
A history of the circum-Pontic river channels marked by climate and sea level changes during the Late Quaternary (25-8 ka BP)

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ABSTRACT

The present paper synthesizes the evolution of fluvial systems tributary to the Black Sea (within 25 – 8 ka BP time frame) by reviewing the existing paleoclimate, hydro-geomorphology, sedimentology, and Late Quaternary chronology. These studies are unevenly distributed throughout the Black Sea (BS) drainage basin and were used to decipher the river response to climatic, eustatic, tectonically induced or vegetation cover changes. The river response was sensitive overall and is visible particularly in terms of the channel planform. The alternation of cold and warm climate phases has controlled to a significant degree the water and sediment inputs along the drainage networks, such that river channels planforms shifted from the braided type to the anastomosed type (with various transitional phases, either wandering or anastomosed), and from macro-meanders to small scale meanders. The climatic model of fluvial evolution was altered by the other controlling factors specific to the large BS drainage basin, including tectonics (in the Pannonian Plain, Western Plain of Romania, Lower Siret Plain), the proximity to coarse-grained sediment sources (typical for medium-sized Carpathian tributaries), the obstruction exerted by glacial sediments generated by the ice cap retreat (as illustrated on the Upper Dnieper), eustatic oscillations (detected on the Danube or Sakarya River). The sea-level drop by more than 100 m during the Last Glacial Maximum resulted in the conversion of ca. 30% of the present sea surface to dry land (mostly on the NW continental shelf); several sinuous-anastomosed paleo-channels pertaining to major rivers (Danube, Dniester, Dnieper) with depths ranging between 30 and 90 m were reconstructed on the surface of this emerged land. Black Sea became connected to the Planetary Ocean during the Early Holocene (ca. 9.4 ka BP). The sea waters flooded extensive areas at the NW and advanced upstream along tributary river valleys. The effects of base-level rise were reflected in the anastomosed style of river channels and the accumulation of deltaic formations.

KEYWORDS fluvial style reconstruction, paleo-hydrological changes, base-level oscillation, Black Sea drainage basin, Late Pleniglacial, Late Glacial

1. Introduction

For more than two decades the Black Sea has been at the core of a heated scientific dispute regarding major level oscillations in the Upper Pleistocene and the Holocene. The most compelling argument is related to the so-called „flood question“ (originating from the Noah flood myth and expressed in the title of the books published by William Ryan and Pittman, 1998 and Yanko-Hombach et al., 2007). Based on an investigation of marine geology widely regarded as remarkable (apud Baker, 2007), Ryan et al. (1997, revised in 2003) hypothesized that the Black Sea was abruptly flooded during the Early Holocene (at ~8.4 ka) and linked the event with the Biblical myth of the Flood. The scientific community was surprised by this interpretation, while the hypothesis had captured the interest of both the media and the general public. In short, this theory assumes that during the last Quaternary glaciation, the Black Sea was a freshwater lake whose level was as low as -120 m (up to -140 m) below the present level. At ~8.4 ka the waters of the Mediterranean Sea swiftly pierced through the Bosphorus strait such that in a very short time frame of approx. 2 years the basin was filled and the water salinity increased (Lericolais, 2017). The sea-level rise resulted in the flooding of more than 100,000 km² of land which is currently part of the continental shelf. According to the authors, the abrupt flooding event led to the sudden migration of populations from around the Black Sea to the inner regions of Europe. Moreover, the authors accredit the idea that the legend of the Biblical Flood originated in this catastrophic event which took place in the Black Sea region instead of the Biblical Mesopotamia.

This bold hypothesis proved to be rather divisive in the scientific community, generating both support and skepticism. However, the rising interest resulted in several investigations undertaken by international expeditions using advanced research equipment which yielded numerous publications on the matter.

Although research has intensified in the Black Sea region, the scientific community is still navigating, to a large extent, a realm of hypotheses, which have gradually multiplied to three main concepts (i.e., catastrophic - Ryan et al., 2003; gradual - Hiscott et al., 2007; oscillating - Chepalyga, 2007),

and later on to four (cf. Yanchilina et al., 2017), as the amount of evidence has augmented as well as the complexity of data interpretation.

Some of the questions persisting on the topic were summed up as paradoxes (Yanko-Hombach and Kîslov, 2018) which originate in several anomalies, including the ones related to the major oscillations of Caspian and Black Sea levels (which were connected repeatedly throughout the Quaternary), to the water sources which generated the oscillations, to the insufficient available numerical data and the low correlation with climate events, or to some contradictions between various datasets yielded by scientific investigations. Among these diverse opinions, however, one theory has gained broad support, stating that the most recent connection of the Black Sea with the Mediterranean Sea occurred during the Early Holocene between 7.5 ka and 9.4 ka, more specifically at 8995 ± 145 cal a. BP (cf Soulet et al., 2011, which reviews state-of-the-art analysis and calibration techniques).

This work does not attempt to discuss in detail all the arguments and evidence supporting either hypothesis (some important references are also included in the bibliography of this paper) or assert opinions regarding the previously mentioned debate. Instead, we focused our attention on a category of landform ensembles that are sensitive enough to preserve the traces of major climatic and eustatic shifts of the Late Pleniglacial as part of their sediment and morphological archives (Vandenberghe, 2002, 2003). River valleys are such landform ensembles suited for this type of approach, more specifically the valleys or rivers tributary to the Black Sea or circum-Pontic rivers, in our case. Danube, Dniester, Dnieper, Don, to name just the largest circum-Pontic watercourses, were forced to adjust their morphological parameters in time such that the geomorphic work can be accomplished: transferring extremely variable amounts of water and sediment to a highly oscillating base level.

Consequently, a significant number of studies of paleoclimatology, hydro-geomorphology and Late Quaternary chronology regarding the rivers of the circum-Pontic region were reviewed. Considering the broad geographical distribution of areas where

research data is available within the region of the Black Sea basin, the studies were grouped into three categories:

(a) paleo-geomorphological reconstructions based on fluvial sediment archives (particularly for Danube, Dniester and Dnieper, as well as for two major Anatolian rivers, Kızılırmak and Sakarya);

(b) paleo-hydrological reconstructions based on the mathematic modelling of paleo-channel morphology (as applied on the fluvial systems of the Russian Plain, such as Bug, Dnieper, Don and their tributaries);

(c) reconstructions of Black Sea level oscillations and effects on paleo-drainage on the continental shelf. The results of reviewed studies were discussed against the background provided by various climate variability records (following the recommendations of INTegration of Ice-core, MARine, and TERrestrial records INTIMATE community, Blockley et al., 2012), as well as by other regional interpretations regarding the response of fluvial ensembles to the combined action of control factors in LQ.

2. Regional setting

The drainage basin of the Black Sea (BS) extends over nearly 1.9 million km² (without Black Sea surface area) (Vespremeanu and Golumbeanu, 2018), from Central Europe (west) to the Russian Plain (north), the Caucasus (east) and the Pontian Mountains and the Anatolian Plateau (south) (Fig. 1). Whereas the Danube is the largest single tributary of BS, with a drainage basin of ca. 801,000 km², the rivers draining the Russian Plain cover more than 1 million km² (Table 1). The sources of the water discharge transported to BS originate in the Alps (partially), the Carpathians (tributaries of Danube and Dniester) and the Valdai Plateau (Dnieper and Don). The southern tributaries of BS are typically shorter in length with comparatively smaller drainage basins. Of these, Kızılırmak (Red River) and Sakarya, which originate in Central Anatolia, are more notable. For the purpose of this investigation, only the rivers included in Table 1 are discussed, which were selected based on the availability of paleo-evolution studies in their morphological ensembles.

The Black Sea is a semi-closed Mediterranean basin with a marginal position: as deep as 2250 m

and over 466,200 km² in area (Vespremeanu and Golumbeanu, 2018). Due to its position of semi-isolation within the planetary ocean, the Black Sea tends to amplify environmental changes, and thus its detailed and sensitive paleoclimatic record has become a focus of oceanographic research (Yanko-Hombach et al., 2007). During its Quaternary history, the BS has undergone numerous stages consisting of alternating phases of complete isolation from the ocean and connection with the Caspian Sea through the Manych channel, ensued by reconnection with the Mediterranean Sea through the Bosphorus (Fig. 1). Throughout this time frame, the BS level has oscillated by as much as 120 m while undergoing large variations in terms of water salinity and a vast array of derived ecosystem shifts (Lericolais, 2017).

As regards the climate of the study area, the drainage basin of the Black Sea falls under the following dominant types: (i) the central European, or transitional type of climate, resulting from the interaction of both maritime and continental air masses; (ii) the continental type of climate dominating a large area pertaining to the Eastern European Plain, to the north of the Black Sea; (iii) the continental type of climate, with humid subtropical influences in some sectors of the seafront (Crimea, Caucasus) and drier traits on the Anatolian seafront. The current types of climates were also characteristic for the Pleistocene environment in this region, albeit with a higher degree of continentalism (i.e., lower temperatures and scarce precipitation during cold seasons, linked to the advancement of the icecap) (Starkel, 1977; Frenzel et al., 1992).

In terms of morphotectonics and morpho-structure, the drainage basin of the Black Sea is characterized by the ensembles created by the Alpine orogenesis (the Alps, the Carpathians, the Caucasus) and the great Eastern European platform. To the south, the drainage basin of BS overlies the region dominated by the North-Anatolian fault, which separates the Eastern European Plate from the Anatolian Plate.

Major fluvial systems which shape this region are presented in Table 1. The availability and spatial coverage in terms of paleo-evolution studies are uneven, at best, both in terms of distribution along the river valleys and temporal coverage of the review.

Table 1 Data related to major tributaries of the Black Sea for which paleo-evolution studies are available and have been reviewed in this paper

River	Drainage basin area, (A, km ²)	River length (L, km)	Water discharge (Q, m ³ /s, annual mean)	Qmax, m ³ /s (mean maximum)	Suspended sediment load (kg/s)
Dnister	68,627	1362	310	610 (June 1969 = 3000)	550
Southern Bug	63,700	806	108	-	63.4
Dniپر	531,817	2145	1670	-	254
Don*	425,600	1870	935	-	-
Kuban*	58,000	870	425	-	-
Danube	801,463	2850	6515	21,867	1534
Tisa	156,087	966	792	-	-
Mureş	30,332	789	186	-	-
Siret	44,835	706	254	2643/4650	275
Kizirlimak **	78,646	1355	185	-	-
Sakarya **	56,504	824	177	-	120

* tributaries of Azov Sea

** major southern (Anatolian) tributaries of BS



Figure 1 Black Sea drainage basin with the most important tributaries (modified after <https://commons.wikimedia.org/wiki/>). Location of the paleo-fluvial and paleoclimatic study areas used in this article (Numbers next to the sites refer to the site names in Annex 1); red stars: sites with large paleochannel remnants (after Sidorchuk et al., 2011)

wed time frame (Pleniglacial, Late Glacial, Early Holocene). For this review we have focused on the Lower Danube and its Carpathian tributaries, the rivers draining the Eastern European Plain and the two most notable Anatolian rivers (Kızılırmak and Sakarya) (to illustrate, investigated reaches and sites where paleo-evolution data is available are pinpointed in Fig. 1 and described in Annex 1). Along with paleo-fluvial data we have used other paleo-environmental information available for the neighboring areas of BS, such as the stalagmite isotopic records obtained at Sofular Cave in north-western Turkey (Fleitmann et al., 2009) or at Karaca Cave in north-eastern Turkey (Rowe et al., 2012). Similarly, we have included in this review the records of Tăușoare Cave in the Eastern Romanian Carpathian (Staubwasser et al., 2018) and the lacustrine sediment pollen records at Preluca Țiganului, in NW Eastern Romanian Carpathian (Feurdean et al., 2014).

According to their nature, fluvial sediment archives typically have much lower resolution in recording the main paleo-environmental and climatic phases compared to other terrestrial records (such as stalagmites, cave ice cores, lakes and peat bogs etc.), as fluvial memory has mainly retained only major climatic, eustatic or tectonic shifts. The most accurate, high-resolution record of past climate for Early Quaternary is the isotopic $\delta^{18}\text{O}$ curve from Greenland (Dansgaard et al., 1993; Rasmussen et al., 2008; Svensson et al., 2008), which is used by the INTIMATE group as a template for reporting terrestrial records of the Northern Hemisphere (Moreno et al., 2014). A stratigraphic division of the last cold stage in Europe (Frenzel et al., 1992) distinguishes the following climate phases during the studied period:

(a) Upper Pleniglacial (28 - 14.65 ka cal BP, includes the LGM) - coldest and driest period but with several weak warming fluctuations;

(b) Late Glacial (14.65 - 11.65 ka cal BP) - was characterized by gradual warming with significant fluctuations (including the cold Younger Dryas: 12.7-11.65 ka BP) visible in the expansion of the forest belt from the east and melting of permafrost;

(c) Early Holocene (11.65 - 8.5 ka cal BP) - was characterized by rapid warming.

We used these major climate phases as time frames, according to which we integrated fluvial change records as reported by reviewed study cases (see Annex 1).

3. Paleo-geomorphological reconstructions based on fluvial sediment archives

Numerous studies on fluvial sediment archives have been published across the board, particularly in temperate environments, as mounting evidence showed that fluvial morphology and sedimentology have the capacity to store paleo-geomorphological information (Schumm, 1977; Starkel, 1991; Vandenberghe and Sidorciuk, 2020). Research works carried out on the tributaries of mid-course and Lower Danube, on the Danube itself, as well as on the largest rivers and the tributaries of the Russian Plain, illustrate how LQ climate changes have generated tangible, dramatic responses of river channels. Our intent was to collect as much data as possible, including substantial results, regarding the behaviour of rivers at contact with BS, which has acted as a base level for the geomorphic activity of tributaries. The scarcity of detailed LQ paleo-fluvial in this area has prompted us to turn our attention upstream to the valleys of these tributaries where such investigation results are available. Finally, we were interested to observe whether there was any synchronicity in the response of rivers to major climate shifts, if other factors intervened in the behaviour changes of river channels (such as tectonics and eustatism), whether this synchronicity was limited to certain morpho-structural units of the BS basin, or, conversely, if this was a dominant phenomenon for all river channels in the investigated region.

Relatively abundant research has been carried out on the paleo-geomorphology of rivers from the Pannonian Basin, particularly on Tisa and its tributaries, with hundreds of cores retrieved and dated using OSL and radiocarbon dating and palynological assemblages established based on successions of fine-grained sediments in order to determine the history and controls on alluvial sedimentation for throughout more than 30 ka (Gabris and Nador, 2007; Kasse et al., 2010; Nador et al., 2011; Șipos et al., 2016; Vandenberghe et al., 2018 and their references). By combining controls of fluvial

processes in a summarized illustration (Fig. 2), several river pattern change phases are distinguished, driven mainly by climate changes, as follows: (i) braided channel at 23 – 19 ka, overlapping the Last Glacial Maximum (LGM), and at 16.5 – 14.6 ka (Oldest Dryas), against a dry cold climatic backdrop, when Tisa and its tributaries received large amounts of sediments they were unable to transport and were thus stored as scroll bars and islands. Moreover, fluvial dynamics was complemented by intensive wind activity, noticeable in the landscape of this region due to the wide-presence of fluvial sands prone to wind

reworking during dry phases; (ii) meandering channel characteristic for warmer, more humid periods, when vegetation abundance resulted in increased dune stabilization and soil formation, thus reducing the sediment transfer to river channels. Prevalent processes include incision and shaping of fluvial terraces. The dominant pattern relied on the meandering, but meander size varied: e.g., meanders which formed between 19 and 16.5 ka had lengths and amplitudes 3 to 4 times greater than current meanders due to proportionally higher streamflow discharge values.

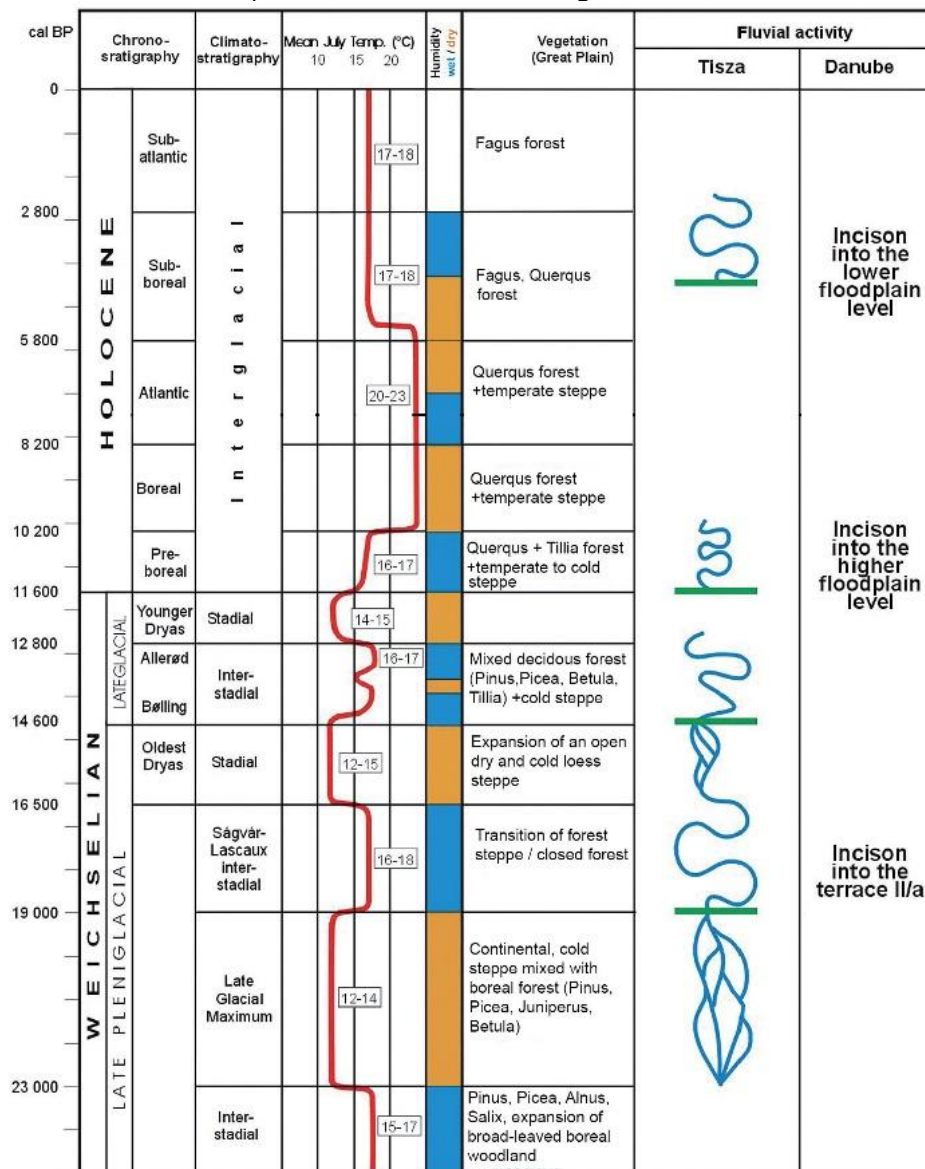


Figure 2 Paleo-environmental changes in the Pannonian Basin and fluvial activity of the Middle Tisza region and the Körös (Criș) basin during the last 25 ka (modified after Gabris et al., 2012)

Downstream of the Pannonian Plain, a group of rivers of interest include the tributaries of Danube, which drain the Carpathian arch. These are typically smaller-sized rivers, with drainage basins that seldom surpass

10,000 km² and their discharges vary in the range of tens of m³/s. The investigations on their LQ fluvial evolution were recently reviewed and summarized (Fig. 3).

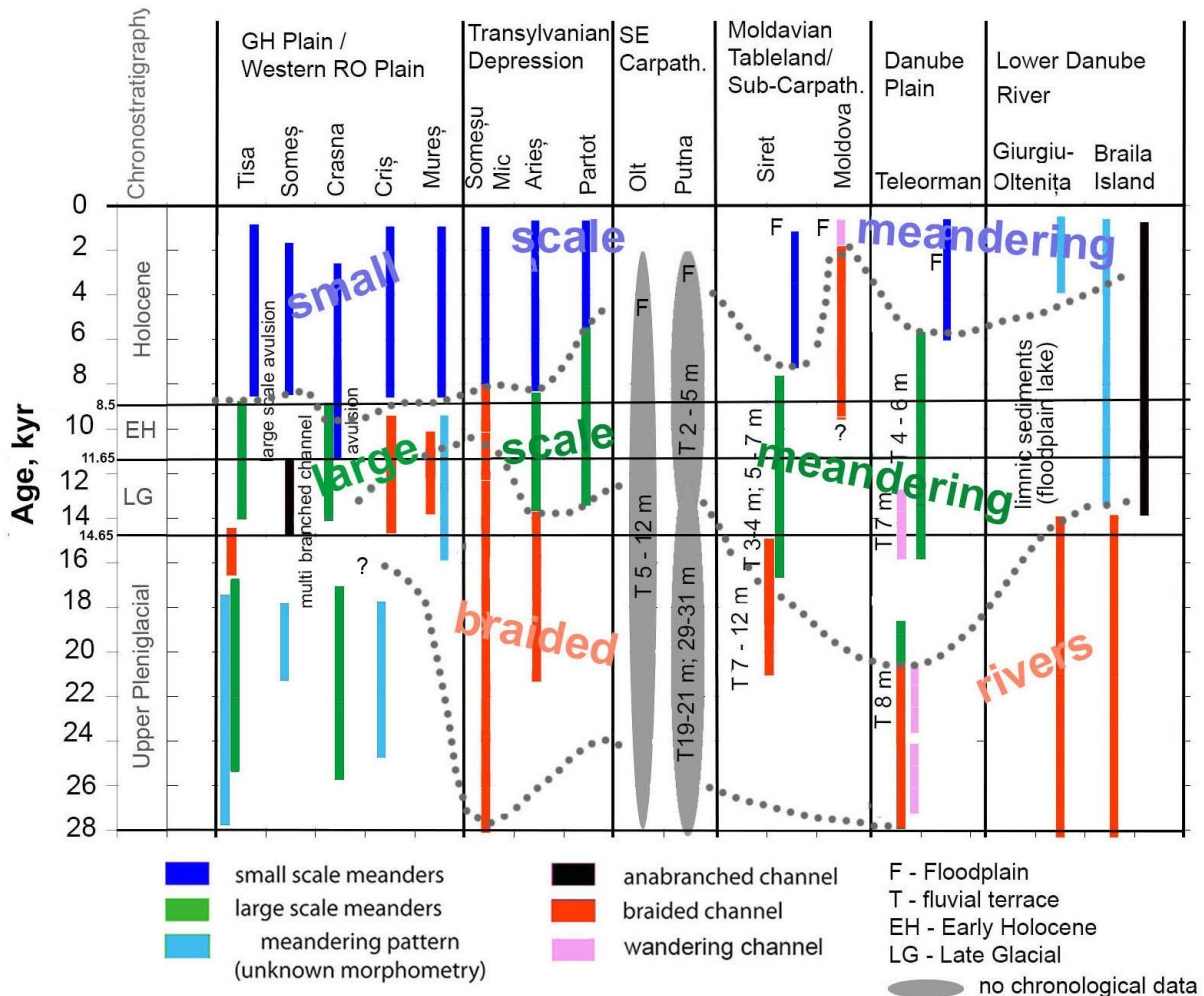


Figure 3 The ages of the lower fluvial features, as reflected by the recent studies on Late Quaternary fluvial evolution in several morpho-structural units from Romania (reinterpreted after Perșoiu et al., 2017, with additions)

Compared to rivers of the Pannonian Basin, whereby the bed material is predominantly fine-grained, the rivers of the Transylvanian Depression and the outer rim of the Carpathians are typically coarser-grained, with beds dominated by gravel, and are characterized by higher energy environments, due to greater slope gradients and shorter distances to coarse sediment sources. Consequently, the response of channel configuration was different in terms of the ability to generate mature channel styles. For instance, during a long period of time (Pleniglacial to Late Glacial) the rivers developed

gravel-bed braided channels with a tendency towards aggradation, albeit they evolved throughout distinct climatic phases. The first major change in fluvial morphology was documented during the Late Glacial when numerous rivers abandoned the braided style for large-scale meandering rivers (i.e., meander size was 3 to 5 times greater compared to present-day meanders). The second major shift occurred in the Early Holocene when rivers maintained their meandering styles, although the meander size decreased significantly. In the case of Carpathian rivers, some synchronicity is evident in terms of the

fluvial activity, which is regarded by Starkel et al. (2015) as a common trait for many rivers in Central and Eastern Europe. The causes for these adjustments of fluvial styles consist in the climate changes and the subsequent dynamics of the vegetation cover. Moreover, shifts generated by tectonic movements overlap climate changes, thus leading to phenomena such as avulsion (e.g., the rivers of the Western Plain, Perşoiu et al., submitted), incision or floodplain aggradation.

As regards the LQ history of the Danube, data is still insufficient for clearly discerning between the role of climate changes (as relayed from the drainage basin through the tributaries) and that of eustatic oscillations at the confluence with BS. Several cores retrieved in the Danube floodplain downstream of

Giurgiu urban area (Fig. 4b, P and G points) have intercepted a massive layer of gravel and coarse sand dated to at least 32.7 and 15.9 ka (OSL dates) and seem to correspond to a braided river (Benecke et al., 2013; Hansen et al., 2017; Vespremeanu-Stroe, pers. com).

The depth at which the gravel layer was intercepted ranges between -17 m at Pietrele (Giurgiu), -14.5 at the junction with Mostiștea, -35 m at Hârșova, -25 m at Brăila, -12 m (just downstream of the junction with the Siret, but in the latter case the drilling stopped at the sands, Țuțianu et al., 2021), and -45 m at Tulcea and Sulina (the latter according to Giosan et al., 2009; Vespremeanu-Stroe et al., 2017).

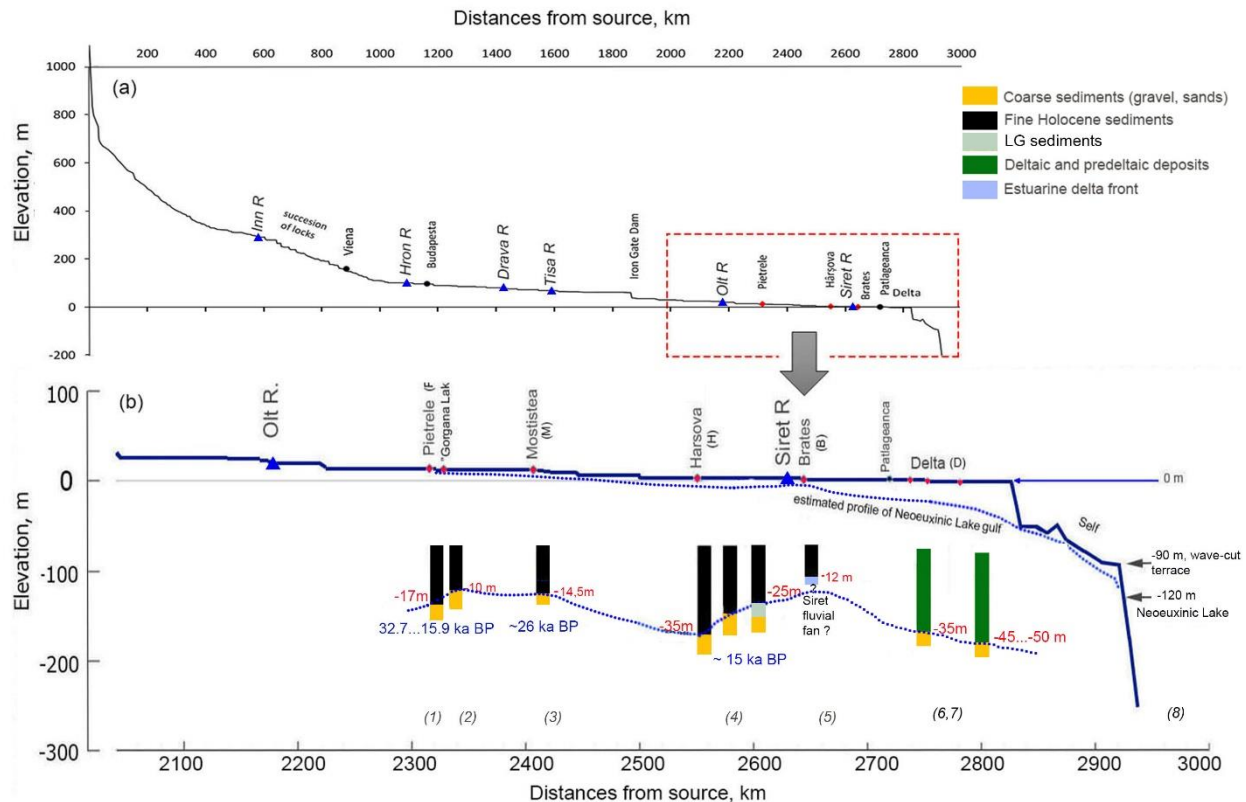


Figure 4 (a) Longitudinal profile of the Danube with marking of the lower sector; (b) Detailed longitudinal profile of the Lower Danube and approximate reconstruction of the neo-Euxinic Danube longitudinal profile (dotted line) with exaggerated drill representation along the vertical axis: (1) Benecke et al. (2013); (2) Hansen et al. (2018); (3) Vespremeanu-Stroe (personal communication) (4) Ghenea & Mihailescu (1991); (5) Tutuianu et al. (2018); (6,7) Vespremeanu-Stroe et al. (2017); Giosan et al. (2009); (8) Popescu et al. (2004, 2015)

The age and facies of the fluvial deposits indicate the course of the gravel-bed channel of the paleo-Danube during the neo-Euxinic phase, when the base

level of BS was more than 100 m below the present-day level (Fig. 4b). This course is irregular and appears as a succession of deeper and shallower reaches,

which is similar to the alternating riffle-pool morphology of current channels. One of the raised reaches of the coarse-grained bed of this course is located adjacent to the confluence with river Siret, thus suggesting a fluvial fan type of landform at the contact between the two rivers (although the authors of the Brateş drill estimate the depth of the coarse-grained bed at -25 m). We prefer to avoid speculating in this phase of the study, which focuses on collecting data; however, the mechanism through which the effects of base-level lowering are transferred upstream is thought-provoking (Posea, 2002 estimated that these effects were transmitted upstream as far as Giurgiu urban area), as well as the mechanisms of downstream transport (water + sediment) and the resulting morphology.

Relating these findings with data reported by studies carried out at Brăila Island (Ghenea and Mihăilescu, 1991) indicated that the lower floodplain continued to undergo an active process of aggradation with traces of avulsion, which advanced along with the anastomosed channel system of the BS inner shelf (Popescu et al., 2004; Lericolais et al., 2010; Popescu et al., 2015). The level rise of BS after 16 – 15 ka favoured the accumulation of finer-grained fluvio-lacustrine sediments corresponding to the deglaciation phase when the level of the Black Sea rose by ~40 m. This led to an increasing occurrence of the anastomosed typology of the river along with avulsion. As a result, the right fluvial branch which delimits Brăila Island, shifted to a

secondary status, whereas the left branch became the main one in the Early Holocene (Ghenea and Mihăilescu, 1991). This process was partially ascribed to tectonics due to the apparent overlap of the southern paleo-branch on the Peceneaga-Camena fault, a major crustal fault separating the north-Dobrogea orogen from the Moesian Platform (Popescu et al., 2004).

To the north of the Black Sea, the vast Eastern European Plain is crossed by several large rivers, among which the Dnieper stands out in terms of the amount of research data yielded by sediment archive-based reconstruction studies. This fluvial system was granted scientific attention due in no small part to the fact that Dnieper River was the only route linking the Black Sea to the decaying Scandinavian ice sheet. The occurrence of glacial meltwater pulses has been widely used to interpret the Black Sea hydrology during the Late Pleniglacial (Lericolais et al., 2011; Sidorchuk et al., 2011; Soulet et al., 2011).

The fluvial history of this drainage system was analysed by Borisova et al. (2006), but more in-depth by Panin et al. (2014, 2015, 2016), including the temporal succession of incision and avulsion processes throughout the past 25 ka (Fig. 5). The upper Dnieper valley formed after the ice cap retreat, which left behind specific residual moraine landforms (drumlins), subsequently shaped by fluvial activity during the Late Glacial and the Holocene.

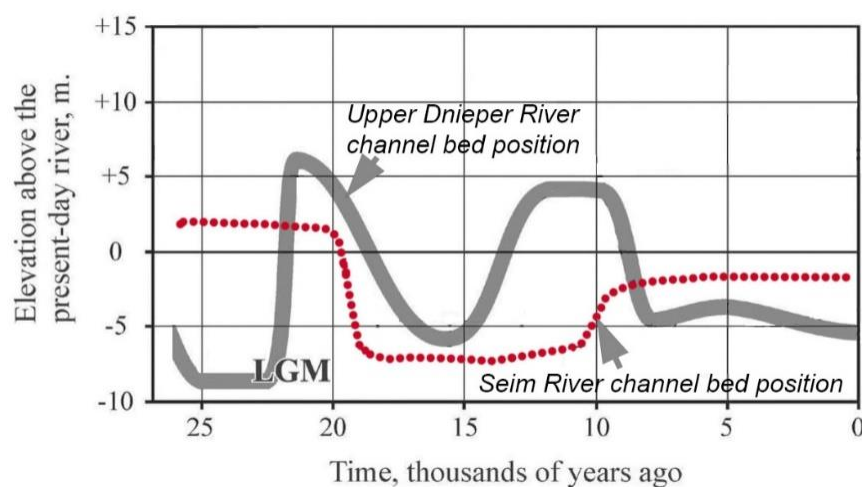


Figure 5 Incision/aggradation dynamics of the Upper Dnieper and Seim River since MIS 3, exhibited by changing position of the base fluvial deposits. (after Panin et al., 2014 and 2016 with additions)

The evolution of the river valley during and after MIS 2 was strongly influenced by proglacial effects, such as glacial damming and valley tilting due to forebulge development. This resulted in rapid aggradation around LGM, ensued by incision during Older Dryas (16.5 to 15 ka), and followed again by aggradation between 15.5 and 12 ka as a fluvial response to valley back-tilting continued in the Holocene. For comparison we included in Fig. 5 the channel dynamics of Seim river, a tributary of the Dnieper located farther to the south from the upper course of the Dnieper, in the middle sector of its drainage basin. This parallel leads to the conclusion that, within the same drainage system, channel aggradation and degradation are not necessarily synchronous for all rivers, and neither are channel planforms. In the case of the upper Dnieper, climate changes (expressed in terms of paleo-hydrology) have acted alongside glacial isostatic adjustment, resulting in valley aggradation and the evolution towards a braided style of channel during late MIS 2. This phenomenon was largely absent on river Seim, which lacks this type of control, and has thus developed a wandering sinuous style. The influence of glacial isostatic effects was probably responsible for the development of the East German rivers that demonstrated continuous aggradation since late MIS 5 until MIS 2 (Mol, 1997; Kasse et al., 2005).

Few paleo-geomorphological reconstructions based on sediment archives are available for rivers located south of BS. Studies focusing on the longest Anatolian river (i.e., Kizilirmak River), tributary of BS, have shown that its channel has undergone incision during the LGM, which was globally the coldest period of Upper Pleistocene. The timing of river response to climate changes was rather dissimilar in the case of Kizilirmak River compared to other European rivers, which have commonly incised their channels in warm-cold and cold-warm phase transitions according to the non-linear theory (Vandenberghe, 2008). This phenomenon was attributed to the relatively high streamflow discharge and the low sediment load, which resulted in augmented stream power, thus amplifying incision (Dogan, 2010). This reflects the contrasting climatic and environmental conditions specific to the two

regions (particularly the vegetation cover) both in the present and the past.

Additional paleo-fluvial information is available for River Sakarya (NW Turkey), whose history was deciphered based on the stratigraphy, geometry, and absolute dating of the four-step fluvial terrace staircases (Erturac et al., 2019; Erturac, 2021). Along a river reach located at ca. 50 km upstream of the river mouth, the authors have identified distinct erosional and depositional periods correlated with eustatic oscillations (Fig. 6). Between ~30 to 9 ka the T3 (+22 m) incision was documented as a consequence of a dramatic drop of BS base level (~140 m b.s.l), which forced the river to abandon floodplain formation and to deepen its channel by at least 25 m, cutting through the bedrock. Subsequently, the abrupt BS level rise recorded after 9.6 ka favoured the accumulation of sediment in the form of the future T2 terrace (+10 m), which would be incised later during the erosion phase at 1.8 – 1.2 ka. The evolution model established by the authors (Fig. 6) is based on several OSL dates, which indicate that the accumulation of terrace deposits occurred during major transgression phases (T3 of +22 m in Surozhian / MIS3; T4 of +55 m in Tarkhankutian / MIS5a), whereas incision and terrace carving took place in the Neoeuxinian / MIS2 and Post-Karangatian / MIS4-3. The latter processes were highly active in terms of their geomorphic effectiveness by achieving both the removal of previously deposited sediment material and the deepening of the channel through the bedrock. According to this model, incision was carried out during a stage when the Black Sea was isolated from the Mediterranean Sea and its level had dropped by 100-120 m. The limited geomorphological evidence and the scarcity of ages determined for the post-25ka period have prevented researchers from providing definitive answers to controversies regarding BS oscillations during this time frame.

To conclude, the comprehensive review of paleo-geomorphological studies based on fluvial sediment archives in the Black Sea drainage basin has led to the following general observations:

(i) the river response to major climate changes in the BS region was sensitive, although it lacks the high

resolution specific to other terrestrial records, such as speleothems or lacustrine sediments;

(ii) as the river size increases, along with the variety of water supply sources and their distribution across ample and diverse physical-geographical units, the sensitivity to climate changes diminishes (e.g., the Danube vs its Pannonian or Carpathian tributaries);

(iii) cold climates have been favourable for displacing and transporting large amounts of sediment from the source basins, such that river channels aggraded, assembled floodplains and evolved to braided channel patterns. The exception to this model was documented in the Anatolian Plateau, where the vegetation cover persisting during the cold phases prevented the massive transfer of

sediment to river channels, such that incision was a dominant event in cold climates;

(iv) by contrast, warm climates were conducive to vegetation growth, which contributed to a large degree to the retention of sediments displaced from the slopes, thus leading to meandering channels and, later on, to incision;

(v) regardless of the fluvial evolution model, other factors could disturb or subdue the role of climate changes, including tectonics (in the Pannonian Plain or the Western Plain of Romania), the vicinity to coarse-grained sediment sources (e.g., the medium-sized Carpathian tributaries), eustatic oscillations (as documented on the Danube or the Sakarya R.), or the accumulation of glacial sediment left behind by the retreat of the ice cap (e.g., on the upper course of the Dnieper).

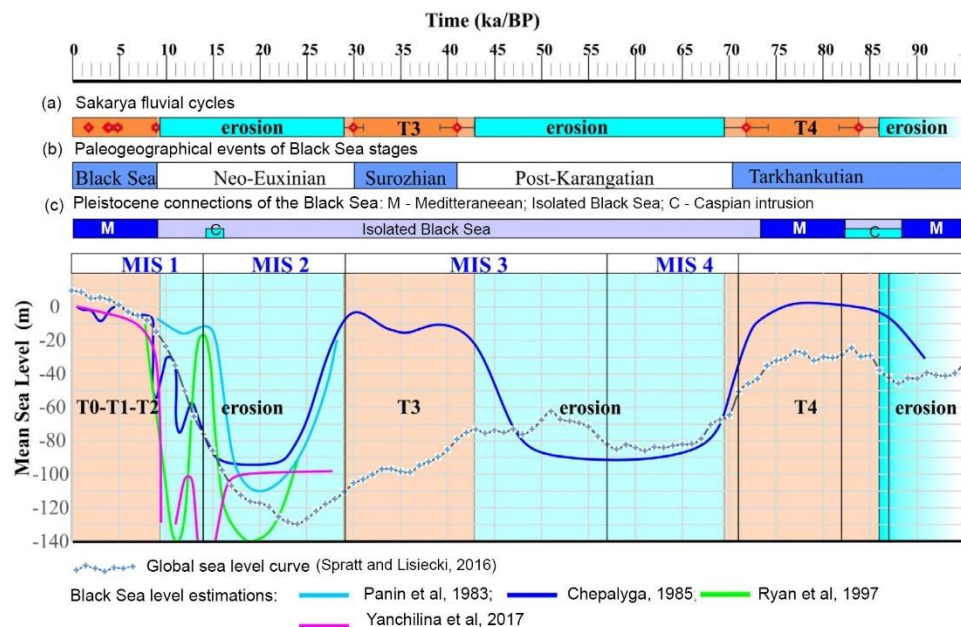


Figure 6 The correlation between the Sakarya fluvial cycles and the global and Black Sea level changes (after Erturac et al., 2019): (a) depositional and erosional periods with reported OSL ages and errors for Sakarya River during the Late Pleistocene T4 and T3, Holocene terraces T2, T1 and T0 (Erturac et al., 2019). (b) Main paleo-geographical events of the Black Sea according to Panin and Popescu (2007) and Yanina (2014). (c) Late Pleistocene connections of the Black Sea inferred from isotope studies (Badertscher et al., 2011)

4. Paleo-hydrological reconstructions based on paleo-channel morphology

Relict fluvial morphologies were used to carry out large-scale, highly accurate paleo-hydrological reconstructions in the Eastern European Plain, which is part of the BS drainage basin. The region accounts for 40% of the total area drained by the BS through

more than 72,000 streams, pertaining mostly to Dnieper and Don basins (to see Fig. 1). Within a latitudinal interval delimited by 57 N and 44 N, a significant number of relict paleo-channels were identified on the lower fluvial terraces or even in the floodplains (of which more than 700 river reaches were analysed, Sidorciuk et al., 2008). The majority of

paleo-channels fall into the meandering typology with amplitudes and wavelengths as high as 15 times larger compared to present-day meanders (Sidorciuk et al., 2001; 2009; 2011; Borisova et al., 2006). By applying a multi-disciplinary methodological

package (geomorphological, sedimentological, geochronological, palynological) on these relict morphologies, researchers were able to reconstruct the hydrological history of rivers in the region (Fig. 7).

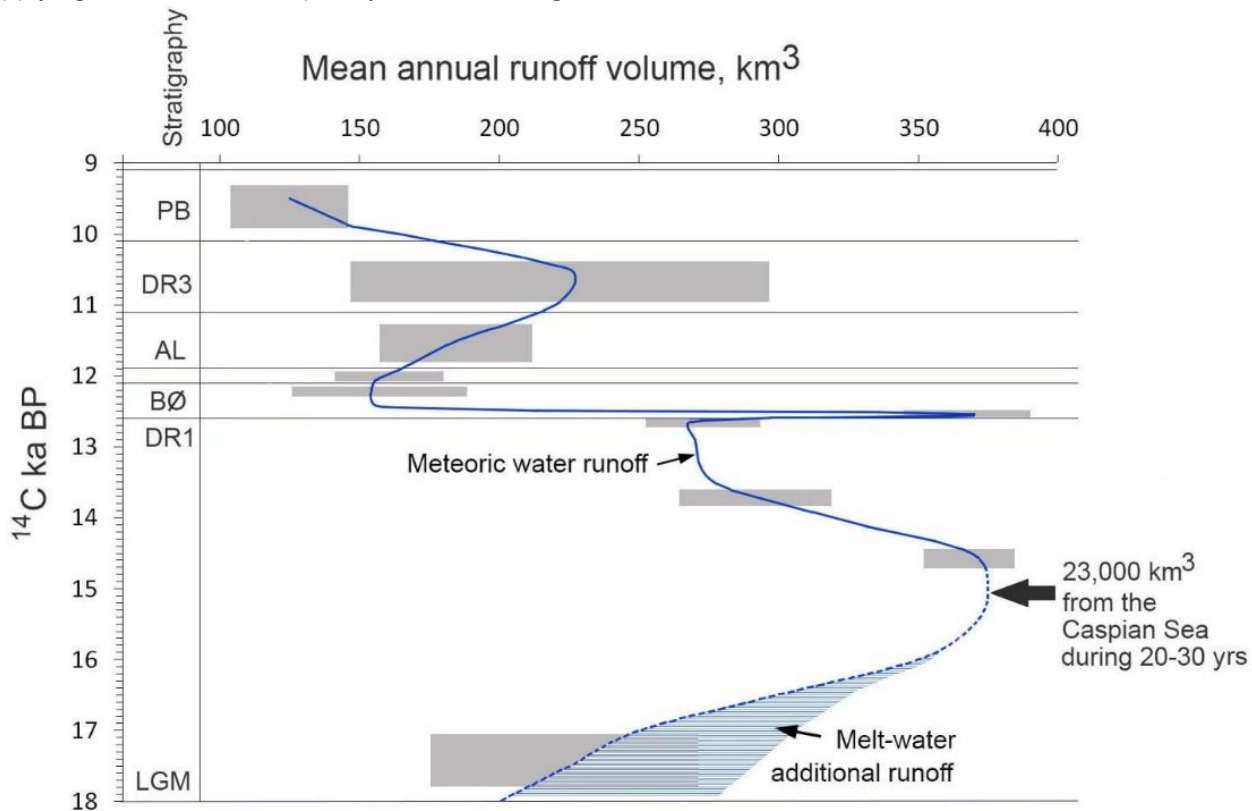


Figure 7 Reconstructed surface runoff in the Eastern European part of the Black Sea drainage basin since the end of Last Glacial Maximum (LGM) till Early Holocene. PB – Preboreal; DR3 – Younger Dryas; AL – Allerød; BØ – Bølling; DR1 – Oldest Dryas. Gray stripes-error of estimation (Sidorciuk et al., 2011)

The considerable differences observed between present-day channel morphology and past morphology point toward a significant change in the hydrological regime and the water discharge which occurred at the final stage of the last glaciation. The largest paleo-channels were active between 19 and 16 ka, i.e., shortly after LGM and towards the end of the last glacial (end of Pleniglacial) (Vandenberghe and Sidorciuk, 2020). The calculation method presented by the authors (Sidorciuk et al., 2011 and references therein) allowed for the spatial reconstruction of surface runoff in the basins of Dnieper and Don and the estimation of the streamflow discharge received by BS from these tributary basins. The peak runoff value recorded during the pre-Oldest Dryas era was documented in

the area adjacent to the ice cap (ca. 600 mm) and decreased southward to ca. 200 m. The maximum amount of discharged water was up to four times higher compared to present-day values, with rivers from the Eastern European part of BS basin equating a total amount of 365 km³/year. Subsequent to this hydrological peak recorded around the end of the Pleniglacial, streamflow discharge decreased overall, albeit at higher values compared to current discharges. The present-day discharge values of rivers pertaining to BS drainage basin were reached at the beginning of the Holocene.

A similar method was employed to reconstruct the volume of water overflow from the Caspian Sea to the Black Sea through the Manych channel. During the hydrological peak, Volga River discharged into

the Caspian Sea $\sim 500 \text{ km}^3/\text{year}$, leading to the Khvalynian transgression, which, for a short period of time, resulted in the communication between the two seas and the subsequent transfer of up to $23,000 \text{ km}^3$ of water into the Black Sea (Fig. 7).

Hydrological events from the Eastern European part of the BS basin are described chronologically as follows (Fig. 7): (a) 18-15 ka was a cold period with lower precipitation compared to the present, albeit the runoff coefficient was higher due to reduced evapotranspiration. River discharge amounted to $200\text{--}300 \text{ km}^3/\text{year}$ in total, including an additional input of meltwater (up to $100 \text{ km}^3/\text{year}$) from Fennoscandinavian ice cap decay and proglacial lakes; (b) 15-14 ka was a warmer, more humid interval, with higher precipitation compared to current values and peak runoff values ($300\text{--}365 \text{ km}^3/\text{year}$), thus resulting in the formation of the largest meandering rivers. During a short interval (of a few decades), a large amount of water was discharged from the Caspian Sea into the BS; (c) 14-10 ka was a period marked by low magnitude climate oscillations which corresponded to runoff decrease. At the end of this interval, large paleo-channel meanders transformed into smaller meanders. In the Holocene the runoff diminished to $100\text{--}110 \text{ km}^3/\text{year}$, which continue to be specific until present.

Similar assessments on the hydrological history of the Danube have not been carried out to date. The drainage basin of the Danube accounts for 2/3 of the total BS basin and discharges into the BS a water amount of ca. $200 \text{ km}^3/\text{year}$, which is twice the water input discharged by the Eastern European tributaries. For example, Sidorciuk et al. (2011) estimated that during the LGM and LG, Carpathian tributaries had mean water discharges up to three times larger compared to the present and similar variations to rivers from the Eastern European part of the BS basin, with its maximum shifted toward the beginning of the LG.

As a final observation regarding paleo-hydrological reconstructions, it should be noted that the high surface runoff was specific throughout the entire LGM – LG interval, at least in the Eastern European part of the BS basin (of more than $350 \text{ km}^3/\text{year}$) compared to current values (of $110 \text{ km}^3/\text{year}$, reached during the early Holocene). The

available hydrological reconstructions reviewed in this study provide no support for the “flood hypothesis” which asserts that BS sea water level was $\sim 120 \text{ m}$ lower prior to the connection with the Mediterranean Sea (at ca. 9.4 ka). Novel data regarding the formation of the subaerial Danube Delta is strong evidence of the sea water level position at ca. 30 m below the present BS level prior to the reconnection with the Planetary Ocean (Giosan et al., 2009; Vespremeanu-Stroe et al., 2017). The level oscillations of the Black Sea and their reconstructions are approached in detail in the following section of this study.

5. Reconstructions of Black Sea level oscillations and effects on paleo-drainage on the continental shelf

The Black Sea is a massive, deep-water body that communicates with the World Ocean through the Bosphorus Strait, whose uppermost threshold is at 35 m depth. The international expeditions from the 1960s and 70s and the seminal work of Degens and Ross (1974) were among the first results on the Late Quaternary history of BS that fascinated the geoscientist community and triggered further interest for knowledge which persists to this day. In addition to bottom waters anoxia and low salinity, another captivating revelation was related to the oscillations of BS water level and their implications. The last 25 ka stand out as the best documented time frame in this regard. During the Upper Würm glaciation (Late Weichselian, Late Valdai), which corresponds to the Neoeuxinic BS phase, the level dropped dramatically at depths ranging between $\sim 90 \text{ m}$ (Chepalyga, 1984) and $\sim 140 \text{ m}$ (Ryan et al., 1997).

Hypotheses diverge not only on the maximum depth reached during BS water level drop but also on the alternation of oscillations during the 25-ka time frame. Fig. 8 sums up some of the most discussed hypotheses (ranked by Yanchilina et al., 2017 into four categories, as previously shown in the introduction), reflecting the variety of interpretations based on the data collected to date. Moreover, we added the runoff volume curve for rivers from the Eastern European part of BS basin (which amounts to ca. half of the volume of water discharged by the Danube) as reconstructed by Sidorciuk et al. (2011)

to gain a better understanding of the link between BS level oscillations and runoff in the drainage basin. However, this study does not aim to examine these disputes in-depth but is instead focused on discerning the role of BS as a base level for fluvial processes of the tributary rivers based on the scarce data available to date.

Regardless of the supported hypothesis, it is certain that the coastline has retreated far from its current position, particularly in the NW, where a large part of the continental shelf was exposed. The BS shelf accounts for 30% of the sea surface area (Panin and Jipa, 1998) and its maximum extension (over 190 km wide) lies in the NW part, between Crimea and the Danube Delta. In front of the Romanian coast the shelf is 50 to 100 km wide. This large area was exposed during the Neoeuxinic period, therefore tributary rivers deepened into the newly exposed terrain to ca. 90 m on the outer shelf. Buried channels were observed since the earliest investigations at Kerch strait and Azov Sea (where a 5-km wide, 62-m

deep valley with gravel bed channel in “a single alluvial complex consisting of the channel, oxbow and floodplain facies” attributed to the paleo-Don was documented - Skiba et al., 1976, cited by Ryan et al., 1997). Furthermore, several international and national expeditions identified on the Ukrainian and Romanian shelves similar submerged relict morphologies buried by recent sediments.

Figure 9 shows the map of reconstructed paleo-geomorphologies within the Romanian shelf (Fig. 9a) based on the data provided by several Romanian-French and Romanian expeditions from 1998 to the present (Popescu et al., 2004; 2015). The continental shelf is composed of an inner shelf delimited by the 27 m to 30 m isobaths and slope gradients ranging between 1.1° and 4°, continued by an outer shelf with slope gradients below 1°. On both shelf units were identified numerous channel beds with widths ranging from 400 to 1500 m and varying depths of 20 to 90 m, buried under a thin layer of fine sediment moulded on their contours.

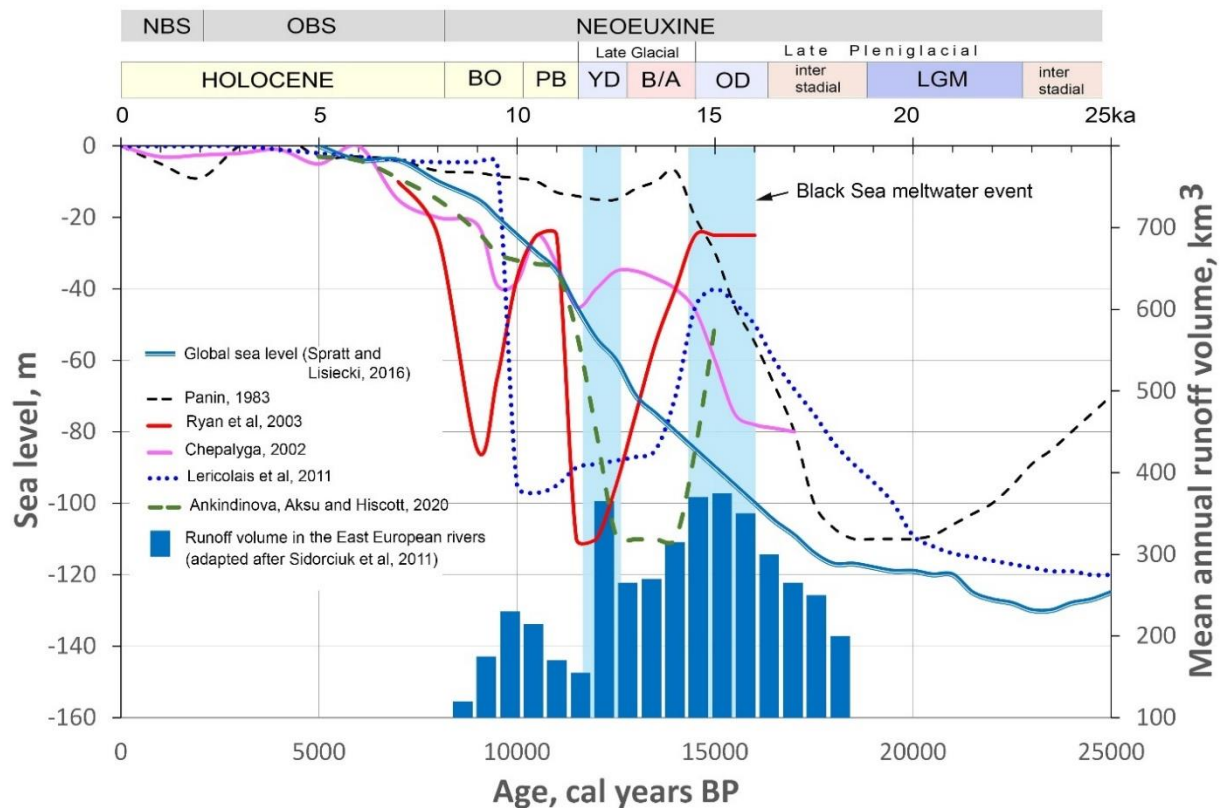


Figure 9 Sea water level reconstructions for the post - Glacial to Holocene Black Sea: NBS - New Black Sea; OBS - Old Black Sea; BO - Boreal; PB - Preboreal; YD -Younger Dryas; BA - Bolling/Allerod; OD - Oldest Dryas; LGM - Late Glacial Maximum. Reconstructed runoff in the Eastern European part of the Black Sea drainage basin is shown after Sidorciuk et al. (2011)

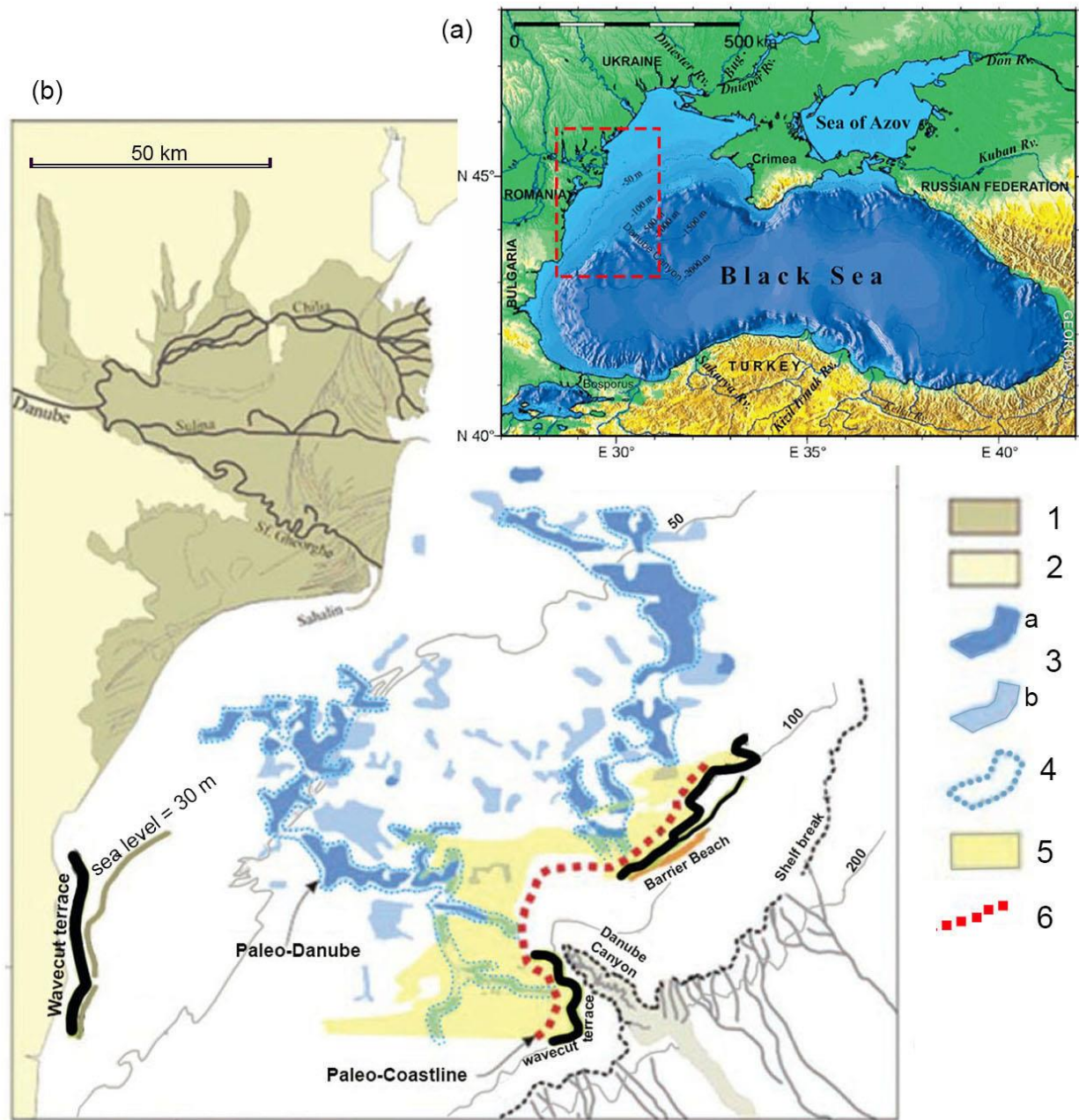


Figure 9 Schematic geomorphological maps of the Black Sea shelf (redrawn after Popescu et al., 2015 and Caraivan et al., 2017): A. Location of the mapped area; B. Romanian shelf: 1, Danube Delta (Holocene); 2, Pre-Holocene deposits; 3, Areas of the buried river channel beds with different degrees of density (a. higher; b, lower); 4, Probable outline of two anastomosed river channel systems; 5, Dunes; 6, Paleo-Coastline

Their stratigraphic position lying directly under the discontinuity at the base of the Holocene suggests they formed during the last lowstand. The distribution of buried channels shows clusters oriented in two directions which indicate distinct drainage systems (Fig. 9b). The sinuous-anastomosed pattern could point to the paleo-

Danube course, which divided into several branch, similar to the present-day Danube Delta. The southern drainage system continues with the Danube canyon, whereas the origin of the northern one is uncertain. This could be a second branch of the Danube. The two rivers (or branches) end their course at the paleo-coastline, which was probably the base

level during the Neoeuxinic period. The paleo-coastline was the contour of an old gulf where the two river branches discharged their waters through a canyon named "al Dunării" or Viteaz. This canyon was entirely submerged and located below the wave action zone, as attested by the position of wave-cut terrace (Fig. 9b). According to the authors (Popescu et al., 2004) it formed due to the low BS base level and the significant sediment input via the paleo-Danube.

To conclude, the circum-Pontic fluvial activity was controlled in part by the BS level during some time frames. For the Neoeuxinic period are notable the reconstructions of sinuous-anastomosed channels of major rivers (Danube, Dniester, Dnieper), as well as for smaller tributaries deepened into the extensive surface of the north-western BS continental shelf. The Danube Canyon incised by the river under submerged conditions, as it appears, along a regional fault line (Pecineaga-Camena) provides a spectacular phenomenon. However, we were unable to find evidence regarding the upstream distances to which the effects of eustatism were encountered along river valleys. Therefore, the discussion remains in the hypotheses stage, such as the knickpoint migration theory. Armas et al. (2018) identified a succession of four major knickpoints along Argeş and Dâmboviţa rivers (tributaries of the Danube ca. 500 km upstream of the BS confluence) which can be correlated with terrace profiles, thus proving "that the influence of marine regressions and transgressions during glacial and interglacial stages, respectively, was apparent active up to Bucharest" (page 15). This hypothesis requires more solid evidence in its support, especially considering that other investigations of present-day fluvial activity concluded that upstream effects of base level oscillations are rather limited (Leopold and Bull, 1979). Moreover, lab-based and theoretical models show that the impact of base level drop in terms of river incision is maximal in its early stages in the confluence area and decreases markedly upstream (Begin et al., 1981; Begin, 1988).

6. Final remarks

Rivers have a heritage, according to Luna Leopold (1915 - 2006), a classic of fluvial geomorphology, but we know nothing of their beginnings. Simply put,

"there is a continual modification, but at any stage the existing system is different from that which existed at a previous state, but has been influenced by that earlier stage" (Leopold and Bull, 1979, page 169). Some authors compare this overlay to a palimpsest, with the sole exception that more recent "writings" are influenced by previous ones, thus providing evidence of evolution. While we are aware that the legacy of rivers is not highly accurate in terms of recording the changes of external stimuli, the sensitivity of their response is well documented. In this case, our contribution consisted in assembling information regarding the legacy of circum-Pontic rivers (Fig. 10) where the focus is placed on the dynamics of fluvial styles, the most visible traits of rivers. The vertical axis indicates the time/age (between 25 ka and 8.5 ka), while the horizontal axis shows circum-Pontic rivers depicted as their channel planforms. On each side of the river diagram are shown the temporal variabilities of two major controls which exerted significant influence during the analysed time frame, namely the climate (reconstructed based on ice core records and other terrestrial records from BS basin) and BS base level oscillations. Thus, we postulate that rivers were constrained from two diametrically opposed directions to which they were forced to respond: to the control exerted by the drainage basin originating upstream and to the downstream control of the oscillating base level.

We illustrated the climate variability at the drainage basin scale using the high resolution, accurately dated NGRIP diagram (Greenland ice records; Rasmussen et al., 2014), which was integral to establishing the timeline of climatic phases in the Northern Hemisphere (Moreno et al., 2014).

From the geographical area of the BS basin, we used the time series of two terrestrial records: the oxygen-isotope series of two stalagmites from Sofular Cave, in NW Turkey, which is regarded as the record with the highest temporal resolution both for the Holocene and the pre-Holocene (Kern et al., 2019; Burstyn et al., 2019), and the reconstruction of mean annual temperature and precipitation based on pollen analyses of a sediment and peat sequence retrieved at lake Preluca Tiganului, Gutâi Mts, in NW Romania (Feurdean et al., 2014). Both terrestrial

records used for this study fit reasonably well with the NGRIP series.

The rivers analysed in this study were grouped into four morpho-structural units which, in turn, illustrate the nuances of river channel responses to the controls mentioned previously. The first group comprises the rivers of the Pannonian Basin, among which river Tisa stands out in terms of size and has been the object of numerous paleo-evolution investigations. The second group includes the rivers draining the Romanian Carpathians. Both of these clusters are tributary to the Danube. The third group consists of the rivers draining the Eastern European / Russian Plain, whereas the fourth one includes just two southern BS tributaries from the Anatolian

Plateau and the Pontian Mts. As previously stated, we have taken into consideration only the rivers for which paleo-evolution data was available and can be characterized as circum-Pontic to some degree.

The non-linear model of river cyclicity as a response to climate changes shows that relatively short phases of fluvial instability occur mainly at the transition from warm (temperate) to cold (periglacial), and from relatively cold to warm periods (Vandenberghe, 2008). Instability is manifested early on through vertical fluvial processes (e.g., a succession of incision or vertical erosion and sediment accumulation). Vertical instability is ensued by channel planform changes and floodplain development during the long stable phases of cold or warm periods.

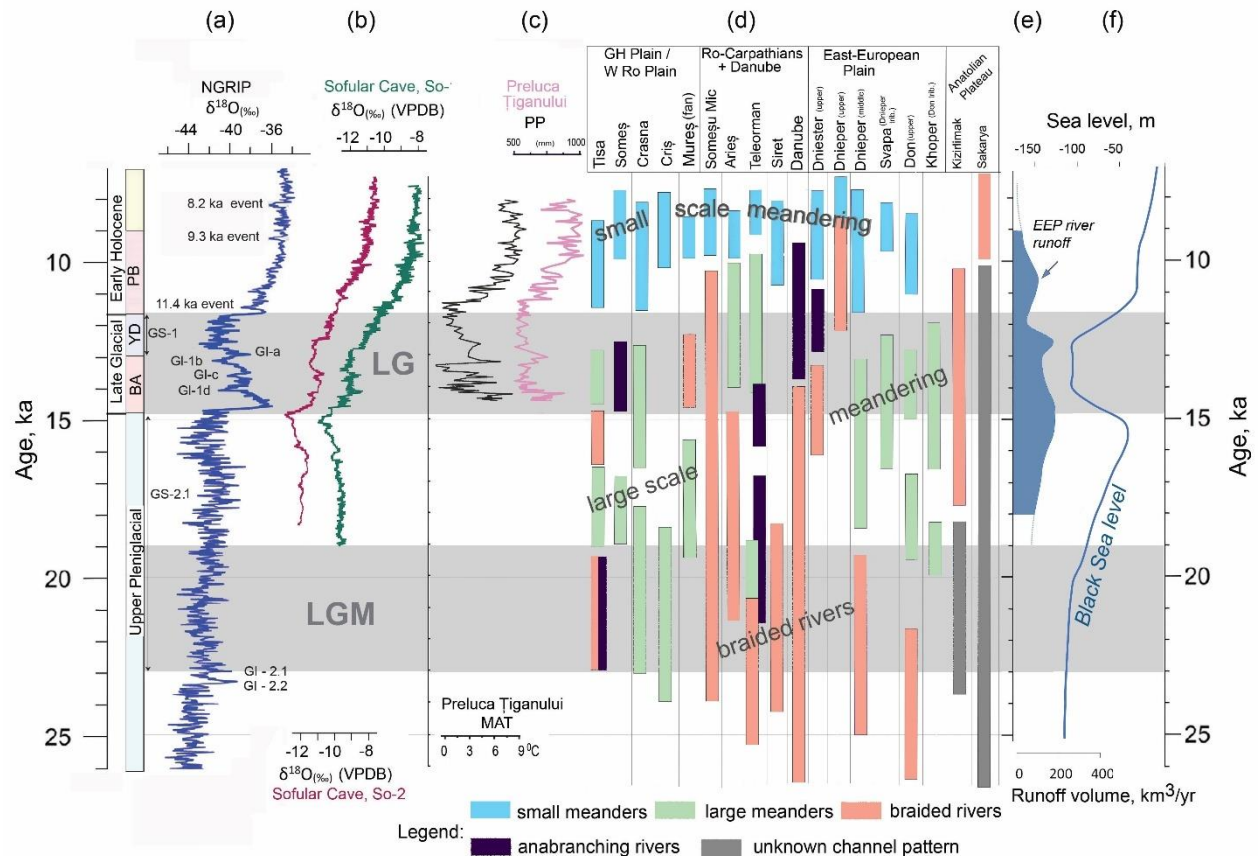


Figure 10 A simplified model of fluvial pattern evolution for circum-Pontic rivers in the Late Quaternary and correlation with paleoclimatic records, river flow dynamics and Black Sea level oscillations: (a) NGRIP $\delta^{18}\text{O}$ curve; GI – Greenland Interstadial; GS – Greenland Stadial (Rasmussen et al., 2006); (b) The $\delta^{18}\text{O}$ time series of stalagmites So-1 and So-2 from Sofular Cave, NW Turkey (Fleitman et al., 2009); (c) A pollen-based quantitative reconstruction of paleoclimate from NW Romania (Feurdean et al., 2008); (d) Circum-Pontic rivers grouped by morpho-structural units of the Black Sea drainage basin; (e) Reconstructed surface runoff in the Eastern European part of the Black Sea drainage basin (Sidorciuk et al., 2011); (f) Water-level fluctuation in the Black Sea since the Last Glacial Maximum (Ankindinova et al., 2020)

This model, which is widely recognized in geomorphological reconstructions, is fundamental for our approach regarding the evolution of the fluvial system as presented in this study: elongated stripes indicate stable phases, interrupted by interphase changes.

The following section sums up the dominant traits of fluvial styles during the climate phases of the 25 – 8.5 ka period and the time frames when the changes were documented (Fig. 10).

(i) The Upper Pleniglacial (28 - 14.65 ka cal BP), or, more specifically, the Late Glacial Maximum, LGM (23 – 19 ka), was a cooler, drier period, marked by the largest southward extension of permafrost, the broadest advancement of mountain glaciers and Scandinavian ice cap, and a significant accumulation of loess. River channels were forced to manage oversized sediment yields which resulted in increased river gradients and the formation of braided river channels, to strong wind activity and dune formation within floodplains were added (Kasse et al., 2010).

Braided channels were the dominant type of fluvial style. From this period, a continuous sheet of gravel and coarse sand is preserved in the structure of low floodplains, mainly in Carpathian rivers, including the Danube, but was also reported in Pannonian or Russian Plain rivers. By contrast, rivers from the Anatolian Plateau showed opposite tendencies by deepening their single channels, which are indeterminate in terms of typology (Dogan, 2010). At the contact with the BS base level, circum-Pontic rivers were bound to carve their channels to the confluence with the sea whose level was, at the time, 100 to 120 m lower compared to present. As such, vertical erosion was the prevailing process, with rivers cutting through their beds as deep as the bedrock in some cases, as was documented on the Sakarya R at 50 km upstream of the BS level. Around the same time, in mid Neoeuxinic phase, the paleo-Danube downstream of Brăila had deepened by 30-35 compared to present, as indicated by drills which intercepted the gravel sheet deposited during the Neoeuxinic phase. It is conceivable that the effect of the base level drop has been propagated upstream as far as Giurgiu urban area (see Fig. 4b). As regards the horizontal plane, sinuous-anastomosed channels formed particularly in the NW plain of the BS

(currently acting as continental shelf), as well as valleys more than 60 m (likely the paleo-Don canyon) to 90 m deep on the outer shelf (paleo-Danube canyon. In other words, the discussion on the upstream distance to which the effects of the base level drop are propagated remains open, particularly for major rivers such as the Danube.

(ii) Towards the late part of the Upper Pleniglacial (16 – 15 ka), due to the warmer, more humid climate conditions, the surface runoff reached the highest recorded values, leading to an increase in mean annual discharge of rivers by 3 to 4 times. The highest increase was documented for the maximum discharge, recorded in spring (i.e., 6 to 7 times higher than current maximum discharge values), and these were instrumental for shaping macro-meanders, as ample as 15 times larger compared to present meanders on rivers of the Eastern European Plain (Vandenberghe and Sidorciuk, 2020). Fluvial systems were subjected to massive transformation, evolving from braiding to large-scale meandering, which was mainly documented in rivers from the Pannonian Basin and the Eastern European Plain. As regards small and medium-sized Carpathian rivers, the braided style persisted throughout this phase, possibly due to the proximity of coarse-grained sediment sources and the preservation of a high energy environment (e.g., the well-documented cases of Someșul Mic river channel in the Transylvanian Depression – I. Perșoiu, 2010 or Moldova and the middle course of river Siret, all under the strong control of Carpathian sediment sources - Ichim and Rădoane, 1990; Rădoane et al., 2008; Chiriloaei et al., 2012; Rădoane et al., 2015). In the case of rivers influenced by the retreat of the ice cap a lack of synchronization of river processes (aggradation-degradation) has occurred, with effect on changes in river styles. The examples of the Upper Dnieper and the downstream tributaries are suggestive in this respect (Panin et al., 2014, 2015, 2016).

During this period, the BS receives the largest amount of water through its tributaries as well as from the Caspian Sea. The sea level rises from -120 m to -40 m, but the BS is still not linked to the Mediterranean Sea (see Fig. 8). All the confluences with the sea are flooded and sedimentation became

the dominant process due to the sea level rise. The model elaborated by Erturac et al. (2019) for Sakarya river (see Fig. 6) shows that phases of sea level rise were favourable for the accumulation of fluvial terraces at ca. 50 km upstream on tributary rivers. Some reviews (e.g., Blum and Tornqvist, 2000), as well as certain empirical studies have indicated that the distance to which the effect of base level rise is propagated upstream is limited to less than 10-15% of the river length (Leopold and Bull, 1979), with factors such as river gradient and composition of bed material accounting for the variation (N. Rădoane, 2002).

(iii) The Late Glacial, LG (14.65 - 11.65 ka cal BP) was characterized by gradual warming with fluctuations in the dynamics of the forest cover which expanded from the east, and by diminishing permafrost. The rapid cooling of the Younger Dryas caused a fragmentation of the boreal forest cover and a re-expansion of steppe-tundra habitats, as well as drop of the upper treeline from 1000 to 700 – 600 m a.s.l. in the Carpathians (Feurdean and Tanțău, 2017). It was ensued by the Early Holocene (11.65 - 8.5 ka), characterised by fast warming which reflected in the expansion of temperate deciduous forest. The channel response consisted in adapting to the streamflow discharge decrease (from 350 km³/yr to less than 250 km³/yr for EEP rivers, see Fig. 10d, and similar trends for the entire BS drainage basin). The channel planforms were constrained as large-scale paleo-meanders transformed to smaller meanders, while both the channel depth and width decreased. Simultaneously, gradual incision of the floodplains occurred in the context of meandering systems. This stands out as the second largest transformation undergone by rivers during their LQ history, after the major shift of LGM and LG, and was mostly ubiquitous throughout the entire BS basin, as illustrated in Fig. 10. However, a contrary tendency was documented in the Anatolian basin of river Kızılırmak. The warming climate of the late LGM generated low precipitation and scarce vegetation which led to channel bed aggradation (with sediment thickness reaching 18 m along the main valley) and the evolution to a braided channel (Dogan, 2010). As regards the BS level oscillation, we have mentioned previously that this period has been heatedly

debated and hypothesised on. We have opted to illustrate in Fig. 10e the curve estimated by Ankindinova et al. (2020) since this is the most recently published and is based on the latest field data. The river response to sea-level oscillations during and post-LG has not been determined accurately in case study investigations, therefore this topic remains open to further research. The best-documented case remains Sakarya river (Erturac et al., 2019) which has been discussed in section 3.

(iv) The Early Holocene was marked by a rapid BS level rise (at a rate of 10 m/100 yrs, such that in 1000 years, the BS reached the same level as the Marmara Sea, cf. Lericolais et al., 2017). The sea water flooded large areas to the NW of the BS and advanced upstream on the tributary valleys. The effects of the base level rise were reflected in the evolution towards the anastomosed channel style, for which the Danube is the best example.

To conclude, this is the story that could be pieced together based on the data regarding the legacy of circum-Pontic rivers available at this time. Aside from the general trend consisting in the dominant control exerted by climate, river channels were exposed to additional influences, including tectonics, the effects of certain types of vegetation in relation to the control of runoff and discharge, and most importantly on sediment displacement, the obstruction by glacial sediments left behind by the ice cap retreat, the river size and proximity to coarse-grained sediment sources, all of which were briefly analysed in documented case studies. As regards the role of Black Sea level oscillations and the response of tributary rivers, this topic requires further in-depth paleo-evolution investigations, which could shed light on the unknown facts which are fuelling the debate. To date, little information has been published on the fluvial history at the contact with the sea, with the exception of the Danube Delta and Lower Danube valley to some extent, but even in this case, more data is necessary to decipher the events of the Early Holocene, whether the connection with the Mediterranean Sea was abrupt or slow and what kind of sedimentary imprints were left by tributary rivers in this time frame (Giosan et al., 2006, 2009; Vespremeanu-Stroe et al., 2017; Țuțuianu et al., 2021). Hiscott and his team, who are known as

authors and major supporters of the Outflow Hypothesis, concluded an important chapter of their work published in 2007 by stating that “more work is

needed to understand fully the evolution of the (...) Black Sea”, which is widely applicable in research, but more so in the case of such an unusual, intriguing sea.

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Annex 1 Compiled data on the circum-Pontic river response to climate and sea level changes during Late Quaternary

	River	Before 14.65 ka Upper Pleniglacial	14.65 - 11.65 ka Late Glacial	11.65 - 9.4 ka Early Holocene	9.4 - 8.5/8 ka Early Holocene	Source
1	Siret, Romania, (dw. Suceava cf.)	20.3ka, aggrading, braided river, coarse gravel	Large scale meanders, estimated water discharge = 5 – 6 times the current discharges	Gradual incision, meandering	9.4 ka medium gravel lobes of lateral accretion	Rădoane et al. (2015, 2018a, b)
2	Moldova (up. Siret cf)			Braided, boulder and coarse gravel at the base of T 4, woods 10...9.5 ka		Chiriloaei et al. (2012); Rădoane et al. (2018b)
3	Someș (in D. Transilvania)			Braided, coarse gravel at the base of T 4 m, woods 9.8ka A generalized channel incision; single channel with large meanders by the maintenance of a still significant discharge; avulsion to NW		Rădoane et al. (2018a)
4	Someș (in Western Plain, up Tisa cf)	28.3 – 15.2 ka – large scale meanders, channel incision	A multi-branching channel system oriented to NNW			I. Perșoiu et al. (2022, submitted)
4a	Crasna (in Western Plain)		Large scale meanders, 13.6 ka avulsion to the NW		Small scale meanders	
5	Someșu Mic, Someșu Cald (in D. Transilvania)	28 ka, meandering pattern, incision of the T8-15 m 25-24.3 ka, anastomosed channel	24.3...11.4ka coarse gravel-bed braided channel, aggrading	10.6...9.7 ka channel metamorphosis from a braided into a meandering pattern; underfit river	Small scale meanders	Perșoiu (2010)
6	Arieș (D. Transylvania)	37.8 ka, T20 alluviation 18.8ka coarse gravel, braided river	14.6-12.9 ka, meandering pattern			Perșoiu and Perșoiu, in prep.
7	Mures (alluvial fan, up Tisa cf)		Braided, frequent avulsions, 3 – 4 times higher	a multibranched system on the alluvial fan	Meandering, 1.5-2.5 times the current discharges	Kiss et al. (2014)

8	Crişuri (W Plain, GHPlain)	Meandering pattern	discharge than nowadays A multi-channel braided fluvial system, neotectonic uplift			Nador et al. (2011)
9	Tisa (NE of GHPlain)	40-33 ka, braided; 33-32ka -large meanders	Large meanders: 5 – 8 times higher discharge than nowadays	Large meanders; channel vertical incisions and avulsions	Decrease of large meanders	Gabris and Nador (2007); Gabris et al. (2012); Kasse et al. (2010)
10	Danube (Iron Gates)			9.5-9 ka settlement abandonment is linked to increased flooding along the Danube	8.2-7.9ka, settlement abandonment is linked to increased flooding along the Danube	Bonsall et al. (2002; 2014)
11	Teleorman (tributary of the Danube, Danube Plain)	37 ka BP coarse gravel braided channel 21.6ka anabranching channel	12.8ka Large scale meanders (up to five times larger than the present ones)			Howard et al. (2004); Macklin et al. (2010)
12	Danube (lower course, Giurgiu-Oltenița)	32.7 ka....15.9ka layer of sands and gravels interpreted as corresponding to a braided river		9.3 ka Limnic phase, interpreted as being linked to the rapid increase in the Black Sea level in the early Holocene		Benecke et al. (2013) Nowacki et al. (2018)
13	Danube (lower course, Mostiște valley)	25ka...20ka layer of sandy gravels with a sandy layer on the top, probably corresponding to a braided river	18ka...8ka Intercalations of thin layers of sands, silt and clay, probably corresponding to a anastomosed fluvial environment	7.5 ka Limnic phase		Vespremeanu-Stroe (personal communication)
14	Danube (Dunărea locality)			8ka Intercalations of fine sediments		Vespremeanu-Stroe (personal communication)
15	Danube (Brăila island) No numerical ages	During this period, the northern part of Braila Island functioned as a gulf of the Black		11 ...9.5ka probably corresponds with a new coarse alluvial sequence reported in the		Ghenea and Mihailescu (1991)

		Sea, extending to the town of Braila		northern part of Braila Island, suggesting the reinstallation of the Danube as a river in this area.	
16	Brateş Lake, Danube-Prut rivers			>8ka, estuarine delta front 8-7.9ka, foreshore 7.9 – 5ka, river floodplain <5 ka, lake	Țuțianu et al. (2018)
17	Upper Dnister, Ukraine	25-18ka, braided channel, T 5-10m, 20m sediments in terrace	13,8-11 ka, traces of oldest meander with widest radius, anastomosing/meandering	8.5-7.8 ka, meandering, first distinct paleomeander	Huhmann et al. (2004)
18	Upper Dnister, Ukraine	15 ka, braided channel, T 5-6 m			Gebica et al. (2016)
19	River Dnieper, upper reach	Significant aggradation occurred as a fluvial response to valley back tilting caused by forebulge collapse	large palaeochannels were active in the Early Holocene between 12 and 8.5 ka; They were formed by flood discharges ca. three times larger, and with a valley gradient some 30 % higher, than those of the present-day river	deep river incision to the modern levels occurred between 9 and 8 ka; the channel type changed, from large braided or single-thread to sinuous	A.Panin et al. (2014) A Panin et al. (2015a, b)
20	River Seim, middle Dnieper, Ukraine - new datings	Braided channel, high level flood Incision 18-14ka	high level flood, large meanders	10 – 9 ka, small meanders	A Panin et al. (2016)
21	Seim River, Svapa River, middle Dnieper, Ukraine	16-14ka width and meander wavelength are 7-10 times greater than those of the modern channels 17 ka ago were abandoned	formation of smaller channels, climate warming	relative stability of hydrological regime and small variations of water runoff	Borisova et al. (2006)
22	Dnister, Dniپر, Don, Bug –	18-15ka, cold and dry, precipitation	15-14 ka, warmer and humid (surface runoff		Sidorchuck (2003)

	Russian Plain rivers	lower than today (surface runoff = 210 km ³ /yr)	=300-365 km ³ /yr), large meandering Caspian S connected Black S			Sidorchuck et al. (2001, 2003) Sidorchuck et al. (2008, 2009) Sidorchuck et al. (2011) Markova et al. (2019) A Panin et al. (2013) cit. Vandenbergh and Sidorciuk (2020) Matlakhova (2020)
22 a	Upper Don, Khoper River	19-17ka, first generation of large paleomeanders	15-13 ka, the second of macromeanders, activation of aeolian processes	Lowering of runoff		
23	River Kizilirmak, middle reach, Turkey	19 ka - incision, then 18 m aggradation, climate and subsidence LGM precipitation 1.9 times high than today;				Dogan (2010, 2011)
24	River Sakarya, Turkey	T3 (22m) - 41 – 30ka (aggradation)	LGM-H (30 – 9ka), incision 25 m, river formed large sinusoidal bend while incising through the bedrock	T2 (10 m) – 9ka...1.8ka aggradation		Gorur et al. (2001) Erturac and Kiyak(2017) Erturac et al. (2019) Erturac(2021)
25	Sakarya delta, Turkey				The marked truncation at the top at about 7- 8 ka during the latest lowstand of the Black Sea. Water depth of 105 m	Algan et al. (2002)
26	Kizilirmak delta				7.9ka – 6.8ka, a lagoon to pond environment with frequent connection to the sea	Berndt et al. (2018)
27	Kuban delta				7.4ka, age in base of sediment column of 20 m thick	Bolikhovskaia et al. (2017)

28	Dniester, Black Sea shelf	-20...-22 m, submerged archaeological sites, ages between 34 ka – 12 ka; buried by thick fluvial sediments					Kadurin et al. (2020)
29	Danube delta					9.8-9.5ka the Danube was building a ramp delta lobe above 40 mbsl. 8–7.5 ka early stage of delta development	Giosan et al. (2009) Vespremeanu-Stroe et al. (2017)
30	Danube Canyon, BS shelf edge	53-40 ka; -10...-20 m BS level (Surozhian), silty clay beds,	27-17ka; -100 m BS level	9.5-7.5 ka: -10 m BS level	7.5 – 3.5 ka; -5...-6 m BS level		Popescu et al. (2004; 2015) Caraivan et al. (2012; 2017) Fleitmann et al. (2009)
31	Sofular Cave, Turkey	A 50 kyr-long exceptionally well-dated and highly resolved stalagmite oxygen (d18O) and carbon (d13C) isotope record					Kern et al. (2018, 2019) Burstyn et al. (2019)
31a	Karaca Cave, Trabzon area, NE Turkey	An oxygen isotope record from a stalagmite that grew between 77 ka and 6 ka in northeast Turkey					Rowe et al. (2012)
32	Tăușoare Cave, Romania	Stalagmite from Tausoare Cave (TC), East Carpathians - data on past climate changes between 69 – 15 ka					Staubwasser et al. (2018)
33	Ascunsă Cave, Romania	A speleothem isotope record (POM2) that provides data on past climate changes in the S Carpathian region from 8.2 ka until the present. A speleothem (POM1) that provides data on past climate changes from 48 ka to 30 ka.					Drăgușin et al. (2014), Staubwasser et al. (2018)
34	Preluca Tiganului, peat, Romania	High-resolution pollen records providing data on past climate changes in the NW Carpathian area between 14.6 – 8 ka					Feurdean et al. (2014)