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Morphological and Stratigraphic Investigation of a Holocene Subaqueous Shelf Fan, North of the İstanbul Strait in the Black Sea

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Abstract :

In 2002, the Bosphorus outlet was mapped using an EM 300 multibeam echo-sounder together with a Chirp sonar system. This survey, carried out on board the Ifremer RV 'Le Suroit' in the frame of the BlaSON project, completes the data previously acquired directly at the mouth of the Bosphorus by Di Iorio et al. (1999) in the frame of a NATO SACLANT Undersea Research project using jointly the NATO RV Alliance, and the Turkish Navy Survey ship 'Çubuklu'. This acoustic imaging has identified a canyon system at the slope and a shallow marine fan, which contains shelf incisions extending the İstanbul Strait incision. Multibeam bathymetry, ultra-high resolution seismic profiling and coring correlations on this subaqueous fan area allowed reconstruction of morphology and patterns of sediment distribution indicative of high energy sediment transport processes. The discovery of a shallow water/shelf type fan directly offshore from the Bosphorus and connected to its outlet is consistent with the theories of sudden discharges of large volumes of water. Age dating obtained at the bottom of this subaqueous shelf fan yielded an age of 6700 yr C14 BP (uncorrected age) for the first marine mollusc encountered at the base. This is in accordance with a last and abrupt reconnection of the Marmara Sea to the Black Sea. A detailed morphological map of the shelf and slope along with seismic profile interpretation and core correlation is presented here. A synthesis is proposed to explain the formation of this subaqueous fan and its relationship with the last connection between Black and Marmara seas after the Last Glacial Maximum. This interpretation can be summarized as follows: stage A corresponds to the first erosion surface seen on the shelf related to the Last Glacial Maximum low stand; stage B is the ravine surface overlapping to ca. -30, -40 m; stage C is a second erosional surface related to a sea level fall and eroding most of underlying Unit 1B; and stage D corresponds to the onset of the fan deposit during a period of high water run-off from the Black Sea entering from the Bosphorus. Avulsion branches show that this fan has been active for a long time.

Keywords : multibeam, high resolution seismic, sea level change, high energy Mediterranean water input, subaqueous fan

1. Introduction

The opening of the Bosphorus, which connects the Mediterranean and Black Sea, played an important role in the establishment of the present sea level of the Black Sea. The sedimentary sequences in the Black Sea are strongly affected by sea level changes driven by global glaciations and deglaciations. Russian investigations have shown that present day conditions in the Black Sea basin are similar to those during interglacial periods, when the level of this basin was high enough to allow sea water penetration from the Mediterranean Sea through the Bosphorus (Fedorov 1988; Svitoch *et al.* 2000). These flow-through regimes should have been interrupted during low stand periods when the Black Sea water level dropped below the sill depth of the Bosphorus. The age and amplitude estimations of these fluctuations vary. A recent summary of the different hypothesis has been published in the book entitled: "The Black Sea Flood Question. Changes in Coastline, Climate and Human Settlement" edited by Yanko-Hombach, *et al.* 2007. Although several authors have suggested various number of transgression and regression cycles during Holocene, these attempts to reconstruct the Holocene sea level for the Black Sea are often unrealistic and lead to confusion of many non specialists. One of the big misunderstanding is in the use of radiocarbon dates with a lack of calibration, as the correction to be applied to these radiocarbon ages are an important subject of concern for the Black Sea (Bahr *et al.* 2006, 2008; Guichard & Assemblage partners 2006; Kwiecien *et al.* 2006, Fontugne *et al.* 2009). This was supported by Giosan (2007), who underlined the misinterpreting of old radiocarbon dates, the absence of age correction and the lack of any vertical ranges for sea-level index points resulting for him in a comparison of apples with oranges (e.g., Fig. 5 in Yanko-Hombach *et al.* 2007). Different transgressive-regressive phases within the Holocene have been published (Arslanov *et al.* 1983; Balandin & Trashchuk 1982; Yanko 1990; Yanko-Hombach *et al.* 2002) leading to proposed sea level fluctuation of the Black Sea varying from -65 m to -35 m between 9.4 and 8.0 ky BP. For these authors transgression-regression cycles would exist between 8 and 5 ky BP, with sea level oscillating from -55 to -15 m and rising in absolute terms to several meters higher than the present level at about 5 ky BP (Svitoch *et al.* 2000; Yanko-Hombach *et al.* 2002; Balabanov 2007). Considering that the Black Sea was connected with the Global Ocean all this time demonstrating that these regressions were real would throw all we know about the Holocene sea level in the ocean in a state of confusion. However it is clear that the level of the Black Sea followed to a certain extent more the regional climate modification than the global eustatic changes (Lericolais *et al.* 2007).

Currently a number of different scenarios exist for the Black Sea level fluctuation since the Last Glacial maximum. Research interest in the Black Sea has been reignited again after the publication of Ryan, *et al.* (1997) hypothesis of an early Holocene catastrophic flooding of the Black Sea by Mediterranean waters. A hard scientific debate on the occurrence of such a flood as well as on its possible cultural consequences followed their publication, among controversy, most important was led by Aksu, Hiscott and co-authors (Aksu *et al.* 2002a; Aksu *et al.* 2002b; Aksu *et al.* 1999; Aksu *et al.* 2002c; Hiscott & Aksu 2002; Hiscott *et al.* 2007, 2002).

Since 1998, the Black Sea was surveyed in the frame of different national, multinational, international and European projects. This study presents results obtained from a synthesis of data collected for one important part in 2002, during a survey carried out on board the Ifremer RV "Le Suroit" for BlaSON project (Lericolais *et al.* 2002), and for a second part by Di Iorio & Yüce (1999). in the frame of a NATO SACLANT Undersea Research project using jointly the NATO RV Alliance, and the Turkish Navy Survey ship "Cubuklu". Here, we present a detailed morphological map of the entire area off the Bosphorus outlet together with very high resolution seismic (Chirp) data correlated to core analyses and dating better characterisation of subaqueous fan existing at the mouth of Bosphorus.

2. Data acquisition

In 2002, the Bosphorus outlet was mapped by using an EM 300 multibeam echo-sounder together with a Chirp sonar system. This survey carried out on board the Ifremer RV "Le Suroit" in the frame of the BlaSON project completes the data previously acquired directly at the mouth of the Bosphorus by Di Iorio & Yüce (1999). for a NATO SACLANT Undersea Research project using jointly the NATO RV Alliance and the Turkish Navy Survey ship "Cubuklu". In 2004, the French R/V "Marion Dufresne" collected long piston cores for the European Project ASSEMBLAGE (EVK3-CT-2002-00090). This survey provided bathymetric data and Chirp Sonar data. EM 300 multibeam data were processed using Ifremer "Caraibes" software and contour extraction, "spline" curves filtering and bidimensional digital filtering were applied to remove multibeam artefacts. The Chirp data having an operating frequency ranging between 1.5 and 7 kHz were also processed. The cores were recovered in 2004 during Assemblage Survey on board the IPEV research vessel "Le Marion Dufresne" in the frame of the eponymous project. Location and parameters of core B2KS02 used in this study is given in Table 1.

3. The subaqueous shelf fan; last connection between Black Sea and Marmara Sea

3.1. Morphology of the shelf area

The morphology of the İstanbul strait outlet shelf area was derived from data acquired in the frame of NATO Project (Di Iorio & Yüce 1999). These data, in conjunction with dating and very high resolution seismic (Chirp) data were used to interpret shelf features.

Interpretation of the 3D multibeam bathymetric map indicates that a prominent cut channel has a direct connection with the İstanbul Strait. This seafloor marked channel trends towards NE-SW and then turns NW to SE direction on the shelf area (Figure 1). Figures 2a and 2b present the 2D bathymetric and contour map of the area, together with the profile locations. Water depth is about 30m at the İstanbul Strait and between 30-45m where channel banks are prominent. Towards the middle shelf, water depth reaches 75m on both sides of the channel. The distal part of the channel system abruptly turns towards the northwest when reaching the mid-shelf. Figure 2b presents this channel system on the combined multibeam echosounder map of the bathymetric data acquired on the proximal shelf by the NATO project, with the Ifremer data collected during the BlaSON2 project at the shelf edge down to the slope toe.

This channel system consists of 1 main and 6 secondary channel. Some of the secondary channels are divided into distributaries. The main channel is directly connected to the İstanbul strait and is well defined in the bathymetry. This NE trending channel abruptly makes a 90° turn and trend towards NW (around latitude ~ 41°20'N). In addition to the main channel six other secondary channels can be followed. The depth of the main channel is min 30m and max 50m. Its width is 800m.

Two other distinctive sedimentary features have been recognised on the shelf area (Figure 3). The first features, which are characterised by their shape and trend, are interpreted as ridges. These ridges are also classified into two types:

- (1) First types, which are ridges perpendicular to the channel axis, are randomly distributed and exists at the distal part of channels 1 and 2. The heights of these perpendicular ridges vary between 1 to 7m. The ridges morphology and stratigraphy indicate that they have settled after the formation of the channel levees.
- (2) Second types, are present at the distal part of the fan system itself and are asymmetrical ridges. Their heights vary between 1 to 5m, and never exceed 10m. The distances between them vary between 200-1000 m and they have been recognised within small groups or arranged into lines (Figure 3). These asymmetrical ridges correspond to diapir-like bodies settling around the channel system. They are generally located away from the system, have circular shapes and are randomly distributed.

3.2. Seismic interpretation of the structures on the shelf area.

3.2.1. Channel-levee system

Many channels are visible on the bathymetric map (channels 1-6, Figure 3; channels 1-2 in Figure 4a). Younger and incisive (sharp) channels are visible on channel banks. In Figure 4a, the profile P24 is crossing these two types of channels. On the seismic section two erosional surfaces are recognised. They correspond to the erosional surfaces named α and α_1 by Hiscott *et al.* (2002). The thin unit between the erosional surfaces α and α_1 is named Unit 1B. This last erosional surface α_1 and Unit 1B disappear at the bottom of the channels.

The fact that these channels are empty might indicate that they are still active or there is not enough sediment supply to have sedimentary deposit in these channels. The channels also present a meandering pattern. The sides of the channels are constituted of levees corresponding to period of overbanking.

3.2.2. Ridges

At its southwestern part, profile 24 crosses ridges that are lying on channel 1 and 2 (Figure 4a). Profile is passing through the western ridges which are shown on the multibeam echosounder map (Figure 3), and which are perpendicular ridges to the main channel of the system.

The top part of these ridges is veneered by recent (Holocene) sediments. These ridges rest on erosional surface α_1 and were defined as barrier bars by Aksu *et al.* (2002a). These features have a characteristic inner structure. They have a gentle slope on stoss side and a steeper slope on lee side. On profiles they are about 7-20m in height and 200-300m in width. There is approximately 1 km between each ridge. Towards the shelf edge these ridges become smaller (3-5m) in height and are only a few tens meters in width. However, this increase could be related to the increase in flux (flow rate) towards shelf edge. Figure 4b shows part of profile 36 that crosses some of the ridges that are seen on the levees. These are very small and are located more closely spaced compared to the ridges on shelf part (parallel ridges to the main channel). P36 trends almost parallel to channel 1 with a high angle ($\sim 20^\circ$ to normal), so we could in order see the levees longitudinally cut. The inner

structures of ridge features are chaotic with high reflectivity. This causes acoustic masking of the underlying sediments.

3.3. Seismic stratigraphy of the channel system

The internal structure of the subaqueous fan is studied using chirp seismic profiles. The seismic stratigraphy is here based on the nomenclature of Aksu *et al.* 2002a. Chirp profile 22, presented in Figure 5a, displays the stratigraphy used in this study in correlation with Aksu's nomenclature. Four different units and two different unconformities have been recognised. Unit 3, corresponding to the basement, is marked by acoustically strong internal reflections including folded and faulted strata. The two erosional surfaces interpreted on the chirp profile correspond to α and α_1 (Aksu *et al.* 2002a), with α_1 representing the erosional surface separating Unit 1B from Unit 1.

Unit 2 presents a set of north dipping reflectors, indicating a progressive sea level fall (regression) and is interpreted as the Cretaceous limestone formation, intercalated with volcano sedimentary formation (Aksu *et al.* 2002a). This Unit is made of seaward dipping strata truncated at the shelf edge by the unconformity surface α . This α unconformity was formed during a low stand erosional phase. Erosional unconformity surfaces were also observed across the whole south-western Black Sea shelf by Aksu *et al.* (2002a), who argued that it was formed during the last glacial maximum low stand.

In contrast Unit 1B consists of cobble sand and shell of brackish molluscs (Figure 5b) (William Bill Ryan, pers. comm. 2008, 2009). This unit is not present over the whole studied area. Unconformity surfaces α and α_1 merge in some places to form a unique horizon where Unit 1 is absent. In this section, Unit 1 overlies a craggy unconformity α (Figure 5b). To the norther, Unit 1B is encountered and lies on the unconformity α . It has a chaotic structure and the limits of the sequence are not clearly defined.

Isopach maps of Unit 1B and Unit 1 are presented in Figure 6. Interpolation was needed to fill the gaps where chirp data are missing. The isopach map of Unit 1B does not match the structure of the channel system. Therefore, the existence of Unit 1B could be explained with deposition before the fan formed. There is a second erosional surface α_1 formed due to a sea level fall. This erosional surface truncated most of Unit 1B. ^{14}C age measurements yield an uncorrected age for this erosional surface of ~ 10750 BP (William Bill Ryan, pers. comm. 2008, 2009). In contrast, sediment thickness map of Unit 1 is compatible with the structure of the channel system (Figure 6b), indicating that Unit 1 settled during the formation of the channel system.

3.3.1. Lowstand wedge

A prograding wedge is recognised at the shelf edge of the studied area. It rests over the α unconformity and gives information about the level of the correlative low sea level (Figure 7). The wedge stands over the underlying clinofolds (above α) and is truncated by α_1 , indicating a second sea level drop (last low stand). These wedges were widely studied by Algan *et al.* (2002). Their architecture correlates with our data.

The depth of sea level during last Glacial Maximum was calculated from the base of this wedge giving a water level at the shelf edge around -110 m for the Last Glacial Maximum (LGM). Demirbağ *et al.* (1999) obtained a depth of -105 m for the LGM. Recent research by Ryan; and collaborators reveals ~ 11800 BP ^{14}C uncalibrated age (William Bill Ryan, pers. comm. 2008, 2009) for Unit 1B.

3.4. Dating of the subaqueous shelf fan

Foraminiferal assemblages compositions were analysed from core B2KS02 at the Department of Marine Sciences, Università Politecnica delle Marche (Giunta *et al.* 2007). Samples were dried (40°C degree) and weighted, washed with running water and sieved (63 micron), and dried again at the same temperature. The residues (> 63 micron) were split (with a microsplits) the number of times necessary to obtain an aliquot fraction of about 200 specimens of foraminifera, which were counted and identified. All the benthic foraminifera were picked and mounted in slides to provide a collection of the benthic assemblages. The collection is available at the Department of Marine Sciences, Università Politecnica delle Marche. During the analysis of the foraminifera assemblages, all the bivalves, gastropods and ostracods were also counted. From the census counts, percentages were calculated together with benthic and planktonic foraminifera, bivalves, ostracods per gram of dry sediment, number of species of benthic foraminifera, and % of water content.

In core B2KS02, 26 samples for isotopic analysis were prepared. On average, 15 specimens of *Ammonia beccarii* were picked from the 150-micron size fraction, this species was chosen because of its continuous presence along the investigated core. Five ¹⁴C AMS(accelerator mass spectrometry) dates are available for this core (Table 2).

Benthic foraminifera in core B2KS02 are present throughout the core (Figure 8). In Unit I-B and II-B benthic assemblages are characterised by a low number and a low diversity of specimens. In the transitional phase (upper part of Unit III-B) the benthic assemblage is dominated by *Ammonia genera*, which is in great abundance in the bottom part of the core. The presence of benthic foraminifera in the entire core testified that ecological condition was ideal for the development of benthic microfauna since 6700y ¹⁴C BP. The site recorded the entrance of salt water (bottom of the core) and strong increasing in the sedimentation rate, that ends with the beginning of the normal sedimentation (Unit II-B).

Shelf cores testified to regional response of the platform during the Holocene evolution of the Black Sea. In the north western part of the Black Sea, benthic foraminifera colonised the sea bottom after that the sapropel deposition already started in the basin. In the western part of the shelf (core B2KS02), the microfauna colonised this part of the Black Sea shelf as soon as the connection with the Marmara Sea was re-established.

4. Discussion and conclusions

This study presents new results obtained on the subaqueous fan located at the shelf of Black Sea outlet of the Bosphorus (Di Iorio & Yüce 1999; Flood *et al.* 2009). The shelf fan is formed of 1 main channel and 6 tributary channels, which are present on the shelf area at the Black Sea exit of the İstanbul Strait (Figure 9). These secondary channels change directions while they avulse. The 1st, 2nd, 3rd and 4th generations of tributary channels are fossils, while the 5th and 6th channels are still actively connected to the main channel. In Figure 9, on the 2D multibeam map, we see the continuation of channel 6. The continuations of the channels are in the direction as indicated by Flood *et al.* (2009). A modern channel is evident on the chirp profile 53 (Figure 10). Furthermore, there is a wide older channel underlying the modern one. This probably indicates that, before the modern channel there was another channel in the same direction during low stand. This may indicate that the system is reworking. However one chirp profile is available for this region, and more profiles are required to test this hypotheses.

In this study, 3 different units and 2 erosional surfaces were observed. The main erosional surface, named as α (Aksu *et al.* 2002a; Aksu *et al.* 2002b) delineates Unit 1B which is directly deposited on this erosional surface α eroded by some channels. Unconformity α

truncates the entire south-western Black Sea shelf. Within Unit 2, north dipping reflectors have been interpreted as being related to a sea level drop. This α unconformity is the erosional surface resulted from this sea level drop. Unit 1 rests on all units at the shelf area and has been divided into 4 subunits by Aksu *et al.* (2002a). These 4 subunits were characterised from their geometry and seismic facies' and interpreted as barrier islands linked to sediment waves and current forming these marine bars. Aksu *et al.* (2002a) suggested that these features are transgressive features formed by relatively rapid sea level rise. Similar bodies have been observed on the Ukrainian and Romanian shelves, where they were interpreted as beaches, sand dunes and coastal features surrounding the Black Sea shrunk lake before the flood (Ryan *et al.* 2003; Lericolais *et al.* 2003).

Unit 1 is interpreted as the unit that was settled during the formation of channel system. Unit 1 is located in the core of the fan, and comprises of grey to green mud. It yield an uncorrected ^{14}C age of 6700y BP (Giunta *et al.* 2007). Unit 1B is present from the inner to the outer shelf, while Unit 1 forms the upper unit of the fan system. Therefore, Unit 1B has different age and formation conditions than Unit 1, and cannot be considered a subunit of Unit 1. The craggy surface of α indicates that, a huge amount of water carrying grained material entered to the Black Sea.

The features that are interpreted as ridge-style features, are increasing in number towards the shelf edge. That is probably related to the increase of the current velocity at the shelf edge. While the current velocity is 70 cm.s^{-1} at the exit of the İstanbul strait, it reaches 90 cm.s^{-1} at the shelf edge (Özsoy *et al.* 1995). The current velocity map published by Ozsoy *et al.* (2001) shows that the direction of the channels are compatible with the directions of currents at the Black Sea exit of the İstanbul strait. Accordingly, the distribution of the directions of the channel system is directly related with the current entering the Black Sea from the Marmara Sea. Also, on recent bathymetric maps published by Flood *et al.* (2009), it is clear that some of the levees are affected by outgoing active currents issued from the Bosphorus. This could only happen in a hydrodynamic background which is today still rather active.

Mounds recognised in this study present acoustic masking or chaotic infilling. Masking might be related to high reflectivity. Equivalent mounds were interpreted as mud volcanoes by Aksu *et al.* (2002a). The core B2KS02 was recovered from such a mound having a weak acoustic masking. No gas indication was observed in the core sediments. Therefore, according to our data, these kinds of structures which are present on the middle shelf area can not be interpreted as mud volcanoes. However, we observed other mud volcano resembling structures on other profiles which are not shown in the given study area (Okay *et al.* 2006). The box on the bathymetric map in Figure 2a, shows the location of mud volcano resembling structures.

The core B2KS02 has dated the base of Unit 1 at 6700 y ^{14}C BP, allowing us to estimate that water input was synchronous with the onset of Unit1. Besides the dating of the fan, the core supplied a major information vital to the understanding of the formation of the fan. The strong concentration of benthic foraminifera at the base of this unit indicates that Mediterranean water brought these elements while penetrating into the Black Sea. This hypothesis questions the previous theories which support a reconnection without high energy and a rapid equilibrium between the two way currents. In the present two way flow regime, benthic foraminifera are rare in the Black Sea. The drop in concentration of the benthic foraminifera around 4 meter deep in the BSKS02 core of Unit 1, is interpreted to be linked to a drop in salinity after the reconnection as the two water bodies entered into equilibrium (two way flow).

The observed wedge at the shelf edge is thought to be formed during the sea level drop when α was formed (Figure 7). The wedge contains downlapping clinoforms and the top of

the prograding horizon is truncated by α_1 surface, indicating that this region was exposed to a sea level drop immediately after a sea level rise.

Except from these structures, some paleo canyon heads were also observed near the shelf edge area. The preservation of these canyon heads, also led us to assume a rapid increase in Black Sea level. In case of slow increase, these structures should have been eroded by the strength of ravinement.

High resolution chirp data in addition with dating show that, after the last low stand the southwestern Black Sea shelf was drowned by Mediterranean waters. Figure 11 outlines a likely scenario to describe the reconnection between the Black and Marmara Seas since last glacial maximum. A low stand systems tract was set at -110 m, with a first erosion surface α on the shelf during the glacial maximum (Stage B). After the LGM (Stage B) ice began to melt around 18 000y BP and flow of big rivers; Dniepr, Dniestr, Bug and Volga increased. Also, melted ice from the Alps fed the Danube. Such phenomena were accelerated after the melt water pulse 1 MWP1 (14 500 Cal yrs BP or 12 500y ^{14}C BP). This transgression raised the level of the Black Sea (Black Sea basin was a closed basin at that moment) by 80 m until reaching the -30/-40 m isobaths. It's not obvious whether the sea level of Black Sea reached to a level which is higher than the Bosphorus sill and whether fresh water of the Black Sea passed into the Marmara Sea but some clues such as studies on fauna seem to agree with this hypothesis and are coherent with recent publications about Marmara Sea studies (Eris *et al.* 2007). Unit 1B was deposited during high stand period.

After the melting stage, (Stage C) Black Sea level began to decrease and a second low stand systems tract between -80m and -100m led to a second erosion surface α_1 on the shelf. Evidence of this decrease includes dated Unit 1B (William Bill Ryan, pers. comm. 2008, 2009). This unit is not existent on everywhere on the shelf, a big erosive phase probably truncated most of the unit. The age of this low level from this analysis is between 11 410y ^{14}C BP and 10 640y ^{14}C BP (uncorrected ages).

Finally, based on the age data from the dating of core B2KS02 we can affirm that Black Sea received salty water from the global ocean at 6700y ^{14}C BP. It is not clear whether this event happened catastrophically, but the two way connection previously proposed by anti-catastrophes cannot explain how that such amount of material have been moved to form such a big shallow fan.

For Stage D, studies show that around 6700 yr C^{14} BP the Black Sea received a big amount of salty water, most likely associated with high energy. In addition, we propose that the Unit 1 sediments came from eroded material of the Bosphorus strait. It is difficult to imagine the influx of such volumes of sediments provided in a short period of time without a strong reconnection. If, as clearly shown by this study, there was a major transgression of the Black Sea 6700 y ^{14}C BP, this last increase of water was not catastrophic. In particular, more detailed data from the area between the İstanbul Strait and the fan would allow us, how the fan material has been provided to the shelf.

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7. Figures

Figure 1. Multibeam bathymetry map of the study area. Multibeam bathymetry acquired during Blason2 survey is combined with existing bathymetry of Di Iorio and Yuce (1995)

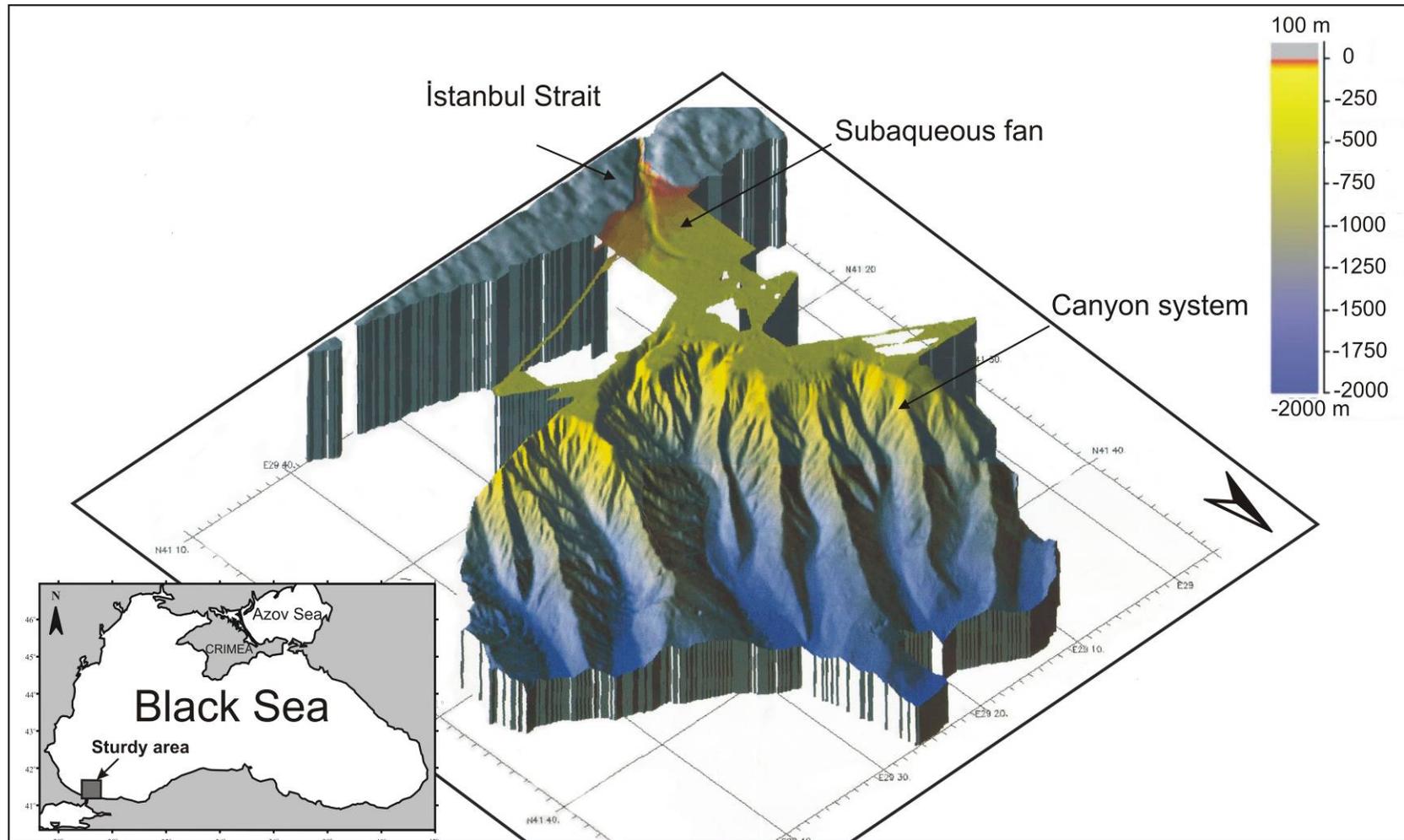


Figure 2. (a) Bathymetric contour map of the study area. The marked black box shows only the location of mud volcano resembling structures area.

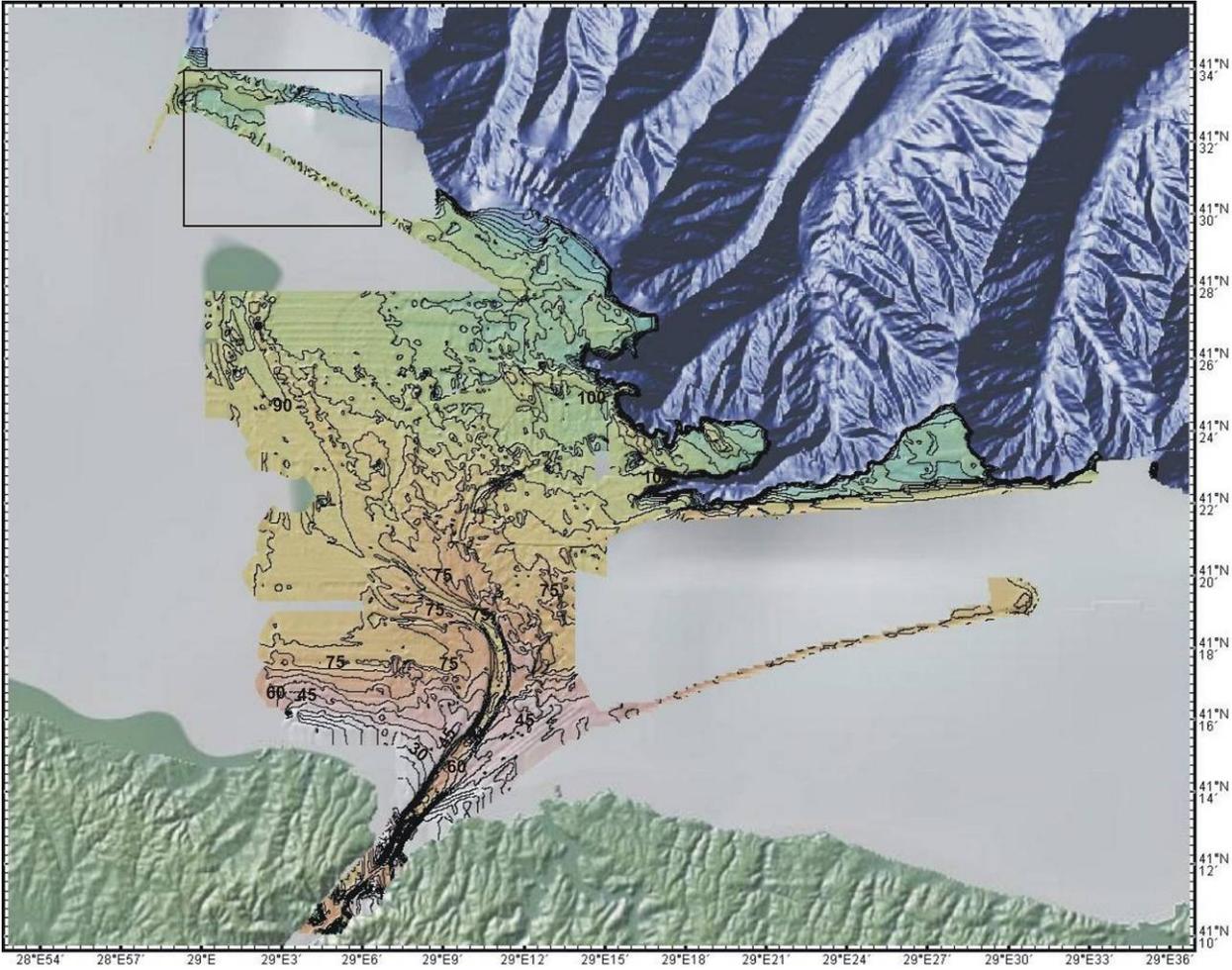


Figure 2. (b)2D multibeam bathymetry map of the shelf fan. Solid lines illustrate the high resolution seismic (chirp) profiles of the shelf fan area and numbers belong to the channel numbers. The star icon shows the location of the core which is used for dating.

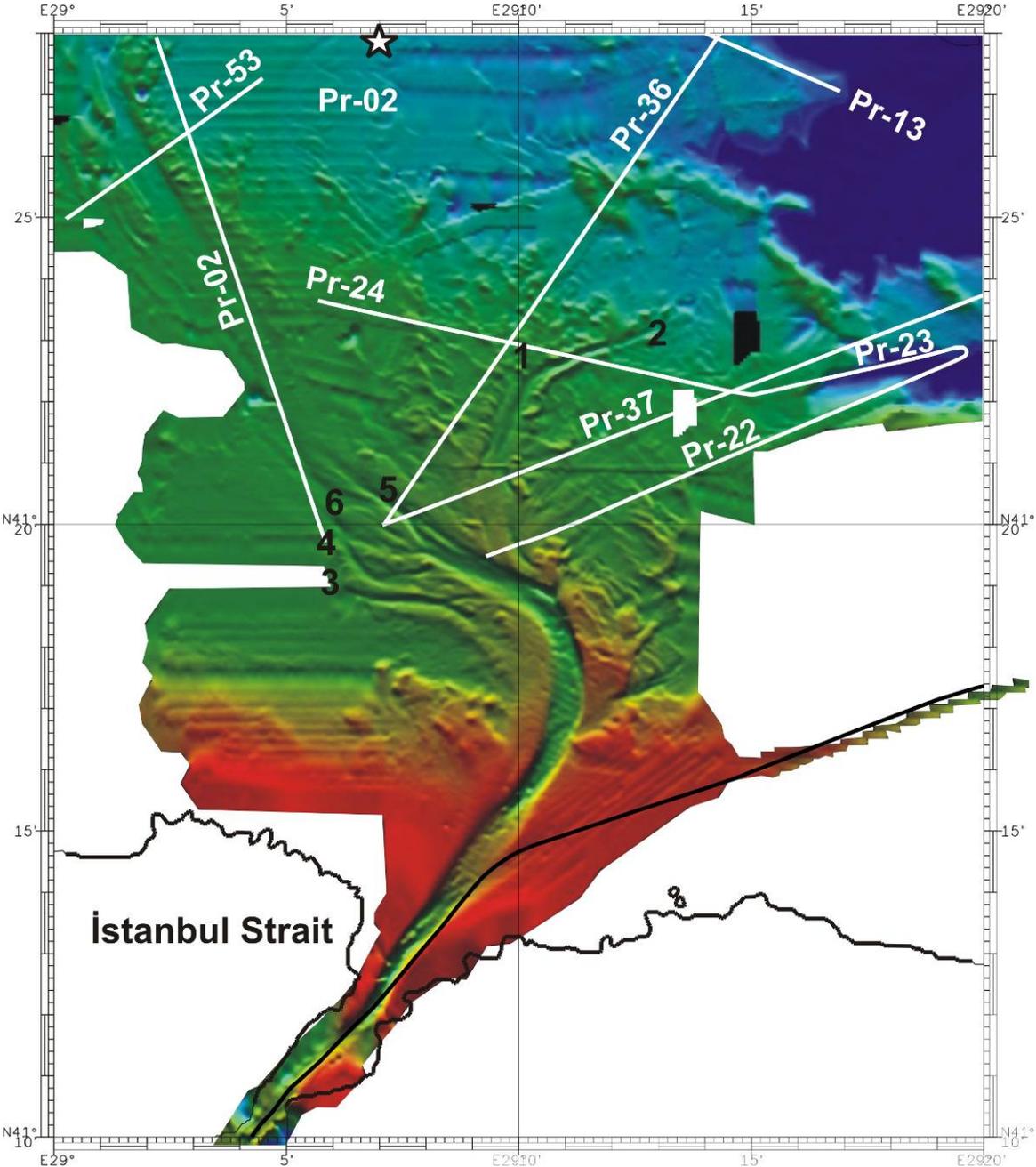


Figure 3. Visualization of ridges on the multibeam bathymetry map showing perpendicular ridges to the channels of the fan and asymmetric ridges at the distal part.

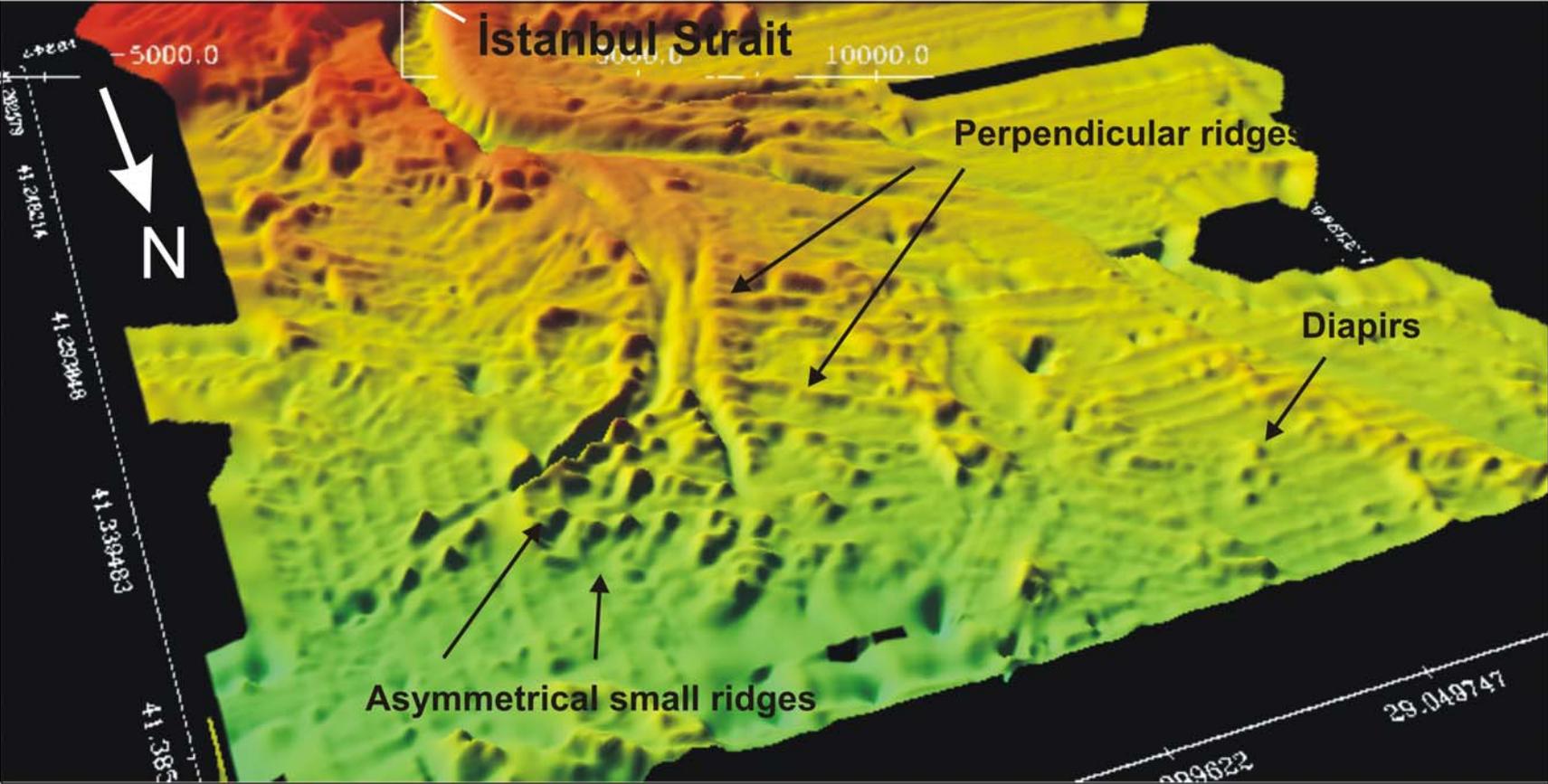


Figure 4. (a) Part of seismic section Pr-24 across the channels 1 and 2 of the fan.

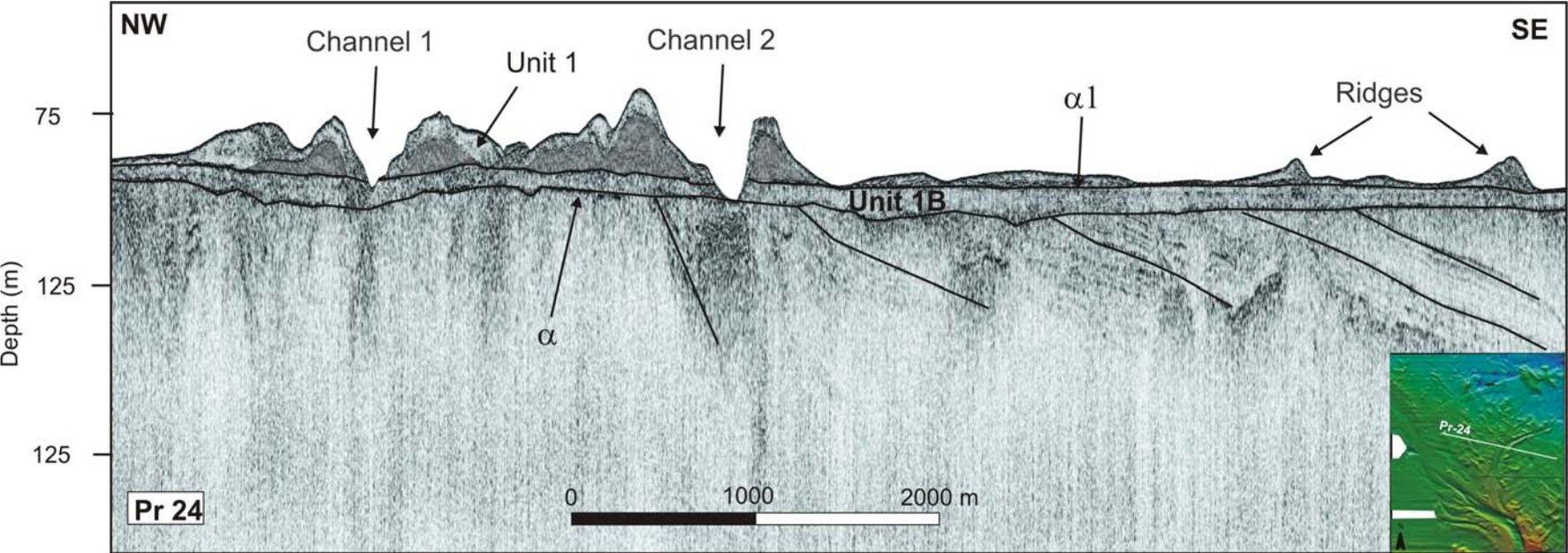


Figure 4. (b) Shelf part of profile Pr-36 which cuts the whole study area in SW-NE direction, crossing channel 1. Ridges are situated on the levees of the channel.

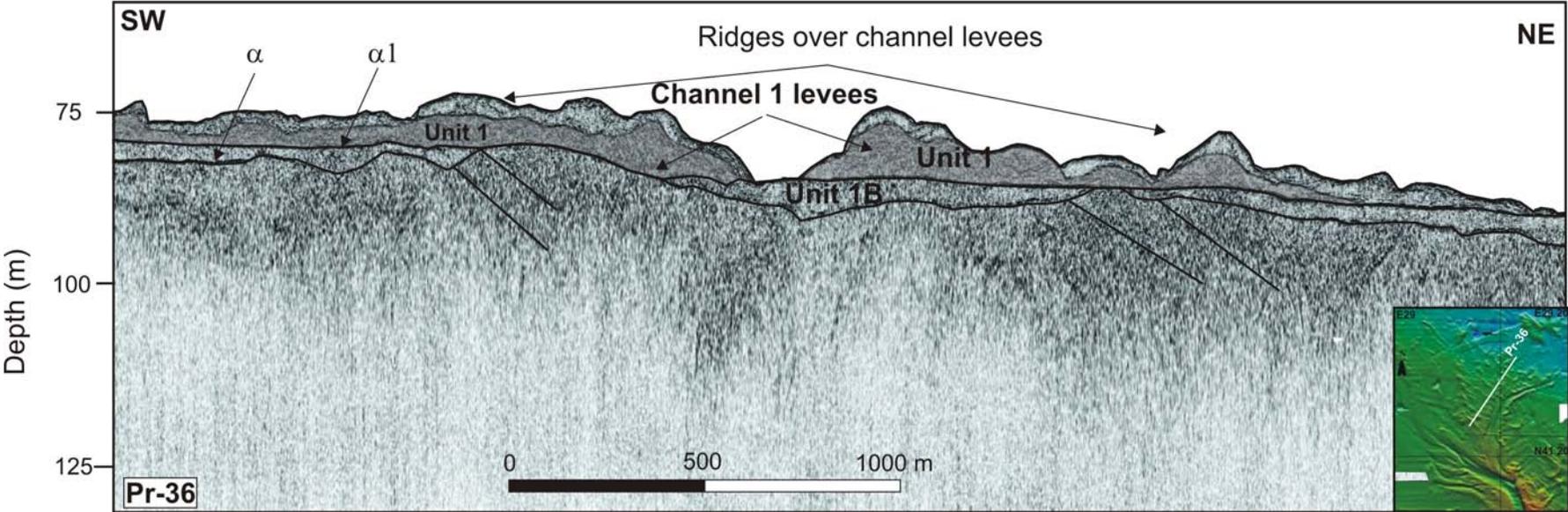


Figure 5. (a) Seismic structure model of the shelf fan, on a profile cutting the fan in SW-NE direction. Four different units are interpreted. Unit 3 is the basement unit, Unit 2 consists of seaward prograding reflectors and it toplaps to upper unit, Unit 1 B has a chaotic structure and Unit 1 which is deposited during the formation of the fan. α and α_1 are different unconformity surfaces.

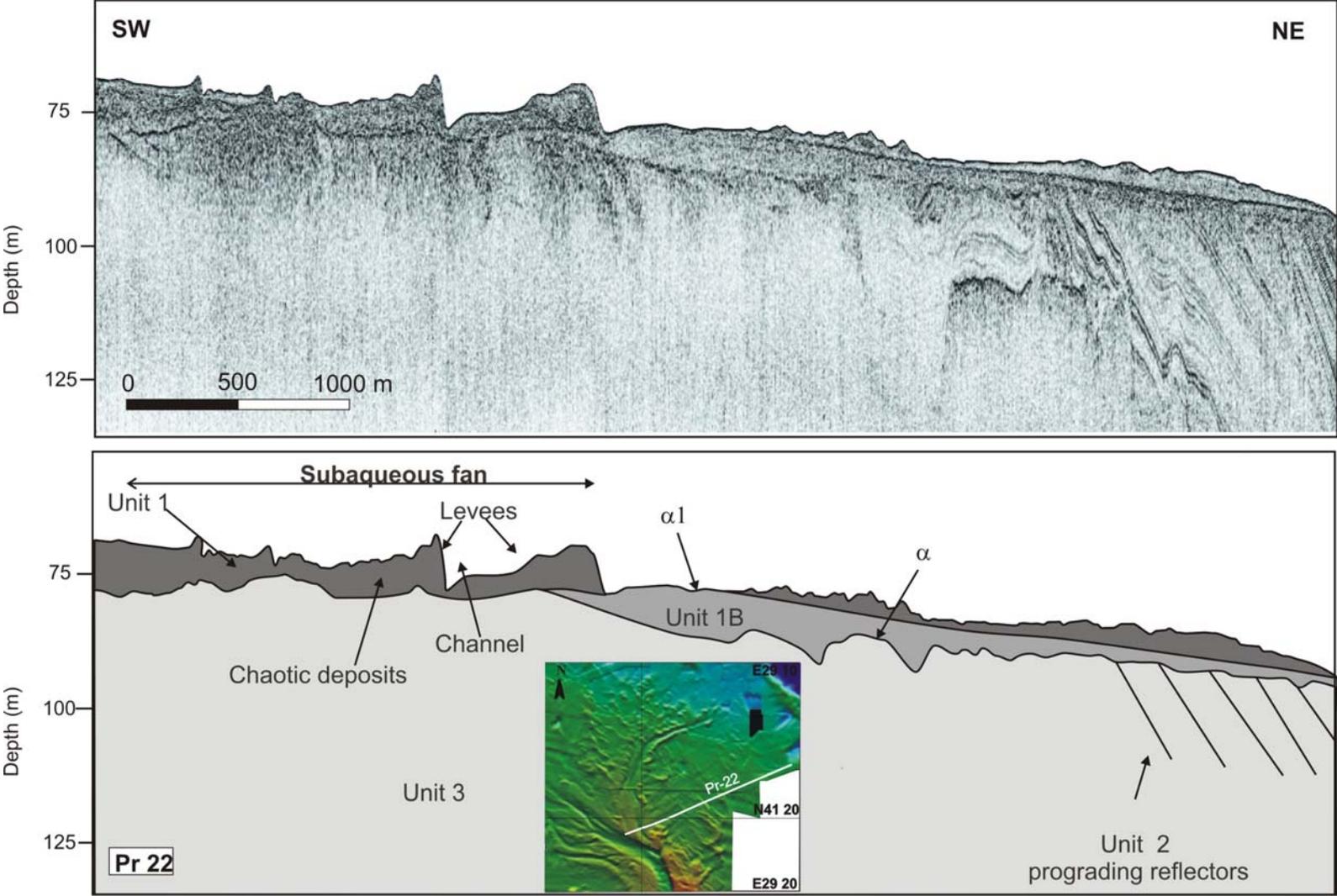


Figure 5. (b) Seismic section Pr-2 across channels 3 and 4 where Unit 1B does not exist.

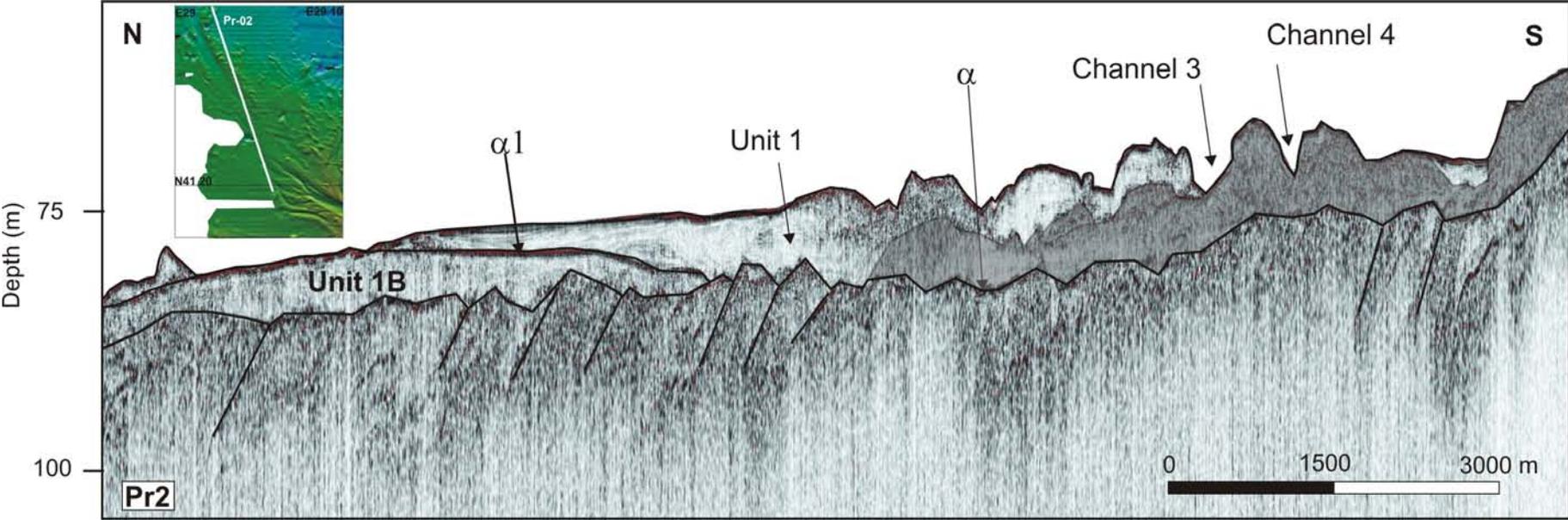


Figure 6. (a) Sediment thickness map of Unit 1B.

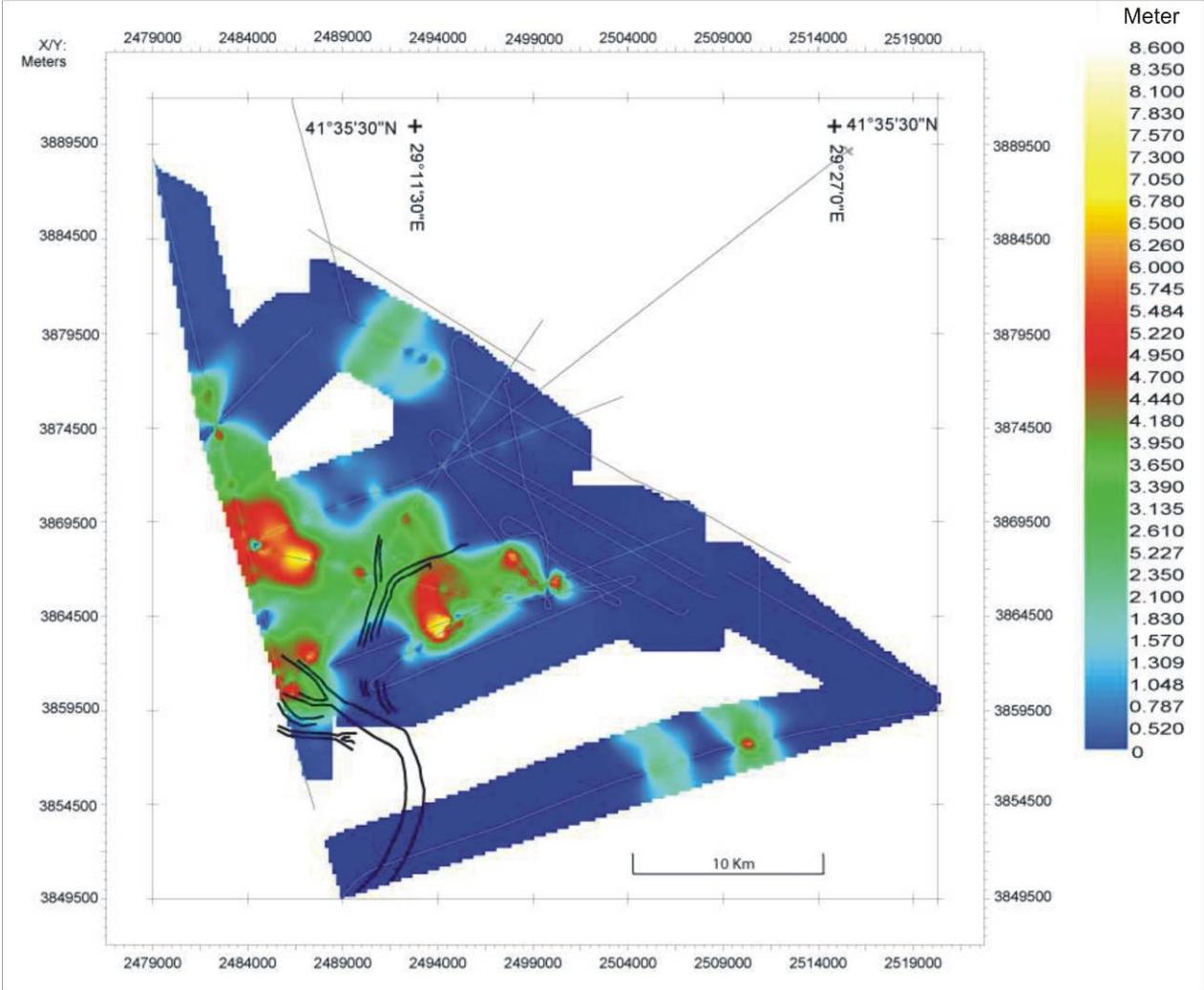


Figure 6. (b) Sediment thickness map of Unit 1.

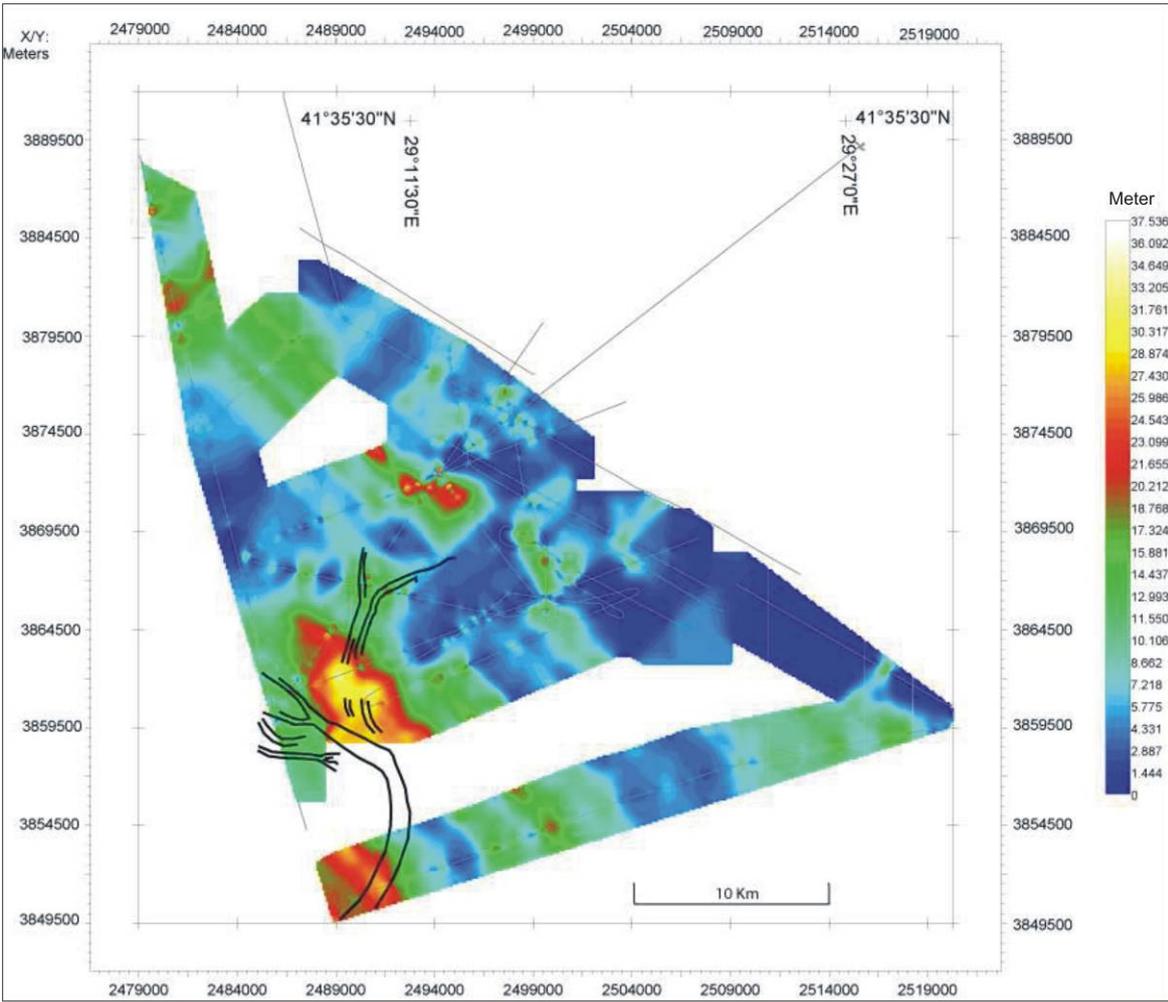


Figure 7. Lowstand wedge on seismic section Pr-13 indicating old shoreline at LGM.

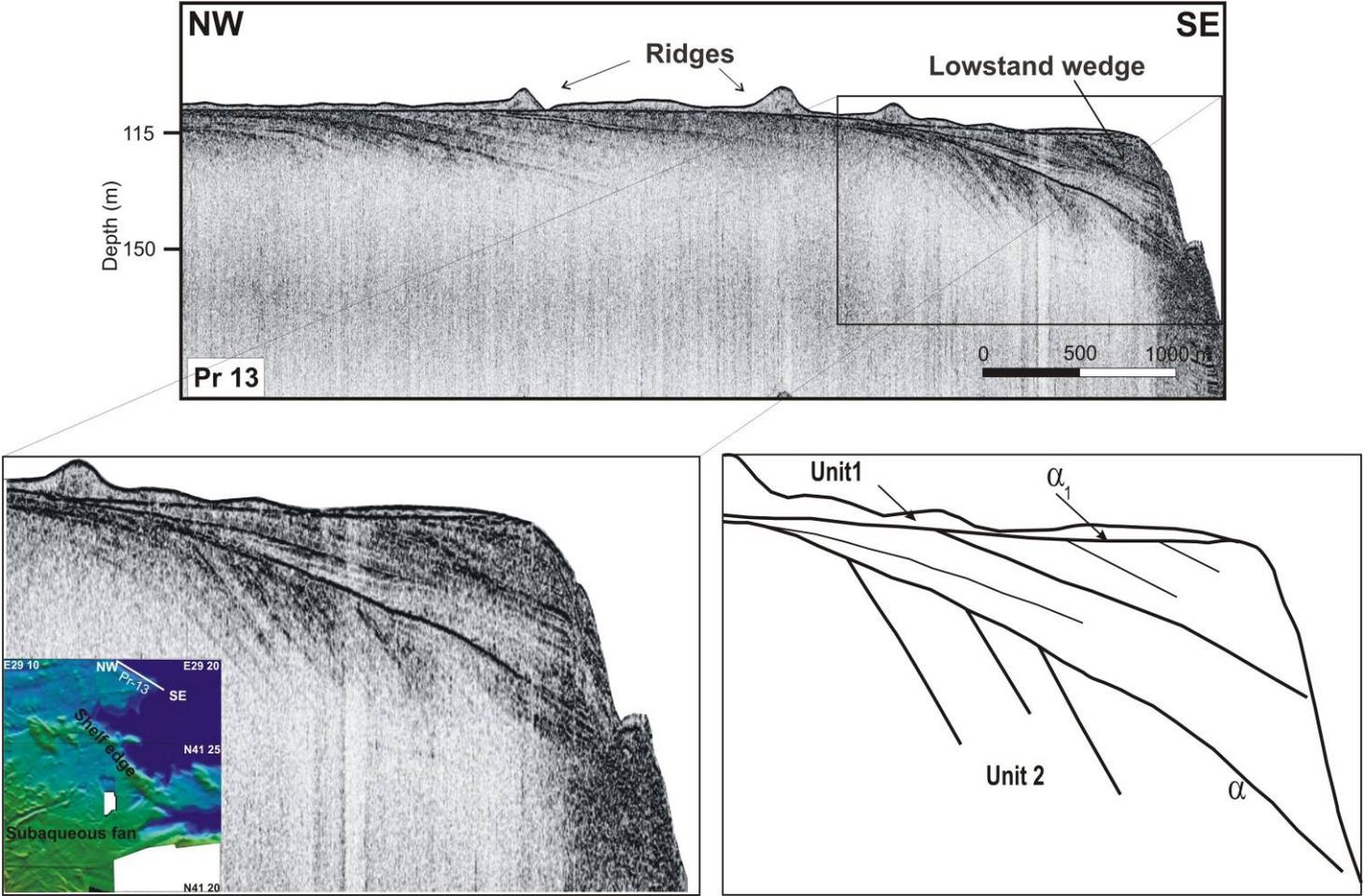


Figure 8. Benthic foraminifera in core B2KS02.

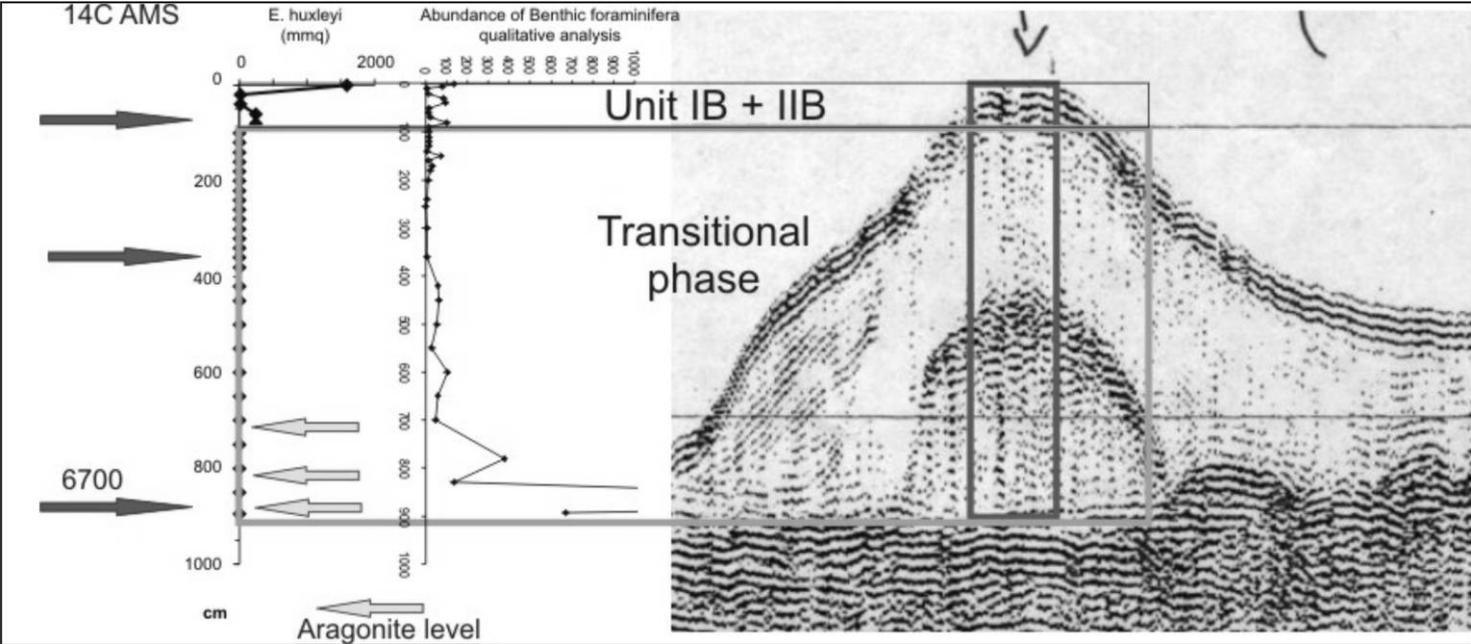


Figure 9. Drawing of the shelf fan's channels. Numbers show the channel numbers in the order of activity. Now Mediterranean flow is active in channels 5 and 6.

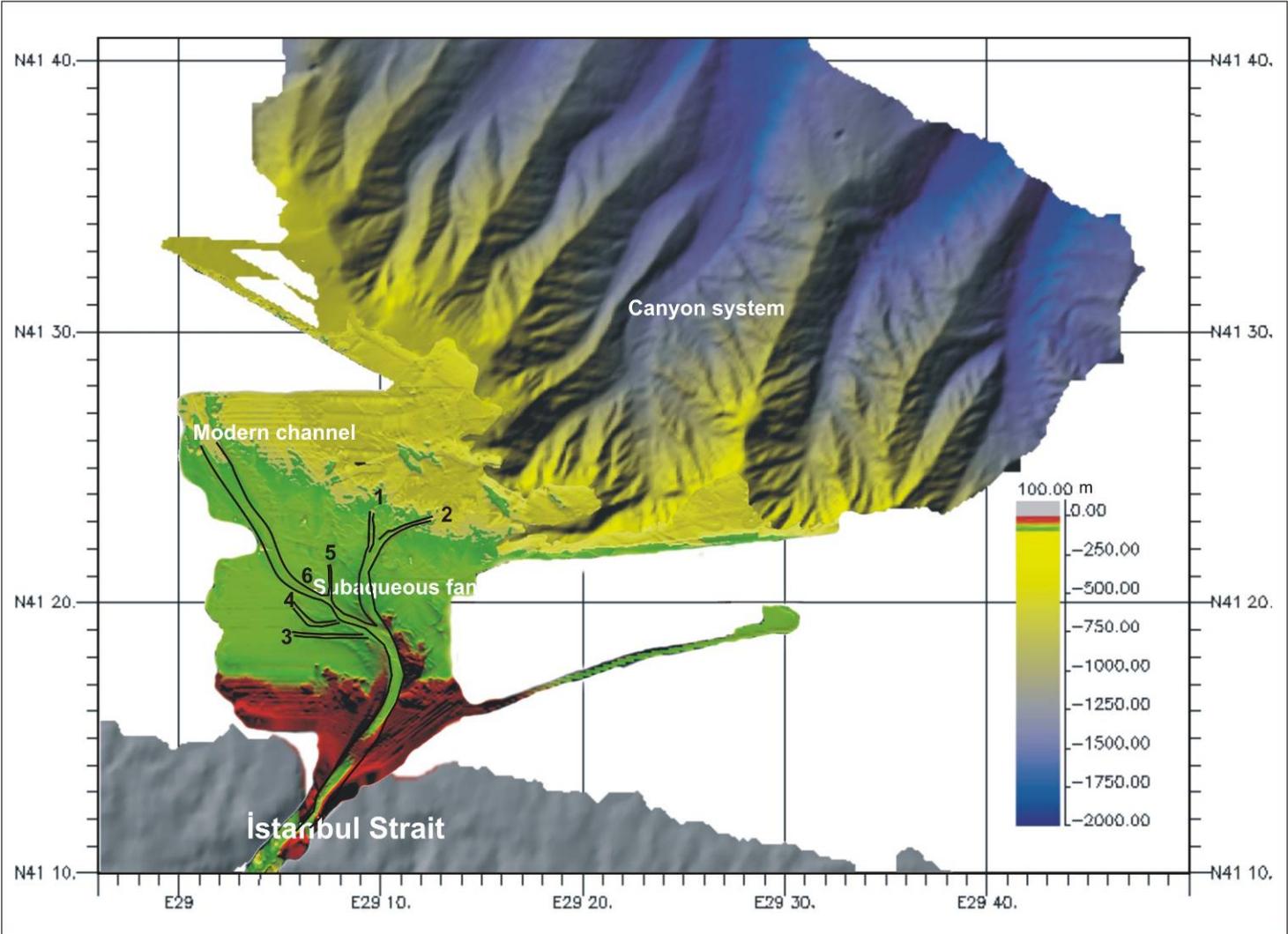


Figure 10. Chirp profile 53, passing through the modern channel.

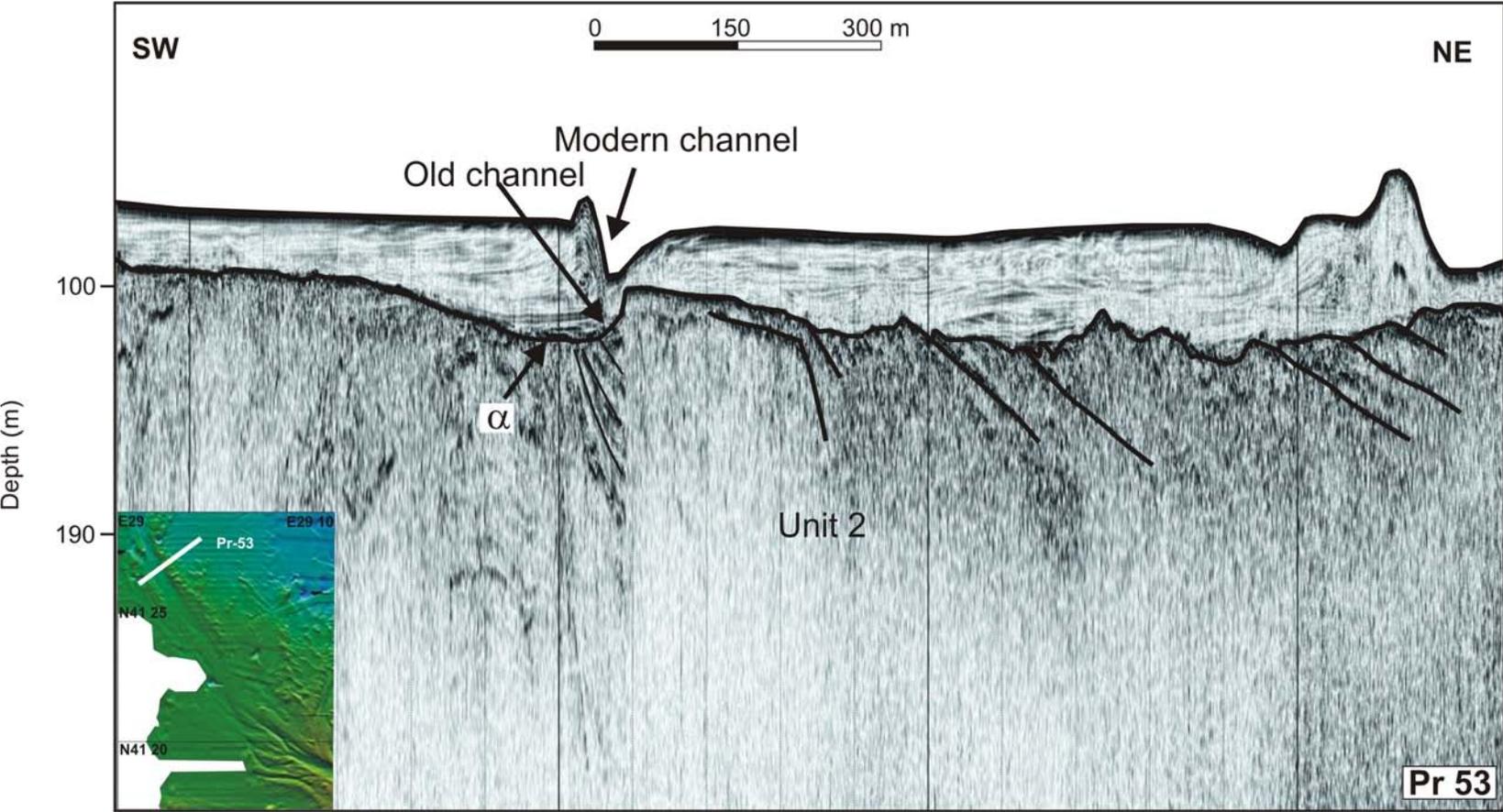
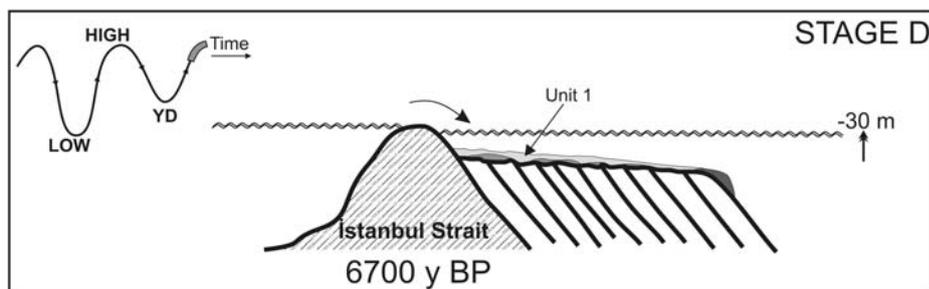
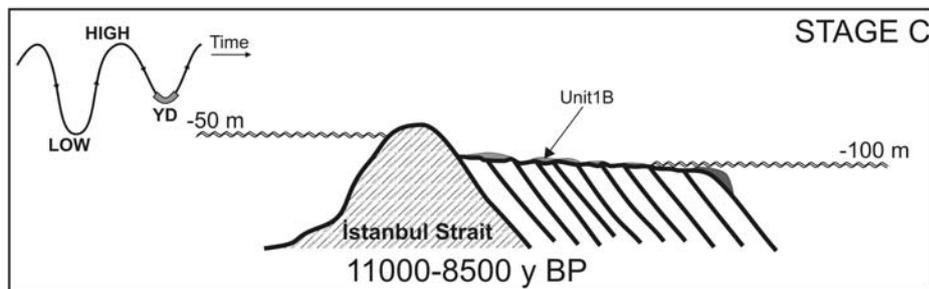
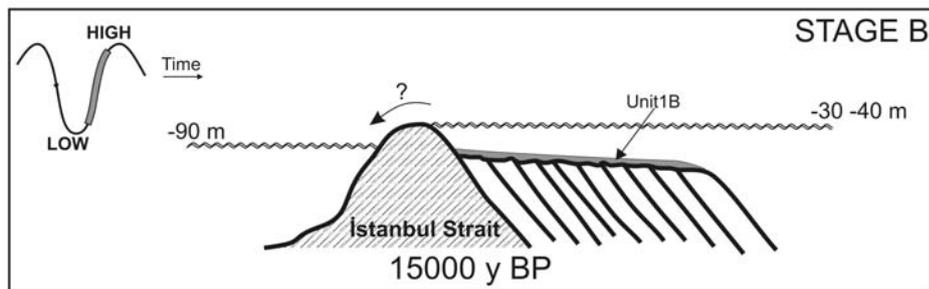
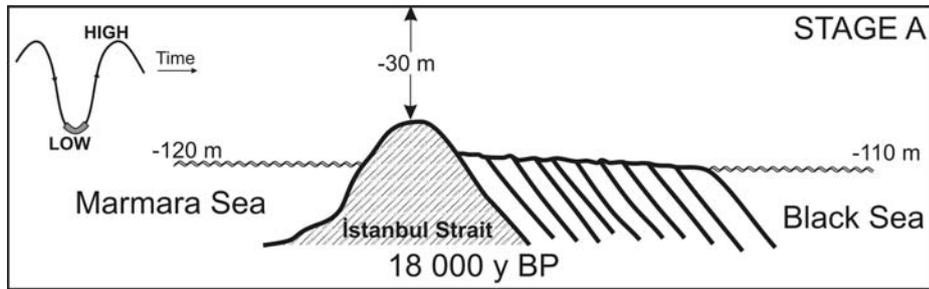


Figure 11. Schematic representation of the stages of the connection between Black Sea and Marmara Sea since Last Glacial Maximum.



8. Tables

Table 1. Location and parameters of core B2KS02 used in this study

Core	B2KS02
Type	Kullenberg
Cruise	BLASON2
Latitude	41°29.734
Longitude	29°07.550
Water depth(m)	88.8
Sediment recovery	9.07
Studied core length(cm)	907

Table 2. Sample type for ¹⁴C AMS dating in core B2 KS02

ID number	Core	depth cm	Sample type	weight (gr)
1	B2KS 02	80-81	Bivalves	0.07
2	B2KS 02	350-351	Bivalves	0.16
3	B2KS 02	875-876	<i>Hydrobia</i>	0.16
4	B2KS 02	875-876	<i>Ammonia beccarii</i>	0.05
5	B2KS 02	893-894	<i>Hydrobia</i>	0.08