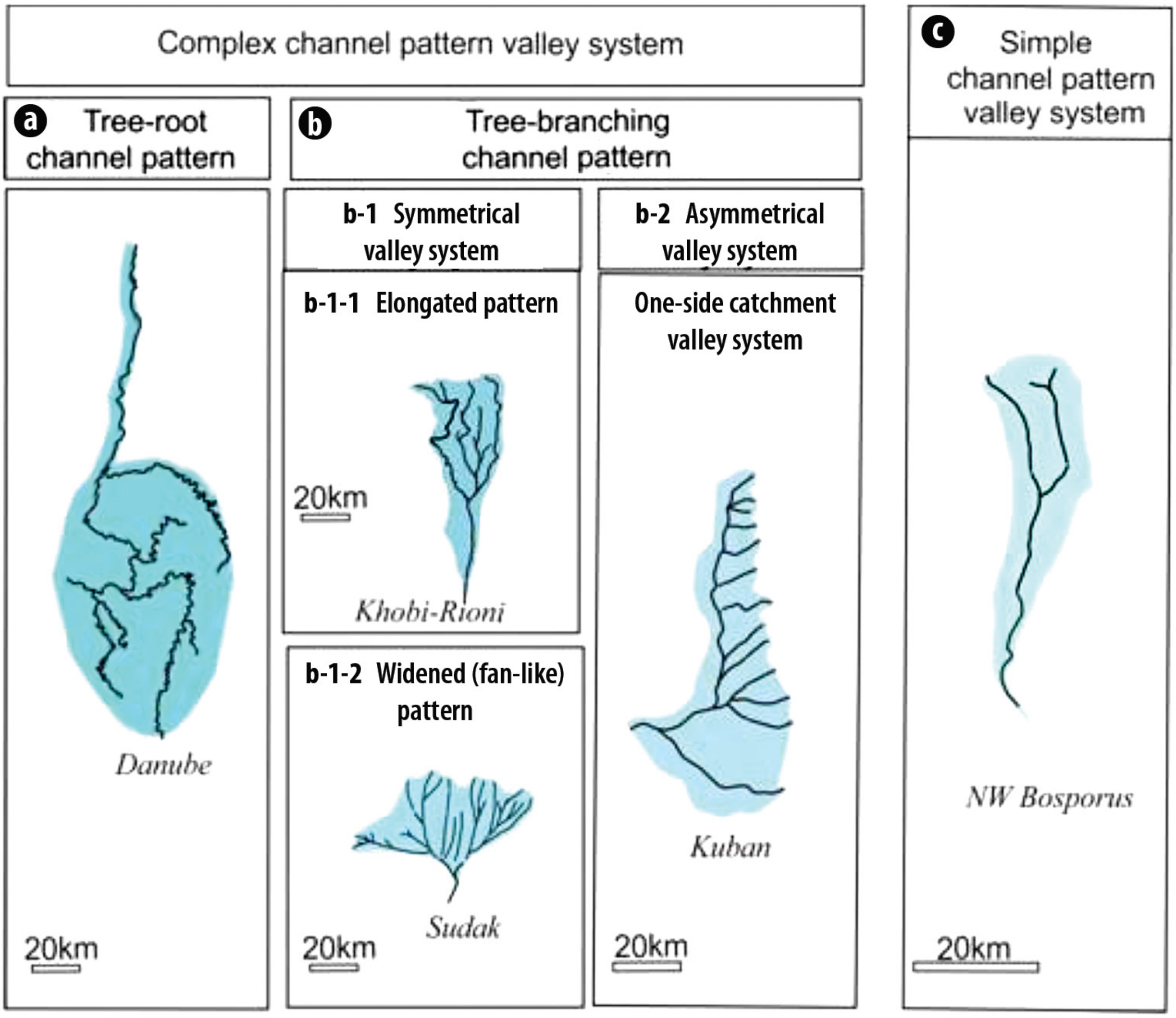

Fig. 18. Main drainage pattern types of the investigated Black Sea submarine valley systems

The *tree-branching-like channel pattern* is displayed by most of the Black Sea submarine valley systems. This model is described by tributary channels that merge together with the main channel in the upstream (continental slope) area, creating a tree-branching-like pattern (Fig. 18b). On the continental rise, a single main channel replaces the dendritic complex.

The tree-like sector of the Black Sea submarine valleys has frequently a reduced number of tributaries. This category includes Tuapse and Sochi in the eastern Black Sea (Fig. 9), Yeshilirmak and Kizilirmak (Fig. 17) and Fatsa, Aziziye and Ordu from the southern Black Sea. Bzyb-Mzymta (Fig. 8) and Gumista-Kodori (Fig. 9), show dendritic systems with many and relatively close-spaced tributaries.

The form and structure of the dendritic, tree-branching-type drainage model is variable. Some systems, like Kuban (Fig. 6), Yeshilirkmak and Kizilirmak (Fig. 13), have only one main channel in the dendritic assemble. Other systems, such as the Bzyb-Mzymta (Fig. 8), Kodori-Gumista (Fig. 9), Supsa-Batumi (Fig. 11) and Sakaria (Fig. 14), have two or more main branches.

Simple drainage pattern valley systems. (Fig. 18c) This type of submarine valley has a slightly curved single-channel channel, upstream bifurcated, sometimes looking as two branches. The length of the simple valleys varies mostly between 15 and 25 km in the escarpment areas or between 35 and 65 km near the Danube Canyon (Fig. 3a), north-west Bosporus (Fig. 15) or offshore Burgas (Fig. 16a).

Simple submarine valleys are canyon-type channel on the continental slope, and extend downslope, on the low gradient slope of the continental rise, with very shallow fan valley-type channels.

Some of the simple drainage pattern valleys in the deep-water Black Sea could be classified as submarine gullies. In many cases, they are longer than 10 km, the maximum length for gullies according to Amblas *et al.* (2017).

5.2.2. Comparative extent of the submarine valley systems

The size of the Black Sea valley systems is estimated in this subchapter by the length and the surface of the tributary drainage area. We define the valley length by the extent of the line segment drawn between the "source" (canyon head) and the outlet (the farthest downstream point of the valley course) of the submarine drainage basin. In the text of the paper, we will use the name "direct length" for this morphometric element.

Following these characteristics, the submarine valley system of the Danube is the most extensive in the Black Sea. The direct length of the submarine Danube drainage basin is about 200 km, and its surface about 5,780 sq km (Figs. 3 and 19). Half of the total length belongs to the Danube Submarine Canyon and its down-slope extension, to the Danube Submarine Channel. The most part of the Danube submarine drainage surface corresponds to the area of the Danube Deep-Sea Distributary Complex (Fig. 3).

The only Black Sea submarine system that is getting close to the size of the Danube is the Kodori-Gumista Submarine Valley System (Figs. 9 and 19). The direct length of this system is about 155 km. The area of the Kodori-Gumista tributary network, of approximately 5,300 sq. km. is given by an extensive network created by three important submarine valley tributaries: Kodori-Gumista, Enguri and an unnamed eastern canyon (Fig. 9).

With a very long (about 100 km) fan-valley and a total length of 190 km, the Supsa-Batumi system is one of the longest (Fig. 18), but its tributary area is only about 200 sq. km. Among the described systems, the tributary network of the Kuban and Yeshilirmak submarine valley systems are the only ones whose direct length exceeds 100 km. The surface of their drainage basins is 1,050 sq. km. and 3,600 sq. km, respectively. The other nine submarine valley systems shown in Fig. 19 have direct lengths between 50 km and 80 km.

5.2.3. Slope gradient of the main Black Sea submarine valleys

To get a general idea on the variation range, the submarine channels axial slope for the most important Black Sea submarine valleys, was determined and graphically represented (Fig. 20). The gradient values come from the ratio between the elevation difference of the extreme points of the investigated channel, and its measured direct length (inlet to outlet).

The slope gradient was determined for each main section (canyon, upper fan valley and lower fan valley) of the submarine valley system.

Our data represent average evaluations of the channel bottom slope. These values are representative, but due to the somewhat subjective way of establishing the boundary between the three evaluated valley sections, they are not entirely accurate numbers and have lower statistical repeatability.

In the prepared graph, the longitudinal profiles of valleys gradient are ordered according to the gradient decreasing value of the canyon-type channels. These canyon gradient values vary between over 80 m/km and less than 25 m/km (Fig. 20). The steepest are the Bosporus (right branch of the system) and Gagra (Bzyb-Mzymta system) canyons. Their depth increases downstream by 82 m/km and 63.5 m/km respectively (1 and 2 in Fig. 20). The Yeshilirmak and Supsa submarine canyons (8 and 7 in Fig. 20) have the mildest measured channel slope gradient (23 m/km and 26 m/km).

The fan valley type channels have bottom slope gradients, which vary from 17 m/km to 2 m/km. Some of the lower fan valley segments, through which the submarine valley extends to the abyssal plain, have gradients of 2 to 3 meters per kilometre (Supsa, Gumista, Gagra and Bosporus) (7, 5, 2 and 1 in Fig. 20). The average slope gradient of the Danube Distributaries Complex (channel-levee network) amounts to 5 m/km (6 in Fig. 20).

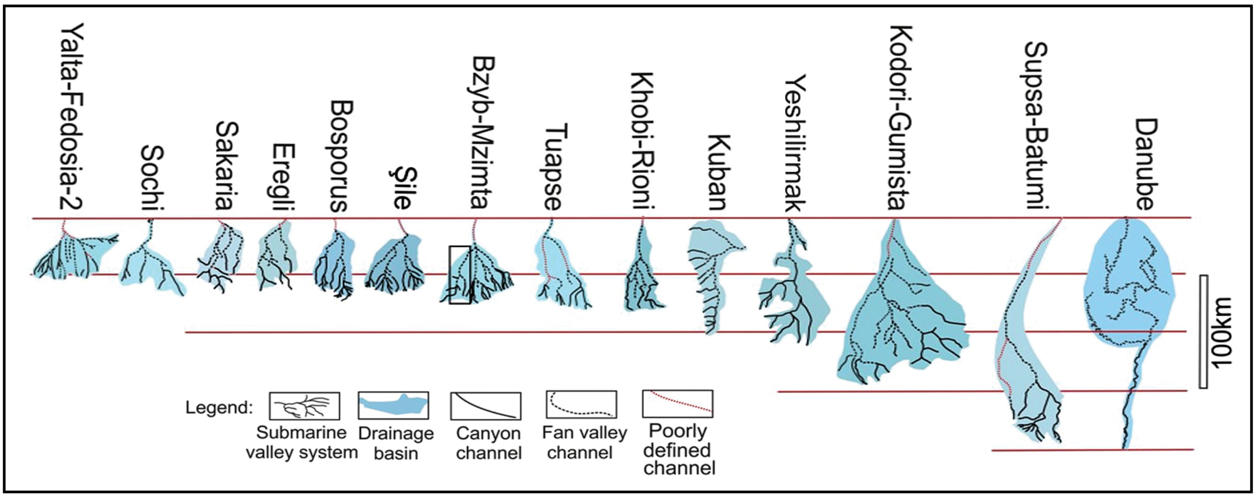

Fig. 19. The comparative extent of the main Black Sea submarine valley systems

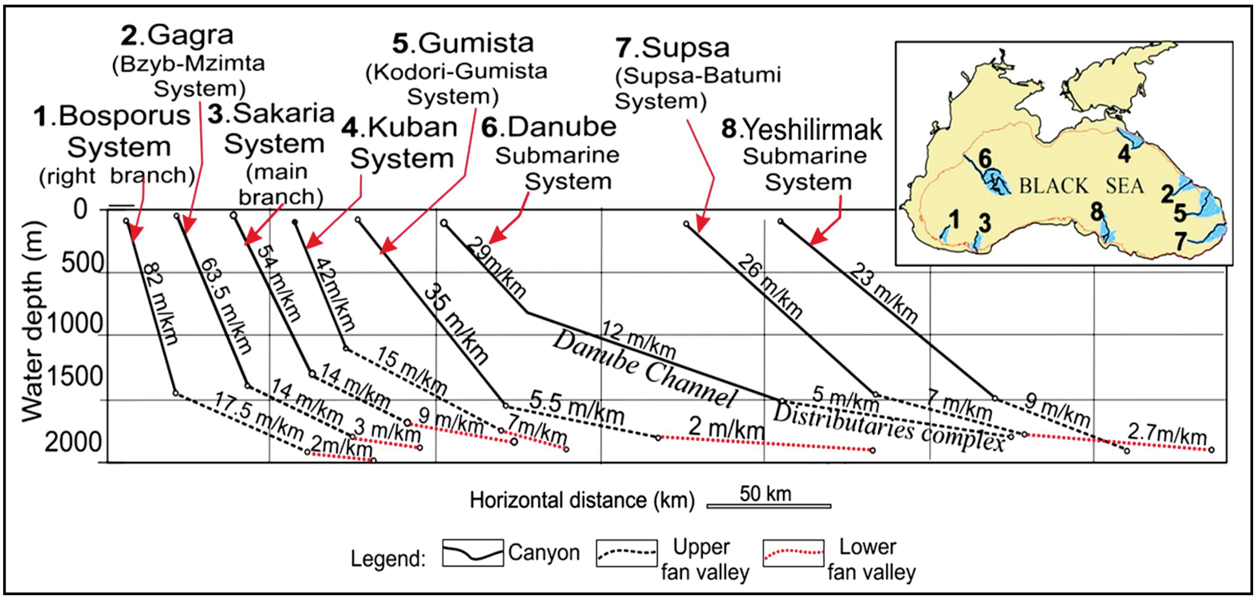

Fig. 20. Slope gradient of the main Black Sea submarine valleys

For most of submarine valleys presented on the graph, there is a significant gradient difference between upper and lower fan valley-type channels. Yeshilirmak valley has a short and steeper undifferentiated fan valley channel (6 in Fig. 20).

The large slope gradient variation range (80 to 20 m/km) of the canyon-type Black Sea submarine channels reflects their diversity of the geological setting, origin and evolution.

5.3. Black Sea deep sea fans

Some of the Black Sea submarine valley systems have generated important deep-sea sedimentary fans (Figure 21). The Danube - Dnieper Fan dominate the north-western part of the deep Black Sea area. The structure of the Black Sea north-western submarine valley network (Danube System, Fig. 3; Dnieper System, Fig. 4) and its sedimentary accumulation suggests these were key to sediment transport and formation of the Danube – Dnieper Fan (Figure 21). However, the formation of a shelf incised canyon to valley system in the north-western slope area probably also contributed with larger sediment volume (Fig. 3a and 16b).

The Caucasus Submarine valley systems network generated the largest areal deep-sea fan-like composite sedimentary accumulation in the Black Sea basin (Fig. 21). The area of the Caucasian Deep-Sea Fan extends from the Kuban System in the north to the Carik, the eastern Turkish escarpment. The Caucasus Deep-Sea Fan is a complex sedimentary accumulation built mainly by the nine Caucasian submarine valleys systems. (15 to 23 in Fig. 17). The width of the Caucasus Deep Sea Fan increases from the north to the south, from a few kilometres to over 200 km. This development corresponds to the south-eastward growing elevation of the of the Great Caucasus Mountains relief, from several hundred meters high hills to over 5,000 m high mountain peaks, the highest in Europe, and correspondingly of the relief energy and sediment supply amount.

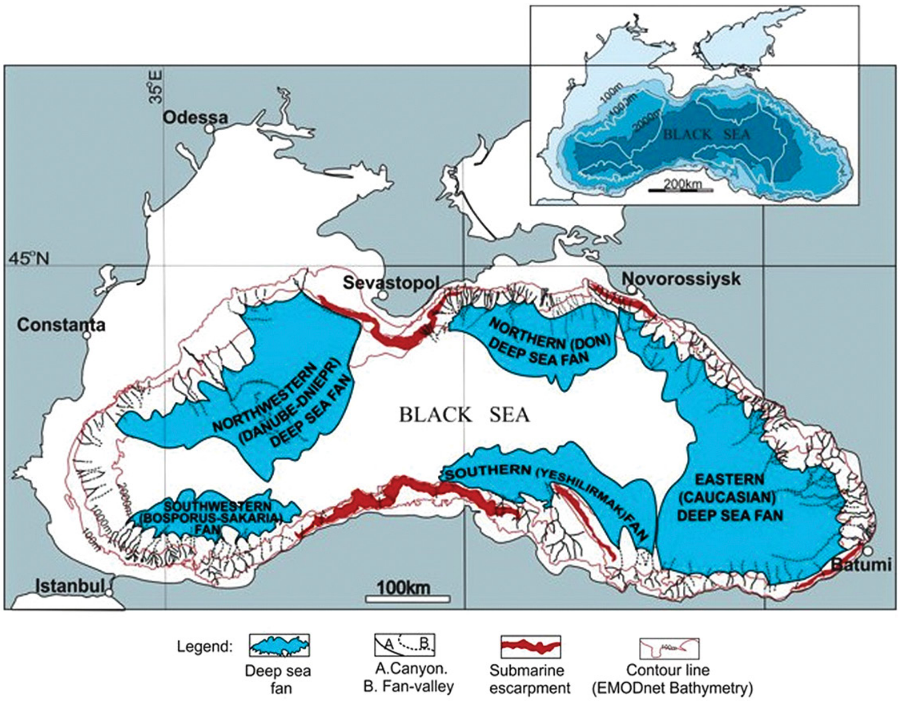

Fig. 21. The main detrital accumulations (deep sea fans) generated by the Black Sea submarine valley network.

Reflecting the magnitude of the clastic material input, the other three deep sea fans in the Black Sea Basin (Don Fan, Yeshilirmak Fan and Bosporus-Sakaria Cone, Fig. 21) cover relatively smaller areas. The Yeshilirmak Deep Sea Fan is formed by the sediment delivered by the major Yeshilirmak and Kizilirmak submarine systems (Figs. 13 and 21), which are supplied with sediment from two of Turkey largest rivers. The Yeshilirmak Deep Sea Fan includes two submarine sedimentary depocenter areas, partly separated by the Archangelsky Submarine Ridge (Fig. 21). The eastern part of the Yeshilirmak Deep Sea Fan, built by the smaller canyons of Fatsa, Aziziye and Ordu (Fig.12 and 21), form a small distinct deep sea fan.

The sediment accumulation in the Bosporus-Sakaria Fan is due to the activity of a network of several underwater valleys, the most important of which are Bosporus, Şile, Sakaria and Eregli systems (5 to 8 in Fig. 17).

The Don Deep Sea Fan (Fig. 21) is outlined by the submarine relief revealed on the EMODnet Bathymetry chart. The knowledge on the Don submarine valley network that has created it is still incomplete or not available. According to our study, the name "Don and Kuban Fan" can no longer be used, although Don and Kuban submarine valleys systems are very close, but the Kuban submarine valley system is associated with the Caucasus submarine valley network (Figs. 6, 17 and 21).

The location of sedimentary deep-sea fans in the Black Sea suggests an overlap between the sedimentation areas. The Caucasian Deep Sea Fan is in contact with the Don Fan and the Yeshilirmak Fan. In the current state of our knowledge, the boundaries between these bodies are conventional. There is a small distance between the frontal boundaries of the Danube - Dnieper Fan and the Bosporus-Sakaria Fan (Fig. 21) allowing mutual sedimentary relationships, as revealed by Lericolais *et al.* (2013).

5.4. The submarine canyon network in the Black Sea - quality of data

The main results of the study presented in this paper are based on the opportunity to use the recent Black Sea bathymetric chart, part of the Europe bathymetry chart, developed by the EMODnet High Resolution Seabed Mapping Project (EMODnet Bathymetry Consortium, 2016).

The Bathymetric chart generated by EMODnet is the highest resolution of the Black Sea seabed existing to date in this marine basin. However, the high-resolution bathymetric investigations whose data were integrated by EMODnet Bathymetry were undertaken only in certain areas of the Black Sea (Fig. 22).

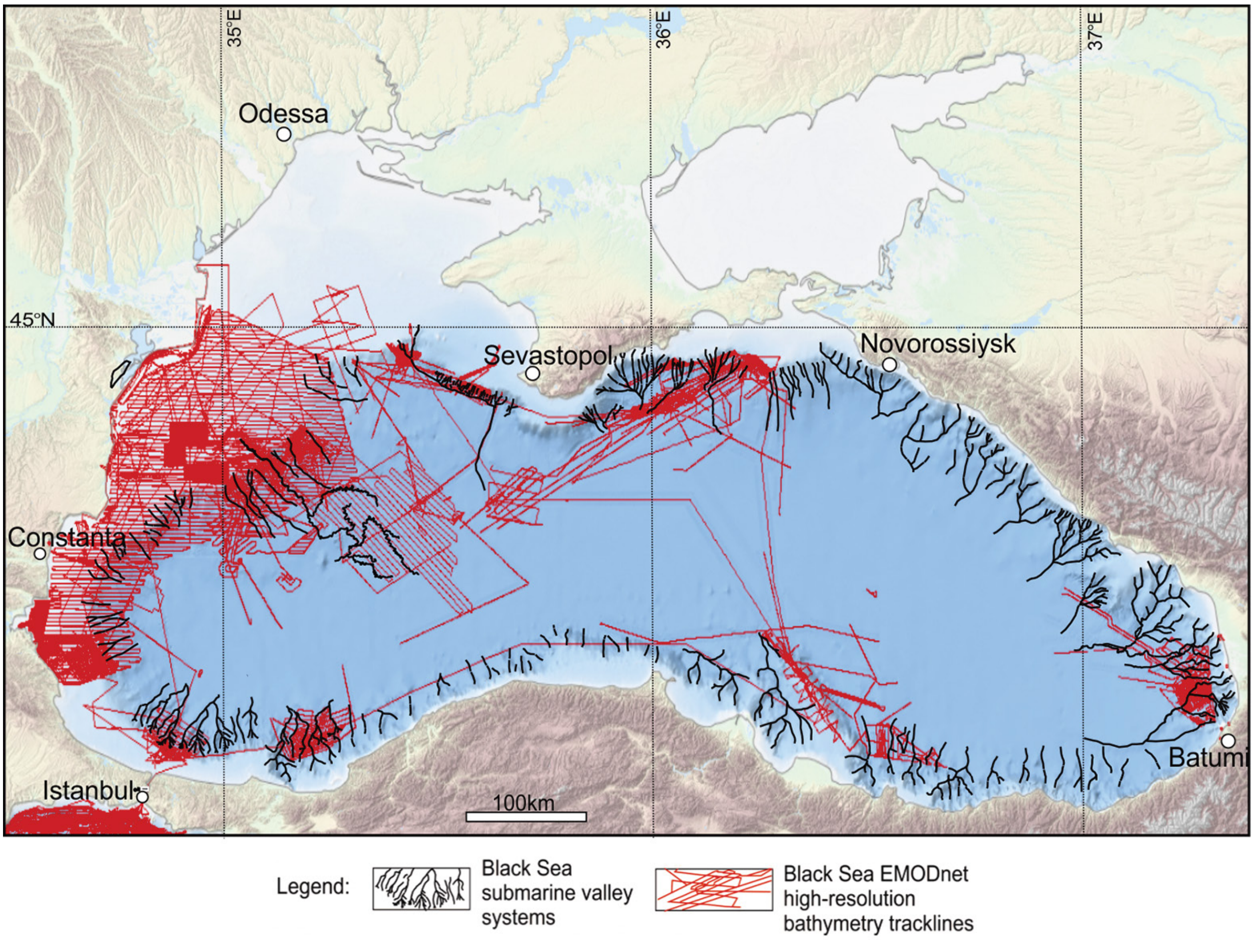

Fig. 22. Black Sea submarine valley network vs. Black Sea distribution of the EMODnet high resolution bathymetry survey tracks. Base map and survey tracks/polygons from the EMODnet Bathymetry portal

The western Black Sea continental margin, offshore Romania and Bulgaria, was intensively investigated with modern geophysical methods (Fig. 22). In contrast, in the Eastern Black Sea marine area the high-resolution data of the EMODnet Bathymetry chart were collected only from small areas between Gudauta Bank and Batumi, but are concentrated off the Poti-Batumi area (Bohrmann and Pape, 2007, Kenyon *et al.*, 2007, Bohrmann and Ohling, 2011, Shipahioglu *et al.*, 2013). Small high resolution investigated areas located on the Turkish Black Sea margin and offshore Crimea also provided high resolution data to the EMODnet Bathymetry project. Therefore, much of the Black Sea submarine valleys highlighted in this paper appear in areas where there are no high-resolution bathymetric data (Fig. 22).

The absence of high-resolution bathymetry data is limiting the details that could be observed in our study. This applys especially to areas where the seabed has low gradients. For this reason, in some areas of our investigation, the submarine valley systems could not be recognized with entire certainty. This is the case of the area south of the Kerch Strait (Fig. 5). Some submarine channel segments are also drown on lower resolution bottom bathymetry, and are marked as „poorly defined channels".

6. CONCLUSIONS

This study presents a detailed picture of the underwater morphology of the entire Black Sea basin, beyond the shelf zone, focusing on submarine valley systems on continental slope and continental rise zones, and partially in the abyssal area. It is among the very few papers that have undertaken such an analysis on a regional scale, for an entire marine basin.

The analysis and the obtained results regarding the characteristics of the Black Sea submarine valleys have been facilitated by using the most recent bathymetric map of the Black Sea. The Black Sea map is part of the bathymetric map of Europe, developed and published by the EMODnet Bathymetry Consortium within the EMODnet High Resolution Seabed Mapping Project, and granting this map to open access status.

The authors distinguished the following sectors along a submarine valley system: *canyon-type channel,* a narrow submarine channel from the shelf-break on the continental slope, it has variable relief and high gradients, and the *fan valley,* crossing lower relief sea bottom, especially of the continental rise area, extending toward the abyssal plain, with lower slope gradient and wide, shallow channels. The fan valley was subdivided into *upper fan valley* and *lower fan valley*.

The Black Sea submarine valleys network is presented in a sketch-map. This network includes 25 valley systems, 5 groups of simple, first order channels and other number of simple, not associated channels. The 25 valley systems are summing up more than 110 main channels and tributaries. Morphological description and analysis of each of these systems is given. The shape and structure, dimensions (length and surface) and slope gradient, as well as the amount of sediments supplied by the valleys to the deep-sea zone, forming the deep-sea fans of each valley system was analysed.

Among the Black Sea submarine valley systems, the Danube is the most extensive. The direct length of the Danube drainage basin is about 200 km, and its surface exceeds 5,700 km^2.

The slope gradient is different for canyon channels and for the fan-valleys. The canyon slope gradient vary between 80 m/km and 25 m/km, while the fan valley type channels have bottom slope gradients which vary from 17 m/km to 2 m/km.

In a previous paper, the authors (Jipa & Panin, 2020) tried to consider the canyons in the Black Sea taking into account their genetic and morphological characteristics. Two distinct types of canyons and submarine valleys have been highlighted: (1) wide shelf canyons, located mainly in the north-western part of the sea and (2) narrow shelf canyons, in the eastern and southern part of the Black Sea basin, in the vicinity of a mountainous high relief (Caucasus and Pontic Mountains).

The difference in response of the two types of canyons to the variation of the sea level was revealed: the wide shelf canyons are active only in the conditions of lowstand, when the sea level rises they become inactive, the shelf being flooded, while the canyons of narrow shelf, with a coastal area of high relief energy, remain active in both sea level stands.

In the Black Sea two deep-sea fans are largely dominant: (1) in the north-western Black Sea there are the Danube and the Dnieper deep-sea fans, adjacent and intertwined, representing an extremely large amount of sediments supplied by the respective rivers, and (2) in the eastern Black Sea, the Caucasus Submarine valley systems network generated the largest area in the Black Sea basin accumulation of sediments as a deep-sea fan-like composite structure.

Concerning the volume of sediments accumulated in the deep-sea fans, the authors give only a qualitative appreciation. Only for the Danube deep-sea fan there is a quantitative evaluation of volumes of sediments accumulated (Wong *et al.*, 1997, Winguth *et al.* 2000, Panin, 2009).

For having a more detailed and precise image of the Black Sea network of submarine valleys the authors state that is necessary to cover the entire basin with a minimum standard network of bathymetric mapping (if possible using multibeam systems) and of high resolution seismic survey. There is also the need to make the connection with the geological constitution and structure of different sectors, as a determining factor for shaping the morphology of the seabed, including of the submarine valleys network.

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