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The “Sink” of the Danube River Basin: The Distal Danube Deep-Sea Fan

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Abstract:

The Danube River Basin and the Black Sea represent a unique natural laboratory for studying source to sink and global change. We will address information on the “active sink” of the system, which represents the area of active deposition: sea level variation, sediment balance, and neotectonics. Also, we will discuss the evolution and quantification of climate, tectonics, and eustasy on the sedimentation in the western Black Sea basin, along both southern and northern margins, obtained from understanding the Danube deep-sea fan processes and sedimentation.

In the last decade, many of the geosciences studies carried out in the Black Sea have focused on the Holocene marine transgression. This topic has been fully discussed and is still a matter of debate. Since the DSDP drillings, the lithology and mineralogy of deep sediments from the Black Sea have been well studied. However, only few recent studies have focused on the deep-sea morphology and turbidite sedimentation in the western Black Sea basin, in which the main depositional feature is the Danube submarine fan.

Oceanographic surveys in the Black Sea in 1998, 2002, and 2004 carried out in the framework of French-Romanian joint project and the European ASSEM-BLAGE (EVK3-CT-2002-00090) project have collected a large amount of data (Multibeam echo sounder data, CHIRP seismic, as well as Kullenberg and Calypso cores). This paper presents insights from recent coring and seismic data recovered at the boundary of influence of both the distal part of the Danube turbiditic system and the Turkish margin. This data set provides a good record of changes in the sedimentary supply and climatic changes in the surrounding Black Sea since the last 25 ka. Based on this study, we demonstrate that the deep basin deposits bear the record of the late Quaternary paleoenvironmental changes.

Finally, the western Black Sea basin constitutes an asymmetric subsident basin bordered by a northern passive margin containing confined mid-size, mud-rich turbiditic systems, and a tectonically active southern turbiditic ramp margin

Introduction

The nature and rate of differing geomorphic-climatic processes that deliver sediments from the source to the sink (mountains to deep sea fan) vary markedly in tectonically stable and tectonically active settings. The parameters controlling the connectivity amongst late orogenic semi-isolated basins, and with open marine environments, respectively, are complex. This results in significant variability in sediment transfer relationships. They are influenced, for example, by interplay between uplift and subsidence creating accommodation space and building sediment source areas (Cloetingh *et al.*, 2007). The two most important factors that influence sedimentation in a sink are changes in sediment supply and water level. One of the most important European sources to sink system is the Alps/Carpathians/Pannonian Basin system drained by the Danube River ending onshore by its famous Delta (Matenco *et al.*, 2011). This system continues offshore using the unique important pathway still marked on the underwater morphology: the Viteaz canyon (Popescu *et al.*, 2004). The sink part of this system is constituted by the Danube deep sea fan studied by Popescu *et al.* (2001) and recently by Lericolais *et al.* (2012). The Alps/Carpathians/Pannonian and Danube/Black Sea system represents a unique natural laboratory for studying the interplay between lithosphere and surface processes and the source to-sink relationship.

Many authors (Flood *et al.*, 1999; Konyukhov, 1997; Wong *et al.*, 1994; Wong *et al.*, 1997) have recognized that sedimentation in the Black Sea was influenced by eustatic sea level changes driven by global glaciations and deglaciations. However, most of these studies have not confirmed that the water level of the Black Sea was controlled by eustatic changes only to a certain extent. Since then, oceanographic surveys have focused on the deep-water architecture and sedimentation in the western Black Sea basin, where the main depositional feature is the Danube deep-sea fan (Lericolais *et al.*, 2012; Popescu *et al.*, 2006; Popescu *et al.*, 2004; Popescu *et al.*, 2001; Winguth *et al.*, 2000): (1) to study the nature of the deposits and the associated sedimentary processes, (2) to understand the stratigraphical evolution of the sedimentary deposits, (3) to provide a scenario on the evolution and quantification of climate, tectonic and eustasy forcing on the sedimentation in the western Black Sea basin, along both southern and northern margins.

The examination at an appropriate scale of sediment path-ways dispersion across the continental shelf towards the slope and the deep sea zone and then of their deposition, compaction and/or possible sliding represents a case study for deciphering the in and out of sediment loads and water fluxes produced during the melting of the ice after the deglaciation. The Danube system is the pathway of the melting produce from the Alps and the Black Sea the end member.

From three major oceanographic surveys carried out in the Black Sea in 1998 (BlaSON1), 2002 (BlaSON2) and 2004 (ASSEMBLAGE) in the framework of French-Romanian joint project and the European ASSEMBLAGE project (EVK3-CT-2002-00090), an important set of data (Multibeam echosounder data, Chirp seismic, Kullenberg and Calypso cores) have been collected. A recent good record of the changes in the sedimentary supply and climato-eustasy in the Black Sea region during the last 25 ka was recently published (Lericolais *et al.*, 2012). This study demonstrates that the deep basin deposits bear the record of the Late Quaternary paleoenvironmental changes. These results combined with previous studies tried to demonstrate that the basin floor deposits from this portion of the western Turkish margin could result of mud-rich gravity currents originated from multiple mass-wasting events along the steep Turkish slope. Such events could be triggered by the earthquake activity of the North Anatolian Fault. The very fine grained trend in the deep basin turbidites is due to a combination of the availability of fine-grained material on the shelf and rapid deposition of the coarser sediments at the abrupt slope break.

A complementary work realised on the cores recovered during the above mentioned surveys was realised using combination of Lu-Hf and Sm-Nd isotope in order to decipher the origin of surficial sediments in the western Black Sea. Such systems offers a potentially unique perspective for investigating continental erosion (Bayon *et al.*, 2009b). Hf and Nd elemental and isotope data are used to confirm that the main provider of the sediment of the deep sea fan is the Danube river and to see to what extend the Anatolian shelf and rivers could have been responsible of the last sedimentation process recognized at the distal part of the deep sea fan.

Geological setting

The Black Sea is a land-locked basin of ca 432.000 km², connected to the Mediterranean Sea by the Bosphorus Strait. The western Black Sea basin is generally considered to be the result of back-arc extension associated with the northward subduction of the Tethyan plate. (Robinson *et al.*, 1995). The north-western Black Sea, infilled by thick sedimentary successions of up to 19 km since the Cretaceous, is the main depocentre for sediment supply from Central Europe via the Danube River and from Eastern Europe through the Ukrainian rivers Dniepr, Dniestr and Southern Bug (Robinson *et al.*, 1995) These sediment supplies contributed to the shaping of the north-western Black Sea margin from the coastal area, marked by deltaic deposits, down to the deep basin, where large deep-sea fan complexes including the Danube deep-sea fan formed (Lericolais *et al.*, 2012; Popescu *et al.*, 2001; Wong *et al.*, 1994) (Figure 1).

The northwestern continental shelf reaches up to 170 km wide off the Dniepr River and the shelfbreak is located at water depths of −120 to –140 m southward of the Danube Canyon, and up to −170 m northward of the canyon possibly due to recent faulting (Figure 2). A relatively steep slope (2.5%) lies between the shelfbreak and the flat abyssal plain (2200 m water depth) (Popescu *et al.*, 2004). The continental slope is dissected by numerous canyons which commonly stop at the shelfbreak with the exception of the Danube Canyon which deeply incised the shelf for 26 km landward (up to −110 m water depth). The Danube Canyon acted as a major gateway for the sediment transfer towards the deep Black Sea (Popescu *et al.*, 2004). In addition to terrigeneous supply, river inputs constantly introduced high amounts of organic-rich material into the Black Sea. The specific history of the Black Sea, including times of periodical sea bottom anoxia, created particularly favourable conditions for the decomposition of organic matter and for gas generation.

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

Danube deep sea fan settings

Beyond the continental shelf is a complex system of canyons, channels, accumulative sedimentary bodies leading to deep-sea fans (Popescu *et al.*, 2004; Popescu *et al.*, 2001) (Figure 2). The Danube deep-sea fan which can be considered as a potential hydrocarbon field, developed in the north-western part of the Black Sea from sediments fed by the Danube but also by the northern rivers: the Dniepr, the Dniestr and the Bug (Popescu *et al.*, 2004; Winguth *et al.*, 2000). It extends for about 150 km downslope of the shelf break, and the distal end of the fan reaches the abyssal plain at 2200 m water depth. Depositional processes are located essentially on the middle and lower slope.

The Danube deep-sea fan (or turbidite system) is developed in the north-western part of the Black Sea, fed by sediments from the Danube (Popescu *et al.*, 2004; Winguth *et al.*, 2000), whereas the northern fan (Dniepr deep-sea fan) was fed by eastern rivers: the Dniepr, the Dniestr, and the Bug.

The development of the northern turbidite complex supplied by the Dniepr and the other Ukrainian rivers appears independent but coeval. Winguth (1998) and Winguth *et al.* (2000) estimated ages of ca. 900 ka for the Danube fan and ca. 800 ka for the Dniepr fan. Both fans are composed primarily of channel-levee systems, intercalated with mass transport deposits. Wong *et al.* (1994;

1997) separated eight seismic sequences in each of these fans; only the six upper sequences, however, contain large meandering channel-levee systems.

The youngest channel-levee system on the Danube deep-sea fan developed most probably during the Neoeuxinian lowstand in a freshwater basin (Soulet *et al.*, 2010) with a water level at least 100 m lower than that of today. Sediments supplied by the Danube were transported over the narrow shelf to the deep basin through the Viteaz (or Danube) canyon, which was directly connected to the leveed channel of this system. Distinct HARP units associated with six bifurcations in this channel-levee system have been identified on the middle fan (Lericolais *et al.*, 2012; Popescu *et al.*, 2004).

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

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

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

Numerous studies including Ryan *et al.* (1997), Major *et al.* (2002a; 2006; 2002b) or Lericolais *et al.* (2010; 2011; 2007a; 2007b) have shown that the relative sea level at glacial times was between 90 and 150 m below the present day sea level. As consequence, the present day shelf of the north-western margin was exposed and the Danube mouth was directly connected to the Viteaz canyon head (Popescu *et al.*, 2001; Winguth *et al.*, 2000). Hyperpycnal flows are supposed to be responsible for the deposition of a large volume of sediments on the slope and the deep basin (Popescu *et al.*, 2001).

The surface of the fan is covered by a distributary network of meandering channels which represent different phases in the evolution of two distinct channel-levee systems. The Black Sea was a freshwater lake during most sea-level lowstands when fan deposition was active. Thus, it is conceivable that despite the many similarities between the Danube fan and other mud-rich fans, the potentially different conditions of sedimentation could have influenced the characteristics of turbidity flows.

Turbidite sedimentation in the deep northwestern Black Sea was not well-investigated before the 1990s (Konyukhov, 1997; Sorokin *et al.*, 1998; Winguth *et al.*, 1998; Winguth *et al.*, 2000; Wong *et al.*, 1994; Wong *et al.*, 1997).

The western Turkish margin

Only a few studies have focused on small parts of the central Turkish shelf (Duman *et al.*, 2006), the Sakarya delta and submarine canyon (Algan *et al.*, 2002), and off the Bosporus strait (Aksu *et al.*, 2002). In addition, Terikoglu *et al.* (2001) and Dondurur *et al.* (2009) have provided a description of the eastern Turkish margin morphology.

Sediments along the western Turkish margin (Figure 2) are mainly transported by the three major rivers which are the Sakarya River (824 km long and 56 504 km2 watershed) and Filyos River (228 km long and 13 156 km2 watershed) and its nearby smaler Bartın River (100 km long and 2 100 km2 watershed). The Turkish continental margin shows a very narrow shelf (locally < 7 km) and a steep continental slope (average from 5° to 9 °). The upper slope is incised by numerous canyons, down to the bathyal plain at about 1800 m deep (Duman *et al.*, 2006). Recent important acoustic dataset were acquired by Dokuz Eylul University of Izmir (Turkey) in the frame of an ESF-TOPOEUROPE project (SourceSink: www.sourcesink.eu). The data reveal an important canyon system offshore the Sakarya and Filyos rivers, where fan development occur (Algan *et al.*, 2002) (Figures 2 and 3). Indeed, the Southern Turkish Black Sea shelf presents a deep water turbidite system characterized by highly dissected canyons with overbank gullies, numerous slide deposits, stacked turbidity–flow leveed channels and large buried debris lobes in the distal area together with sediment waves (Küçük *et al.*, 2011) (Figure 3).

As our data do not cover the slope and shelf, we used the ETOPO 2 bathymetric charts for additional information along the western Turkish margin, updip of the cores location presented by Lericolais *et al.* (2012). The transition between the continental slope and the bathyal plain is marked by a very sharp change in slope. Previous studies of the western and the eastern basins mentioned flat-relief morphology and the absence of sedimentary bodies in the deep basin (Rotaru, 2010; Zonenshain and Pichon, 1986). But it is clear that terrigenous sediments are sourced from two large rivers: Filyos and Bartın rivers (Figure 3). This sediment input from land is later transported from the continental shelf to the deep basin most probably by turbidity current activity along the canyon systems (Küçük *et al.*, 2011).

Black Sea Circulation characteristics

The upper layer waters of the Black Sea are characterized by a predominantly cyclonic, strongly time-dependent and spatially-structured basin-wide circulation. Many details of the circulation system have been explored by numerous hydrographic data and resulting analyses (Chu *et al.*, 2005; Oguz *et al.*, 2002; Oguz *et al.*, 2000; Ozsoy and Unluata, 1997; Ozsoy *et al.*, 1993; Stanev, 2005; Stanev *et al.*, 2001; Stanev *et al.*, 2004).

These analyses reveal a complex, eddy-dominated circulation with different types of structural organizations of water masses within the interior cyclonic cell, the Rim Current jet confined mainly along the abruptly varying continental slope and margin topography around the basin, and a series of anticyclonic eddies along onshore side of the Rim Current (Figure 4). The overall basin circulation is primarily forced by the curl of wind stress throughout the year, and further modulated by the seasonal evolution of the surface thermohaline fluxes and mesoscale features arising from the basin internal dynamics. The strong topographic slope together with the coastline configuration of the basin governs the main pattern of the Rim Current system but it modulates seasonally from a more coherent structure in the winter and spring to more turbulent structure in the late summer and autumn. The fresh water discharge from the Danube contributes to buoyancy-driven component of the basin-wide cyclonic circulation system.

Rim Current dynamic structure appear to be the major factor for the shelf-deep basin exchanges. They link coastal biogeochemical processes to those beyond the continental margin, and thus provide a mechanism for two-way transports between near shore and offshore regions.

Materials and methods

Acoustic mapping

The bathymetry and acoustic imagery are provided by a multibeam echosounder (SIMRAD EM1000 and EM300) conducted on the R/V *Le Suroît* during the 1998 BlaSON and the 2000 BlaSON 2 cruises. Additional multibeam data (Thomson SEAFALCON 11) has been collected on the R/V *Marion Dufresne* during the 2004 ASSEMBLAGE1 cruise. Seismic lines were also collected during the BlaSON 1 & 2 cruises. The very high resolution source was a Chirp sonar single channel, with a frequency sweeping from 1.8 to 5.3 kHz. The Multibeam results have been published recently by Lericolais *et al.* (2012) (Figure 3)

Sedimentary cores

143 cores (Kullenberg, Calypso, vibro or push cores) were collected during the BlaSON 1 & 2 cruises and the ASSEMBLAGE 1 cruise (Figure 5). Physical properties of cores were logged on board with a Geotek Multisensor Core Logger (magnetic susceptibility and gamma density). Thin slabs of 15 mm thick were sampled on each cores and analysed with the SCOPIX X-ray image processing tool (Migeon *et al.*, 1999). Subsamples were taken in order to obtain the carbonate content (using gasometrical calcimetry) and the grain size measurement (using a Malvern MASTERSIZER S). Sedimentary facies have been defined using: (1) photography, visual description, and x-ray imagery; (2) grain size analysis and CaCO3 content; (3) usual facies classification used in similar environments (Normark *et al.*, 1997; Zaragosi *et al.*, 2000).

Nd isotopes in marine sediments:

The use of ε_{Nd} isotope systems potentially offers a unique perspective for investigating continental erosion, and informs on sediment origin of the Danube deep sea fan sediments. Samples of different superficial core samples of the core data set of the BlaSON 1 and 2, and Assemblage 1 cruise were analyzed. All sediments were dissolved either in steel-jacketed Teflon bombs, using HF-HClO4 mixtures, or by alkaline fusion (Bayon *et al.*, 2009a). Both procedures ensure complete sample digestion, including the dissolution of highly resistant minerals such as zircons. The leaching procedure used here was realized following the Bayon *et al.* (Bayon *et al.*, 2009b) protocol and a series of tests were performed using of diluted HCl and HNO3 solutions. Hafnium and Rare Earth Elements (REE) concentrations in sediment samples were analyzed using three different ICP-MS (VG Plasmaquad II+, Agilent 7500 s, and Element2). The precision on measured concentrations was typically better than 5% for Sm, Nd and Hf, and better than 10%, in most cases, for Lu. Details on analytical techniques for Hf and Nd separation chemistries and isotope measurements can be found elsewhere (Bayon *et al.*, 2006; Chu *et al.*, 2002). Nd isotopic ratios were determined at IFREMER either by TIMS (Finnigan MAT261) or by Neptune MC-ICP-MS.

Results

Stratigraphic analysis

Stratigraphic analysis of the north-western margin of the Black Sea using swath bathymetry and high resolution seismic reflection data were used to better understand the base-level variation in the Black Sea during the Late Quaternary (Lericolais *et al.*, 2012; Popescu *et al.*, 2004; Popescu *et al.*, 2001). Submarine canyons, like the Viteaz Canyon (or Danube canyon), are known to evolve due to the influence of sedimentation, slope failure, sediment-gravity flow erosion, and topography (Pratson and Coakley, 1996). The Danube canyon head is distant of more than 100 km from the coast line at -110 m of water depth. This canyon is now disconnected from the river (Lericolais *et al.*, 2007a; Popescu *et al.*, 2004) and present highstand river inputs are mostly trapped into the delta. Whilst, high energy and thin particles (mud) surges flow southwards along the coast southward of the Danube

Delta front mobilized by the northern currents induced by both wind and waves. During lowstand periods the shore line was located between -90 and -150 m below the present water level and the Danube canyon drained an important amount of sediments from the shelf to the deep sea. The first and obvious signature of sediment-laden flows inside the canyon is the Danube deep-sea fan and the clear connection of the canyon to the youngest channel-levee system of the Danube fan (Popescu *et al.*, 2004) suggest that the canyon has been directly connected to the high sediment outflow from the Danube River. Numerous channels of paleo-rivers cross cutting the shelf (completely filled at present times) show the connection between the shore and the shelf and the canyon head (Lericolais *et al.*, 2010; Lericolais *et al.*, 2007a; Popescu *et al.*, 2004). The sediment transfer through the canyon is supposed to have been intensely and extremely erosive. The Danube canyon indents the shelf to 26 km upwards the shelf break and its erosive thalweg continues as an entrenched channel through the Danube Channel-levee system (Popescu *et al.*, 2004). Its morphology presents numerous meanders build within steep flanks up to 30° often cut through by lateral gullies.

Recent models describe how submarine canyon and deep-water clastic deposits are generated and how their formation can be related to base level fluctuation (Beaubouef and Friedmann, 2000; Beaubouef *et al.*, 1998b; Garfield *et al.*, 2000). Building off of the Exxon Lowstand Fan Model (Vail and Mitchum, 1977) these authors propose a three-stage lowstand model: (1) during early lowstand, falling sea-level induces slope failures caused by pressure-related destabilization of slope mud and erosion by sediment-gravity flows. Continued erosion by turbidity currents, focused into the incipient topographic lows and further deepening and widening by marginal slumping and knick point migration leads to the development of canyon scale slope valleys. These mass wasting processes on the slope are associated with mass transport complex (MTC) deposition (slumps, slides, debris flows) downslope; (2) during middle lowstand, coarse sediment that bypasses the exposed shelf is transported through canyons and slope channels and deposited in distributary channel and lobe complexes (DCLC) within the basin-floor fan beyond the toe of slope; (3) during the late lowstand/early transgression, coarser bed load sediment begins to be trapped on the shelf. Muddier suspended load sediment and more limited sand-grade sediment continues to be transported downslope by low-concentration turbidity currents. Overbank spillover and flow stripping processes common to low-concentration turbidity current channels contributes to the development of levees and leveed channel complexes (LCC) which are prevalent at this time. These develop above and landward of the sand-rich distributary channel and lobe deposits of the basin-floor fan.

The sequence stratigraphic model described above can be related to 4th and 5th order base-level cycles (Beaubouef and Friedmann, 2000; Beaubouef *et al.*, 1998b). Repetitive seismic facies stacking patterns, consistent with this high-frequency sequence stratigraphic model are observed in the Danube Fan (Figure 6). Low amplitude, chaotic seismic facies are overlain by an extensive high amplitude continuous to semi-continuous seismic facies unit which is inturn overlain by gull-wing seismic facies. These gull-wing facies are interstratfied with thin, areally restricted high amplitude reflection packages (HARPs). These seismic facies associations are comparable to the lowstand depositional succession of muddy mass transport complexes (MTC), sand-rich distributary channel/lobe complexes (DCLC) and leveed channel complexes (LCC) observed in other areas (Beaubouef *et al.*, 1998a; Flood *et al.*, 1994; Pirmez *et al.*, 1998). The fact that most of the Danube deep-sea fan sedimentation took place in fresh water suggests that hyperpicnal processes may have contributed to the generation of the turbidity currents that deposited the leveed channel and distributary channel and lobe deposits.

At least two distinct depositional cycles are observed below the water bottom and are interpreted to be Late Quaternary in age. The uppermost cycle is imaged in figure 6 and given the following depositional interpretation. Gull-wing seismic geometries represent leveed channels which are seen on the water bottom today. Three distinct leveed channels are observed in a land-ward stepping or retrogradational stacking pattern. These are interpreted to have been deposited during the Holocene base-level rise. The relatively thin and restricted high amplitude reflection packages (HARPs) interstratified with the large muddy levees are interpreted to be channel-mouth distributary channel and lobe deposits. These interstratified leveed channel complex and HARP units are stratigraphicaly younger and distinct from the extensive distributary channel/lobe deposits lying beneath them. The later represent the updip portion of a large basin floor fan which extends at least a 150 kilometres further in to the basin beyond the image captured in figure 6. Leveed channels are also seen to cap the distributary channel/lobe deposits of the basin-floor fan in the underlying depositional cycle (not shown). In both cycles the levees are better developed in a landward direction. The extensive distributary channel/lobe facies that lie beneath the levees in the upper two depositional cycles represent a much larger sediment volume, and are interpreted to be sand rich based on acoustic impedance properties. The interpreted higher sand content, greater sediment volume and further basinward extent of these facies suggests that they formed during periods of maximum base-level fall when sediment flux and shelf bypass were at a maximum. These deposits most likely formed when the Black Sea was isolated from the global oceans. The chaotic mass transport complexes that underlie the basin-floor distributary channel/lobe complex facies in both depositional cycles lie above erosional unconformities and were deposited in a toe of slope position, pinching out landward of the overlying distributary channel/lobe deposits. These facies are interpreted to be comprised of remobilized slope muds due to seismic geometry and acoustic impedance properties. Mass wasting processes associated with the formation of the Viteaz Canyon during periods of falling base-level are interpreted to have contributed to the development of these chaotic mass transport complexes downslope of the canyon.

Distal part of the Deep Sea Fan

Seismic reflection profiles in the area (Figures 7 and 8) show that this area consists of the distal termination of the Danube turbidite system in the deep basin inter-fingered with distal basin plain deposits. Three distinct seismic units are observed. The lowermost seismic unit (P1) consists of acoustically low amplitude to transparent, sub-horizontal continuous reflectors (Figures 7 and 8). This pattern is often associated with fine-grained distal turbidites (Winguth *et al.*, 2000). The seismic unit P1 is overlain by a thick, chaotic to low amplitude, chaotic to bedded continuous reflectors package (L2). The seismic unit L2 is divided in three sub-units (L2-a, L2-b and L2-c; Figures 7 and 8), interpreted as three individual depositional bodies.

L2-a is a prograding sub-unit, mainly composed of chaotic to continuous bedded reflectors of generally high amplitude. The unit downlaps P3 (Figure 8).

L2-b and L2-c are retrograding sub-units showing chaotic to poor-continuous bedded reflectors, where small-size filled channel-like features can be recognized (Figure 8).

Seismic unit P3 onlaps L2 and shows the same acoustically pattern than P1 (i. e. sub-horizontal, low-amplitude to transparent echo-facies). In this unit, several echo-facies variations are recognized, although they could not be interpreted in terms of subunits due to the lack of internal major unconformities. The sedimentary architecture of the basin plain in this area suggests that two sources of sediment are inter-fingering at 2200 m water depth. A northern source is characterized by the stacking of > 50 ms thick (TWT) distal lobes; a southern source onlaps these lobes and is interpreted as thick distal deposits from the Turkish margin, out of the DTS influence (Figure 8).

Use of trace element analyses

Neodymium budget

The neodymium (Nd) isotopic compositions of terrestrial rocks and minerals are variable over a range of scales and Nd isotopic composition is related to radioactive decay. Natural variability in Nd isotopic compositions is expressed as ratios of the abundances of the radiogenic daughter isotope to a suitable non-radiogenic isotope of the same element. The abundance of 143Nd is rationed to that of (non-radiogenic) 144Nd. The observed natural variability in Nd isotopic composition is small, and usually expressed in $\varepsilon_{\mathrm{Nd}}$ notation, which is deviation from the Chondritic Uniform Reservoir (CHUR) in parts per 10,000 as follows:

$$\varepsilon_{\mathrm{Nd}} = \frac{{}^{143}\mathrm{Nd}/{}^{144}\mathrm{Nd}_{sample} - {}^{143}\mathrm{Nd}/{}^{144}\mathrm{Nd}_{CHUR}}{{}^{143}\mathrm{Nd}/{}^{144}\mathrm{Nd}_{CHUR}} \times 10^4 \qquad (1)$$

$\varepsilon_{\mathrm{Nd}}$ composition is heterogeneous in the continent, and these variations are redistributed into the ocean via lithogenic inputs (Goldstein and Hemming, 2003). The properties of Nd as a oceanic water mass tracer have been recently extensively studied (Arsouze *et al.*, 2007; Bayon *et al.*, 2009b; Bayon *et al.*, 2012; Bayon *et al.*, 2006; Jeandel *et al.*, 2007; Jones *et al.*, 2012; Lacan *et al.*, 2012). The oceanic $\varepsilon_{\mathrm{Nd}}$ distribution is governed by sources and sinks alongside ocean circulation. Neodymium isotope composition ($\varepsilon_{\mathrm{Nd}}$) against Nd concentration (shown as 1/Nd pmol/l) is one of the way to represent the potential distinction in between the sources of sediment recovered n the studied cores (Figure 9).

Sediment origin

Three different provinces are recognized as being source of the surface Black Sea sediments.

1. Sea of Marmara

Rivers flowing into the Marmara Sea are few and provide a small amount off sediments. Sediments accumulated in the Marmara basin are probably relics of former old early to middle Cenozoic sedimentation issued from the Anatolia and reworked by the flows in between the Mediterranean Sea and the Black Sea.

2. Black Sea south western province

To understand the sediment repartition in the Black Sea, it is important to consider the present day sea surface circulation (cf. Figure 9).

The South-west current flowing along the Romanian coast and the Bulgarian ones permit to explain the link existing between the Danube sediment types and the south-western Black Sea sediment types. The sediment provided by the Danube delta are transported by this along shore drift current to the south-west of the Black Sea. Nevertheless this study is not précised enough to decipher the contribution of the small Bulgarian rivers sourced from the Balkan Mountains as the Neodynium signature is rather similar to the one sourced from the Danube (Moores *et al.*, 1998; Tockner *et al.*, 2009).

3. Black Sea central province

This province is the most delicate to interpret and of course the one of interest for this study. Two sedimentary poles can be distinguished on Figure 9 (ε_{Nd} against Nd): the Marmara pole in pink on the figure and the pole south-western Black Sea (province SO) in blue on the figure.

The yellow dots on the figure would let consider that the sediment provenance of the central province of the Black Sea would be a blend in between the two previous poles (Danube and Marmara). Nevertheless, it has been demonstrated that there is not such important sediment transport of sediment at the Bosporus outlet (Algan *et al.*, 2001; Lamy *et al.*, 2006a; Lericolais *et al.*, 2002; Okay *et al.*, 2011). This leads to consider a probable Anatolian origin for the yellow dots.

The Anatolian rivers contribute to the detritic sedimentation on the southern part of the Black Sea. The Sakarya river is the third longest river of Turkey flowing into the Black Sea (8,6 x 106 tons/year, over 3 times more than the Dniepr) (Algan *et al.*, 2002). Sediments provided by the Sakarya are added to the western gyre in the middle of the central province.

Discussion

Evidence for earthquake-induced, unchannelized gravity currents sourced from the Turkish margin

The sedimentary units P1 and P3 (i. e. deposits originated from the Turkish margin for P3) consist mainly (> 80%) of thick mud turbidites associated with thick transparent units visible on the chirp profiles (Figures 7 and 8). Such sequences showing thick structureless homogeneous "Te" muds have already been described along deep basin plains such as in the Mediterranean (Kastens and Cita, 1981; Rothwell *et al.*, 2000; Stanley, 1983), the NW African basin (Wynn and Stow, 2002), and the Oman basin (Bourget *et al.*, 2011). Presences of transitional sandy-muddy and muddy debrites are common in distal fan settings and are often transitional and therefore related to underlying turbidites (Hickson and Lowe, 2002). These deposits are usually resulting from poorly channelized to unchannelized, large volume turbidity currents (Bourget *et al.*, 2011; Wynn and Stow, 2002). Some authors proposed that the unusual thickness of the muddy "Te" could result from several, successive surges occurring in a voluminous, mud-rich turbidity current rather a discrete gravity flow (Lowe, 1982; Tripsanas *et al.*, 2004; Wynn and Stow, 2002). A possible explanation is that these thick muddy turbidite deposits would be due to successive mass-wasting along the continental slope (Bourget *et al.*, 2010; Wynn and Stow, 2002). In the Makran (a semi-desert coastal strip along the coast of the Arabian Sea and the Gulf of Oman) active margin, these processes and the thick distal deposits that they produce have been linked to major earthquakes (Bourget *et al.*, 2010).

The Turkish margin is bordered by the highly active North Anatolian Fault (Figure 2). Previous studies in the Eastern Black Sea have shown that the activity of the North Anatolian fault is also evidenced offshore (Cifci *et al.*, 2003; Dondurur and Cifci, 2007; Rangin *et al.*, 2002) and suggested a minor impact of the N.A.F. on the triggering of mass wasting processes along the continental slope based on the relative size of the slide scars. Inversely the observations of a dense distribution of slump-scars along the margin (Cifci *et al.*, 2003; Dondurur and Cifci, 2009) support the hypothesis that submarine landslides as an important mechanism for triggering turbiditic flows. Recent earthquake distribution from USGS (http://earthquake.usgs.gov/earthquakes/world/turkey/density.php) shows that a portion of the Turkish margin located upward of our cores is particularly active. Earthquakes could generate the destabilize small portions of the shelf-edge and continental slope and form repeated mass-wasting events, possibly generating successive tsunamis waves and gravity flows (Bourget *et al.*, 2011; Bourget *et al.*, 2010; Talling *et al.*, 2007; Wynn and Stow, 2002). Several historic tsunamis have been reported along the Black Sea Turkish coast (Altinok *et al.*, 2011; Pelinovsky, 1999) and have been triggered by the activity of the North Anatolian strike slip fault (Figure 2). Conversely the thick-mud turbidites observed in the deep basin plain could correspond to the "homogenites" studied by Kastens and Cita (1981) or the "unifites" of Stanley (1983). Reeder *et al.* (1998) restrict the term “homogenite” to deposits having an homogeneous nature and related to the expression of a unique event with a definite stratigraphic position (Cita *et al.*, 1996). Such “homogenites” have also been described in deep basins of Marmara Sea (Beck *et al.*, 2007) or as the LGM Black Sea, in lakes (Chapron *et al.*, 2006; Chapron *et al.*, 1999). Cita *et al.* (1996) proposed that after a tsunami, resuspended sediments form a turbulent particle cloud that settled out gradually. In the Marmara Sea as well as in lake environments, such homogeneous deposits have been attributed to “seiche” effect (i. e. lake water oscillation in response to earthquake-induced mass wasting processes). The water column oscillation is generally related to seismic activity (Cita *et al.*, 1984), directly (by direct seismic wave propagation) or indirectly (earthquake induced mass wasting processes such as slides or slumps). If “seiche” effects are commonly generated in confined basin such as lakes or the enclosed Marmara Sea (Beck *et al.*, 2007), the Black Sea basin, which extends on 432,000 km^2, appears to be a wide undergo “seiche” wave generation.

Previous work (Popescu *et al.*, 2001; Winguth *et al.*, 2000) clearly concluded that the northwestern rivers stop providing sediments to either the Danube deep sea fan and to the Dniepr-Dniestr deep sea fan after the LGM. From the dates obtained in the studied cores, informing we can hat P3 was deposited after LGM although the Danube sediments were not reaching the deep basin. Therefore, we can conclude that the thick mud turbidites observed in the deep basin sediments, especially for P3, are sourced from the Turkish margin and are the result of synchronous mass-wasting events along the slope, such as observed along the Makran (coast of the Arabian Sea and the Gulf of Oman) active margin (Bourget *et al.*, 2011; Bourget *et al.*, 2010). Such events could be generated during earthquakes related to the N.A.F activity.

The nature of the distal deposits and the unusual amount of mud in the turbidites are also likely related to the physiography of the margin. Indeed the loss in flow velocity induced by the sharp change in gradient at the break of slope and the very low slope gradient (< 0,1 °) in the basin plain lead to rapid deposition of coarser sediments, with only the finer-grained portion of the initial sediment load being transported to the basin. In addition, abrupt break of slope such as the one observed along the Turkish margin can limit the downslope formation of submarine channel and thus enhance the generation of unchannelized gravity currents in the basin plain (Bourget *et al.*, 2011). The general low-amplitude and acoustically “transparent” echo-facies observed in the sediments sourced from the Turkish margin (Figures 7 and 8) are typically thick, mud-rich turbidites (Beck *et al.*, 2007; Chapron *et al.*, 1999; Cita *et al.*, 1996; McHugh *et al.*, 2006). The thickness of the clayey layers finally requires an abundant source of fine-grained sediments in the catchment area and shelf (Bourget *et al.*, 2010), which is the case along the Turkish shelf (Duman *et al.*, 2006).

As after the LGM, it is known that the Danube deep sea fan does not receive any sediment from the northwestern rivers and according to the regional seismic activity, it comes that earthquakes may be the more common initial triggering mechanism of the mass-wasting inducing thick mud turbidites constituting P3 sequence, at least on this portion of the Turkish margin. Off the major Anatolian rivers, i. e. off the Sakarya and Filyos, rivers, a small-size fan development may occur in the proximal part (e.g. Algan *et al.*, 2002; Dondurur and Cifci, 2007), possibly built by recurrent hyperpycnal currents (that could exit in the semi-freshwater Black Sea during sea level low-stand). Sediment overloading on the steep slope or gas hydrates (classically observed onto the Turkish shelf; Cifci *et al.*, 2003) constitute additional triggering mechanisms which would explain the occurrence of typical distal turbidites also recovered in our cores.

Quantification of climatic, eustatic and tectonic forcing on the gravity sedimentation in the western Black Sea basin.

The last concordant sequence is onlaping the distal deposits of the Danube Turbidite System at 2200 m of water depth. During glacial times, the gravity sedimentation from the Turkish margin appears to be controlled by both regional tectonics and climatic forcing (i.e. enhanced sediment supply during deglacial and unusual wet periods). At a smaller scale, past work in the area has shown that the sediment supplied onto the shelf is controlled by climate at Eastern Mediterranean (Lamy *et al.*, 2006b). Due to their very short source-to-sink sediment transport route, active margins are indeed more likely to be influenced by high-frequency climate changes and the later are likely to be recorded even in the distal most turbidite deposits (Bourget *et al.*, 2010). Tectonics, sea-level and climate changes are actively influencing the transfer of sediments along active margins and equally influence the stratigraphic architecture of the turbidite system at relatively short time-scales (< 100 ka).

Conversely, the north-western margin shows the development of medium-size, mud-rich turbidite systems (i. e. the Danube and Dniepr deep sea fans). Here the sediments are transported to the deep basin from a point source. The flows are channelized, confined (Winguth *et al.*, 2000), typically depleted in fine sediments along the slope and in the bathyal plain until they reach lobe deposition at their most distal part. During the LGM, the Black Sea was a lowstand lacustrine body and the Danube deep sea fan was functioning. The direct connexion between rivers and canyons suggest a climate driven sedimentation at high resolution along the north-western shelf (Kwiecien *et al.*, 2009). However at the scale of the Late Quaternary, the Danube Turbidite System activity is mainly control by lake level fluctuations and is inactive during the Holocene when a large delta progrades at the river mouth onto a wide shelf (Popescu *et al.*, 2004; Popescu *et al.*, 2001). In general, our results illustrate the multi-scale forcing variability on the western Black Sea sedimentation, from the north-western passive margin controlled by lake level fluctuations and glacial cycles, to the south-western margin on which tectonics shaped a typical ramp system and actively control the source-to-sink sedimentation.

Conclusion

Our study focuses on the deep-water architecture of the western Black Sea deep basin and its sedimentological characteristics. The Late Quaternary Danube turbidite system (to the North) displays a well-constructed morphology, underlined by at least six channel-levee systems associated with distal lobe complexes, reaching the 2200 m isobaths. The adjacent deposits, onlaping the Danube Turbidite System distal lobes in the deep basin, show a linear, drape-like morphology, represented by thick continuous reflections on seismic profiles. They generally consist of distal turbidite deposits supplied from the Turkish margin. Most of these turbidite sequences show a thick upper unit composed by homogeneous clastic clays, thus forming thick mud turbidites. Following previous work in similar basin settings, we interpret these facies to result from large volume unchannelized turbidity currents generated by successive mass-wasting events. The abrupt break of slope at the bathyal plain transition enhances the rapid deposition of coarse-grained material and limits channel development in the bathyal plain. We relate the origin of these deposits with the very high seismic activity of the North Anatolian Fault on the Turkish margin. The Neodymium analyses of the sediment provenance are in accordance with this observation.

Our study is based on data at the boundary of influence of the Danube Turbidite System and the Turkish margin, and provides a new record of the changes in sedimentary supply, climate and sea level that occurred in the Black Sea region since the last ~ 25 ka. The deep basin deposits bear the record of the Late Quaternary paleoenvironmental changes (Lericolais *et al.*, 2012). The Last Glacial Maximum Period (~25 to 18 ka BP) was characterized by an important and relatively stable sediment supply with sediment transferred to the deep basin from both the northern Danube Turbidite System and the southern Turkish margin. The relative stable LGM period was followed by an increase of sediment transport to the deep basin, which is locally illustrated by progradation of lobe deposits from the Danube turbidite system in the deep basin, downlaping the Turkish deposits. Influx of meltwater to the Black Sea resulted in a early highstand sea level. The following Bolling-Allerod Preboreal warm period and the Younger Dryas cold event have experienced alternative sea level lowstands and highstands that are not clearly underlain in the deep basin sediments (Lericolais *et al.*, 2012). The onset of sea-level highstand after the Holocene marine invasion (~ 9 kyr BP) (Lericolais *et al.*, 2012;

Soulet *et al.*, 2011) induced the end of the activity of the Danube Turbidite System whereas the gravity supply from the Turkish margin remained active throughout the Holocene.

We conclude that the western Black Sea basin constitute an asymmetric subsident basin bordered by a northern passive margin with confined mid-size, mud-rich turbidite systems, and a southern turbidite ramp built in a tectonically active margin setting.

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Figures

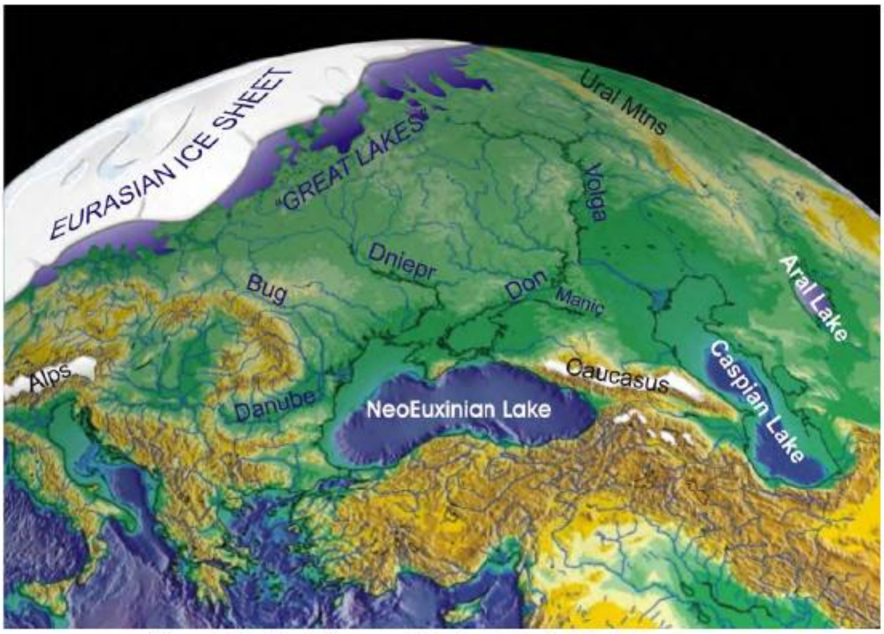

Figure 1. The Black Sea area at the time of the last glacial maximum.

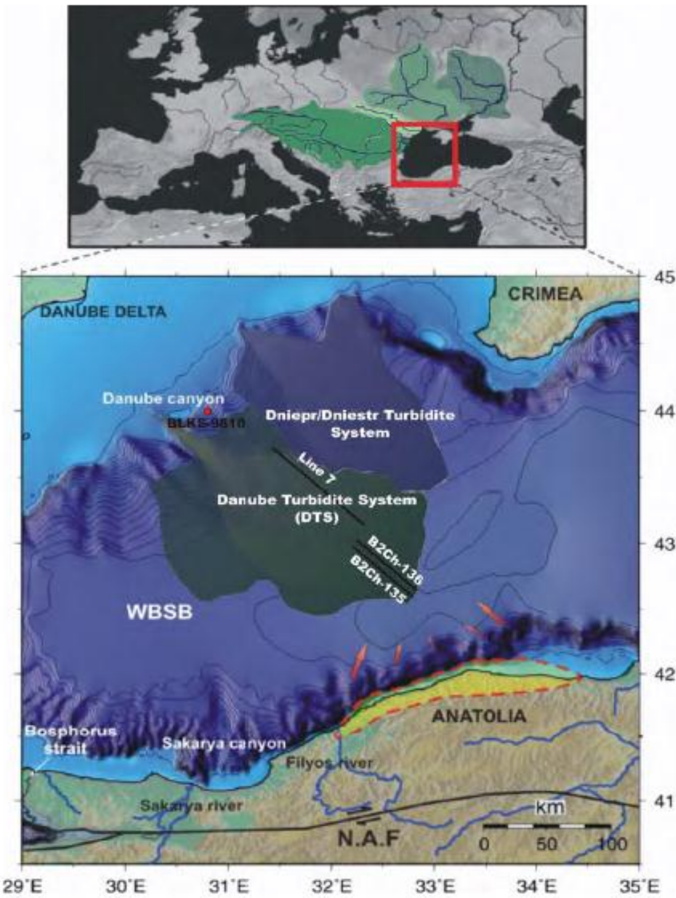

Figure 2. Location map of the study area, showing extension of the two main sedimentary features in the western Black Sea Basin (WBSB): the Danube Turbidite System (DTS) and the Dniepr Turbidite System (after Popescu *et al.*, 2001; after Wong *et al.*, 1997); bathymetry contours are from 50 m interval (source: ETOPO2); locations of the CHIRP seismic line B2CH-135 and B2CH-136 (black solid line) and of the multi-channel seismic line 7; location of the possible sediment source for the portion of the deep basin studied, out of the DTS influence (red dashed line and arrows); location of the North Anatolian Fault (N.A.F). Bathymetric font modified from (Gillet *et al.*, 2007; Lericolais *et al.*, 2012).

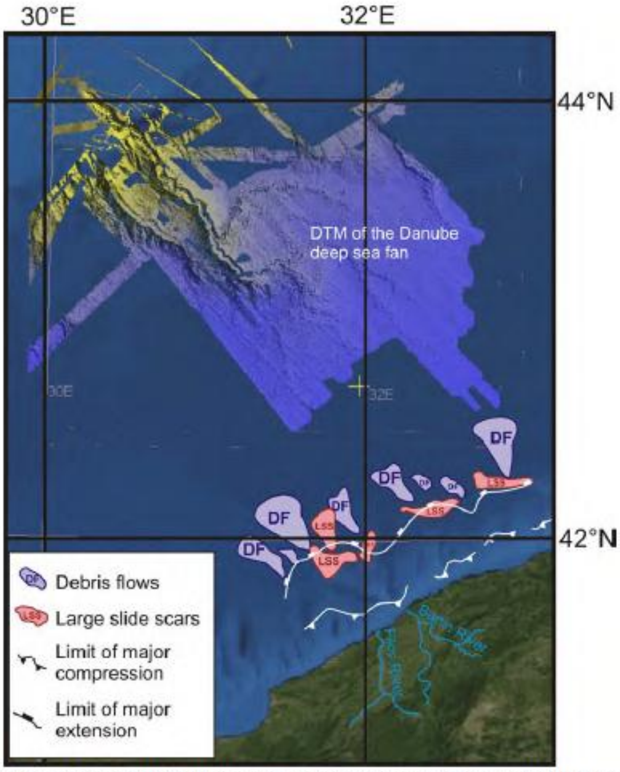

Figure 3. Structural and morphological elements of the southern part of the studied area obtained from acoustic survey carried out by Küçük *et al.* (2011). This study shows that important debris flows (DF) and large slide scars (LSS) are present on this tectonically active margin and could reach the distal part of the Danube deep sea fan. The DTM of the Danube deep Sea fan has been studied by Lericolais *et al.* (2012).

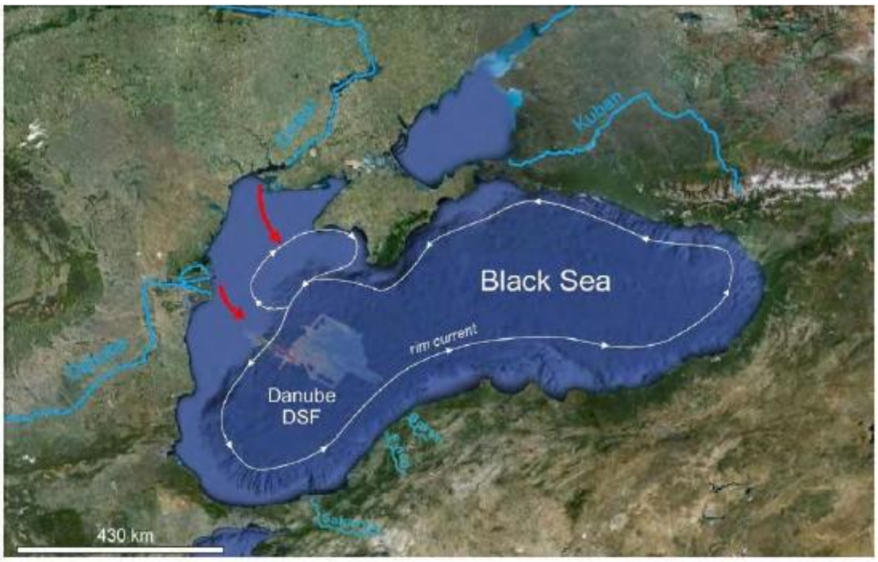

Figure 4. Regional setting of the Black Sea, showing the main drainage systems and offshore rim currents. Red arrows point out major sediment discharges at river mouth.

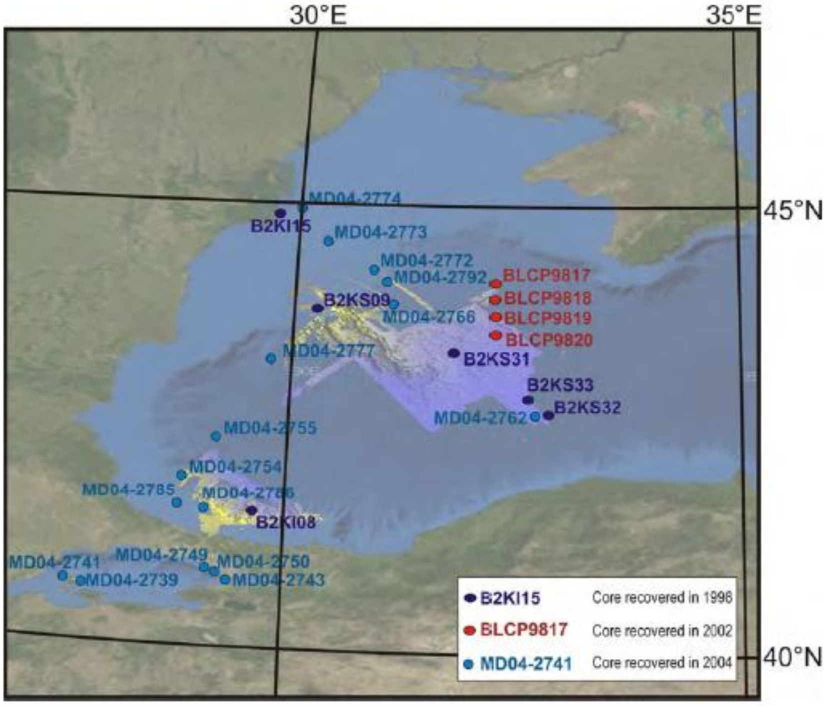

Figure 5. Location map of Black Sea cores used for the rare earth element analyses.

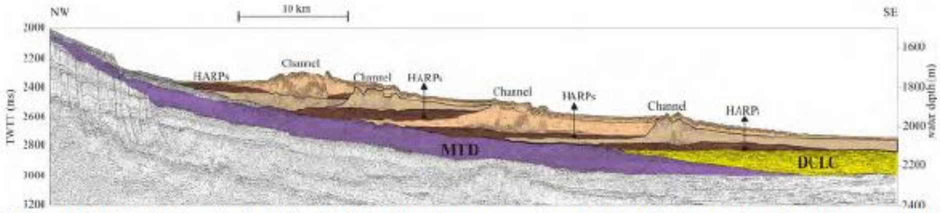

Figure 6. Part of BLASON 24-Channel seismic line 7: MTC = Mass transport complex; DCLC = Distributary channel and lobe complex; HARPs = High amplitude reflection packets. Modified from Popescu *et al.* (2001)

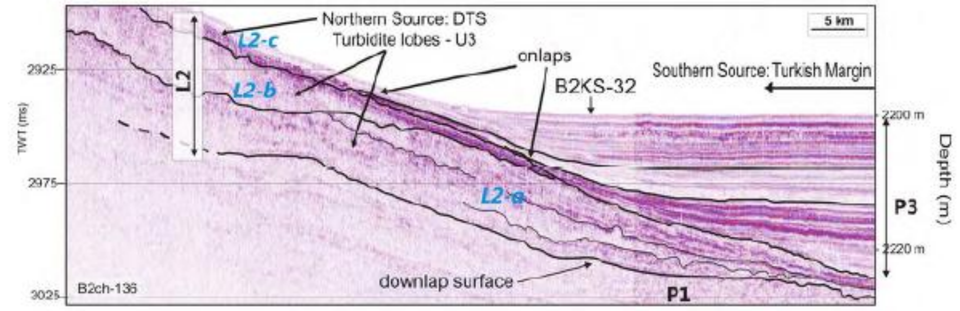

Figure 7. CHIRP seismic profile B2ch-136 showing core location for B2KS-32. Seismic units P1 and P3 are associated with fine-grained distal turbidites. Unit L2 corresponds to a chaotic to bedded continuous reflections package. L2-a, L2-b and L2-c are three sub-units of L2 corresponding to three individual depositional bodies (*cf.* Lericolais *et al.*, 2012).

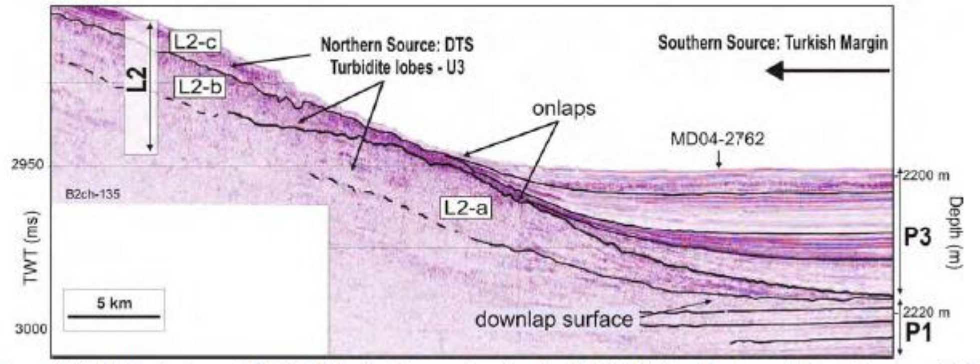

Figure 8. CHIRP seismic profile B2ch-135 showing core location for MD04-2762 and interpretation. Seismic units P1 and P3 are associated with fine-grained distal turbidites. Unit L2 corresponds to a chaotic to bedded continuous reflections package. L2-a, L2-b, and L2-c are three sub-units of L2 corresponding to three individual depositional bodies (*cf.*, Lericolais *et al.*, (2012).

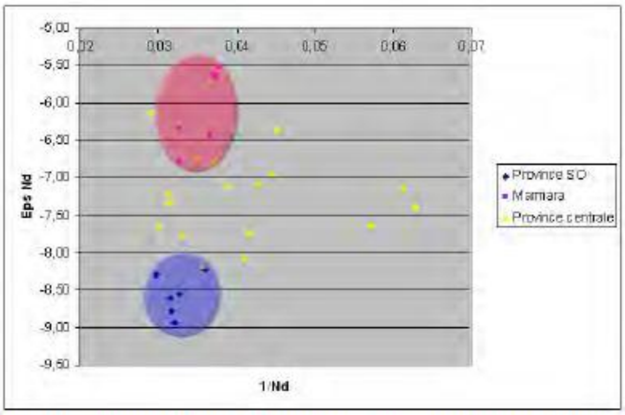

Figure 9. Neodymium isotope composition (εNd) against Nd concentration (shown as 1/Nd pmol/l). Two poles are well identified: (1) Pink pole corresponds to the Marmara pole characterized by low εNd and a low 1/Nd value as well; and (2) Blue pole corresponds to the southwestern Black Sea province (Province SO) having the same value as the core sediment recovered in front of the Danube delta. Yellow dots are values between the two poles. Three values are characterized by high values of 1/Nd but are considered as not representative, probably consequence of presence of residual carbonates not washed over by the acetic acid.