Turkish Journal of Earth Sciences (Turkish J. Earth Sci.), Vol. 20, 2011, pp. 287–305. Copyright ©TÜBİTAK
doi:10.3906/yer-1001-16 First published online 14 June 2010

TÜBİTAK

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

SEDA OKAY[1], BENOIT JUPINET[2], GILLES LERICOLAIS[3], GÜNAY ÇİFÇİ[1] & CATHERINA MORIGI[4]

[1] Institute of Marine Sciences and Technology, Dokuz Eylül University, Bakü Bulvarı No: 32, İnciraltı, TR–35340 İzmir, Turkey (E-mail: seda.okay@deu.edu.tr)

[2] UMR 6538 – Domaines Océaniques, UBO-CNRS, IUEM, Place Nicolas Copernic, 29280 Plouzané, France

[3] IFREMER- Centre de Brest, DCB/GM, BP 70, 29280 Plouzané cedex, France

[4] Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark

Received 20 January 2010; revised typescripts receipt 22 May 2010 & 07 June 2010; accepted 14 June 2010

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 C^{14} 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 onlapping 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.

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

İstanbul Boğazı Karadeniz Çıkışındaki Holosen Sualtı Şelf Fanının Morfolojik ve Yapısal Özelliklerinin İncelenmesi

Özet: BlaSON projesi kapsamında, 2002 yılında, araştırma gemisi RV 'Le Suroit' kullanılarak yapılan bu çalışmada, İstanbul Boğazı'nın Karadeniz çıkışı EM300 çok ışınlı ekosounder ve chirp-yüksek ayrımlı sismik sistemi kullanılarak haritalanmıştır. Bu verilere ek olarak, NATO SACLANT Denizaltı araştırma projesi kapsamında NATO'ya ait RV Alliance ve Türk Askeri Araştırma gemisi 'Çubuklu' kullanılarak Boğaz ağzında toplanan bu akustik görüntüleme verileri ışığında, boğaz çıkışında yer alan şelfte, sualtı fan sistemi ortaya konulmuştur. Çok ışınlı ekosounder, ultra yüksek ayrımlı sismik profiller ve karot korelâsyonları, morfolojinin tekrar ortaya konması ve yüksek enerjili tortul taşınımı göstergesi olan tortul dağılımı paternlerinin ortaya konmasını sağlamıştır. Boğaz çıkışındaki şelfte bu sistemin varlığı ve Boğazın ağzındaki kanalın devamı olarak yer alması, büyük miktarda ani su girişinin olduğunu kanıtıdır. Bu sualtı fanının tabanından elde edilen yaş tayini ve tabanda görülen ilk denizel yumuşakçaları için elde edilen 6700 yr C^{14} BP yaşı (düzeltilmemiş), Marmara Denizi ve Karadeniz'in son olarak ve ani şekilde tekrardan birleşmesi ile uyum içerisindedir. Şelf ve yamacın ayrıntılı morfoloji haritası, yapılan sismik profil yorumları ve karot korelasyonları ile birlikte incelenerek bu fanın oluşumu ve bu oluşumun Son Buzul döneminden sonra Marmara Denizi ve Karadeniz arasındaki son bağlantının kurulması ile ilişkisini açıklayan bir sentez ortaya konulmuştur ve aşağıdaki gibi özetlenmektedir: Evre A, son buzul dönemi düşük su seviyesi ile ilişkili erozyonel yüzeye karşılık gelmektedir, Evre B, –30–40 m ye onlap yapan aşınma yüzeyidir, Evre C, su seviyesi düşmesiyle bağlantılı ikinci erozyonel yüzey olup, altta ikinci birim olan Birim 1B'yi traşlamıştır, Evre D, Boğaz'dan Karadeniz'e büyük miktarda boşalan su ile birlikte oluşan sualtı fan sistemine denk gelmektedir. Ayrıca bölgenin batimetri haritasından faydalanılarak, bu fan sisteminde gözlenen avülsiyon kollarının varlığı (kanallar) fanın uzun süre aktif olduğunu kanıtlamaktadır.

Anahtar Sözcükler: çok ışınlı ekosounder, yüksek ayrımlı sismik, deniz seviyesi değişimleri, yüksek enerjili Akdeniz suyu girişi, sualtı fanı

Introduction

The opening of the Bosphorus, which connects the Mediterranean and Black seas, played an important role in the 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 confuse many non-specialists. One 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 misinterpretation 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., figure 5 in Yanko-Hombach *et al.* 2007). Different transgressive-regressive phases within the Holocene have been published (Balandin & Trashchuk 1982; Arslanov *et al.* 1983; 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 metres 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 into a state of confusion. However it is clear that to a certain extent the level of the Black Sea followed the regional climate modification more than 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 Ryan *et al.* (1997) published the 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 the participants in the controversy the most important were Aksu, Hiscott and co-authors (Aksu *et al.* 1999, 2002a, b, c; Hiscott & Aksu 2002; Hiscott *et al.* 2002, 2007).

Since 1998, the Black Sea has been surveyed under 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), supported by a NATO SACLANT Undersea Research project, using jointly the NATO RV Alliance, and the Turkish Navy Survey ship 'Çubuklu'. Here, we present a detailed morphological map of the entire area off the Bosporus outlet, together with very high resolution seismic (Chirp) data correlated to core analyses and dating, providing a better characterisation of subaqueous fan at the mouth of the Bosphorus.

Data Acquisition

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 & Yüce (1999) in a NATO SACLANT Undersea Research project using jointly the NATO RV Alliance and the Turkish Navy Survey ship 'Çubuklu'. 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' as part of the eponymous project. The location and parameters of core B2KS02 used in this study are given in Table 1.

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

The Subaqueous Shelf Fan: the Last Connection Between Black Sea and Marmara Sea

Morphology of the Shelf Area

The morphology of the İstanbul Strait outlet shelf area was derived from data acquired funded by a 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 channel trends NE–SW and then turns NW–SE on the shelf area (Figure 1). Figures 2 and 3 present the 2D bathymetric and contour map of the area, together with the profile locations. Water depth is about 30 m in the İstanbul Strait and between 30–45 m where channel banks are prominent. Towards the middle shelf, water depth reaches 75 m on both sides of the channel. The distal part of the channel system abruptly turns northwest when reaching the mid-shelf. Figure 3 presents this channel system on the combined multibeam echosounder map of the bathymetric data acquired on the proximal shelf in the NATO project, with the Ifremer data collected during the BlaSON2 project at the shelf edge down to the foot of the slope.

This channel system consists of 1 main and 6 secondary channels. 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 turns 90° and trends NW around latitude ~ 41°20´N. In addition to the main channel six other secondary channels can be followed. The depth of the 800-m-wide main channel ranges between 30 m and 50 m.

Two other distinctive sedimentary features have been recognised on the shelf area (Figure 4). The first

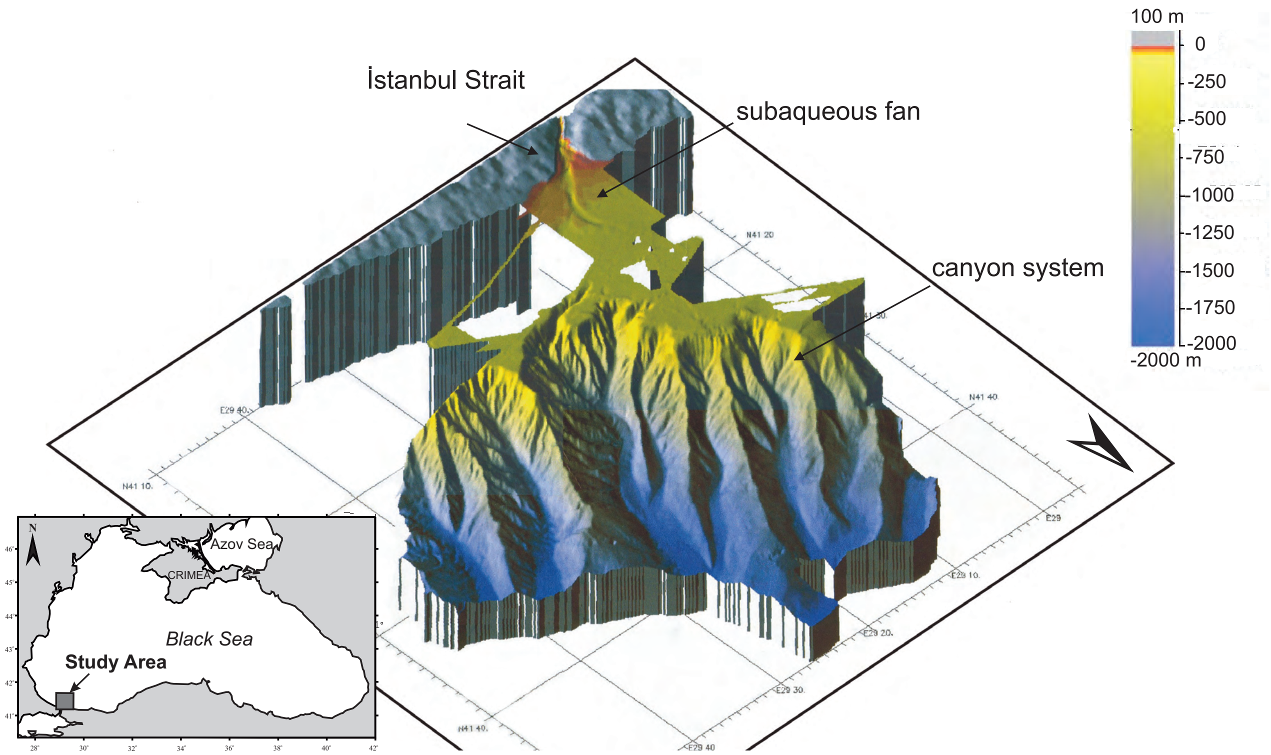

Figure 1. Multibeam bathymetry map of the study area. Multibeam bathymetry acquired during Blason2 survey is combined with existing bathymetry of Di Iorio & Yüce (1995).

features, characterised by their shape and trend, are interpreted as ridges, which are classified into two types:

(1) Type 1 ridges are perpendicular to the channel axis, are randomly distributed and occur at the distal end of channels 1 and 2. Their heights vary between 1 to 7 m, and their morphology and stratigraphy indicate that they formed after the formation of the channel levees.

(2) Type 2 ridges are asymmetrical and occur at the distal part of the fan system itself. Their heights vary between 1 and 5 m, and never exceed 10 m. The distances between them vary between 200–1000 m and they have been recognised within small groups or arranged into lines (Figure 4). These asymmetrical ridges correspond to diapir-like forms around the channel system, which are generally randomly distributed away from the system, and have circular outlines.

Seismic Interpretation of the Structures on the Shelf Area

Channel-Levee System– Many channels are visible on the bathymetric map (channels 1–6, Figure 4; channels 1–2 in Figure 5). Younger and incisive (sharp) channels are visible on channel banks. In Figure 5, profile P24 transects these two types of channels. On the seismic section two erosional surfaces are recognised, corresponding 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. Erosional surface α_1 and Unit 1B disappear at the bottom of the channels.

The fact that these channels are empty might indicate either that they are still active or there is not enough sediment supply for deposits to fill them. They also present a meandering pattern, and their sides are levees formed in a period of overbanking.

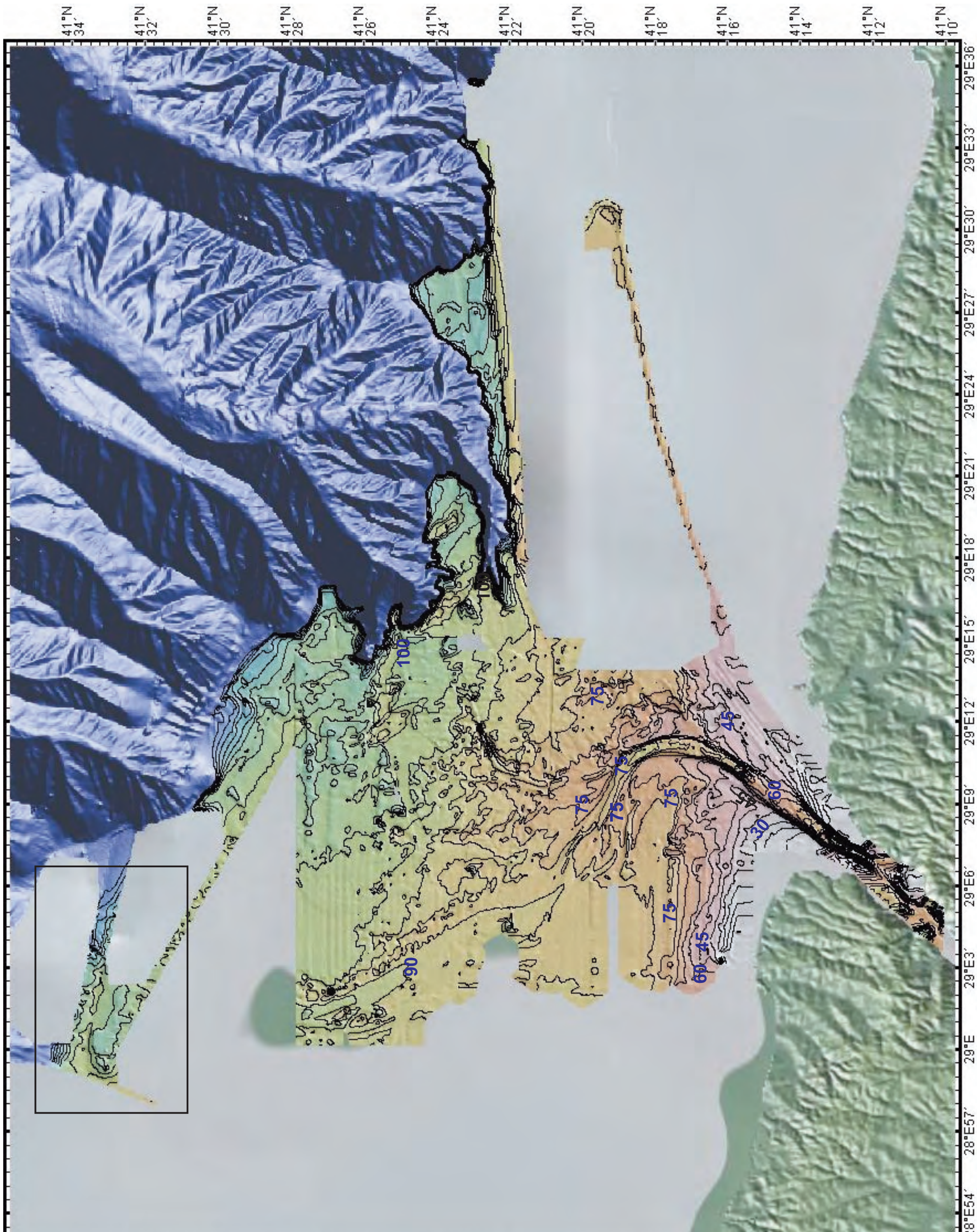

Figure 2. Bathymetric contour map of the study area. The marked black box shows only the location of structures resembling mud volcanoes.

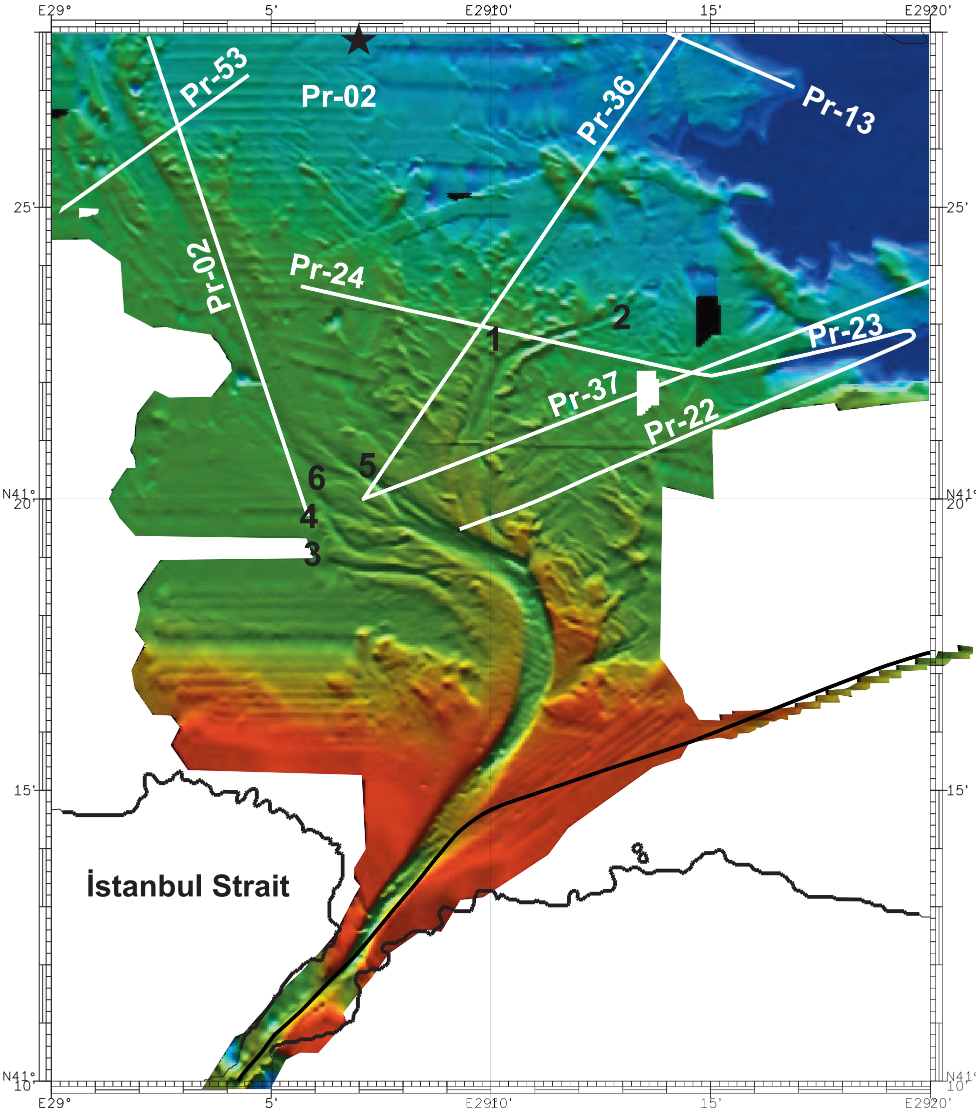

Figure 3. 2D multibeam bathymetry map of the shelf fan. Solid lines illustrate the high resolution seismic (chirp) profiles of the shelf fan area and numbers belong to the channel numbers. The star icon shows the location of the core which is used for dating.

Ridges– In its southwestern part, profile 24 crosses ridges superimposed on channels 1 and 2 (Figure 5). The profile passes through the western ridges, shown on the multibeam echosounder map (Figure 4), which are perpendicular to the main channel of the system.

The tops of these ridges are veneered by recent (Holocene) sediments. These ridges rest on erosional surface α_1 and were defined as barrier bars by Aksu *et al*. (2002a). They have a characteristic inner structure, with a gentle stoss side slope and a steeper lee side slope. In profile they are about 7–20 m high and 200–300 m wide. There is approximately 1 km between each ridge. Towards the shelf edge these ridges become smaller (3–5 m high) and are only a few tens of meters wide. However, this increase could be related to the increase in flux (flow rate) towards shelf edge. Figure 6 shows part of profile 36 that crosses some of the ridges seen on the levees. These are very small and are more closely spaced than

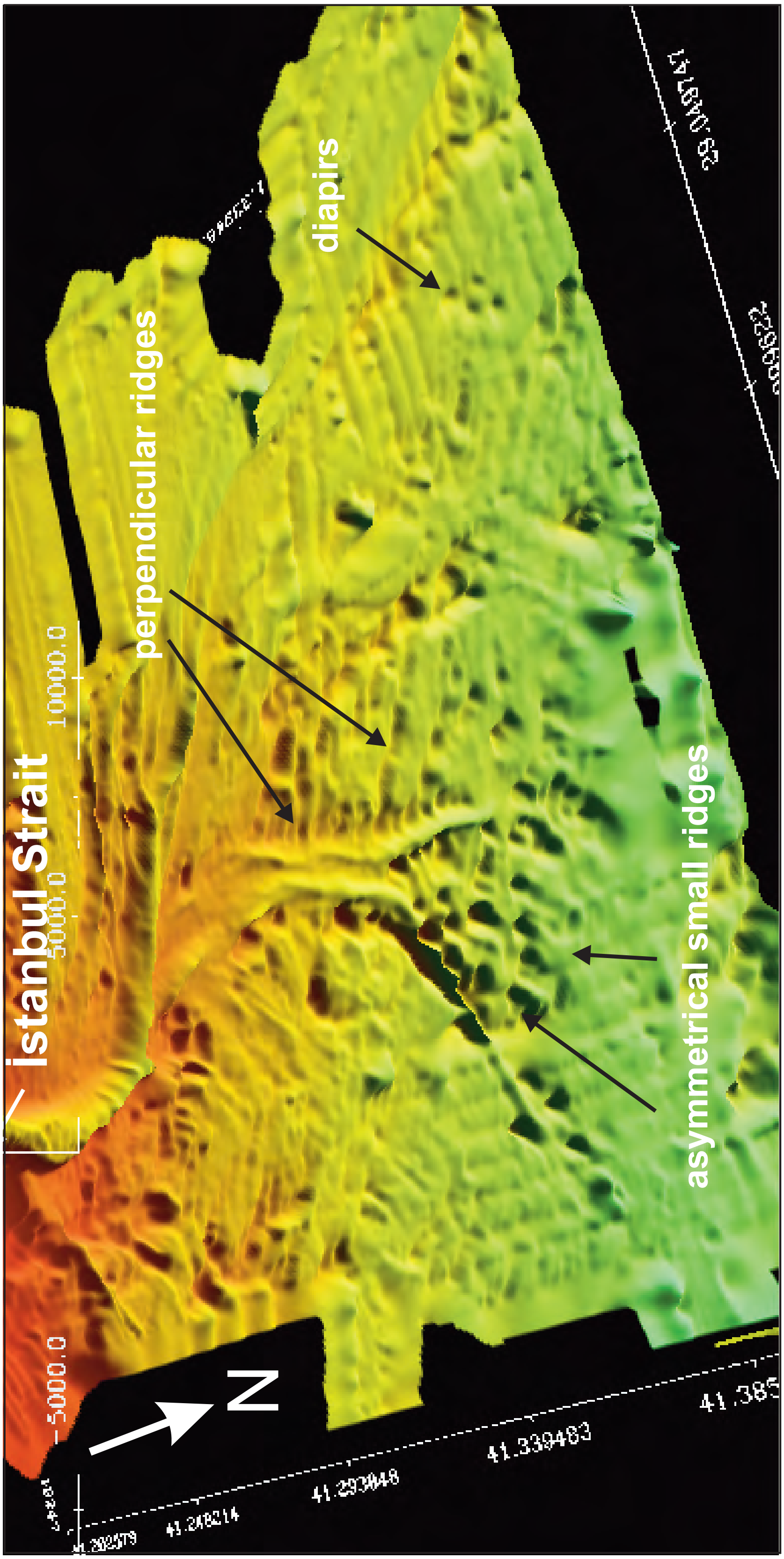

Figure 4. Visualization of ridges on the multibeam bathymetry map showing ridges perpendicular to the channels of the fan and asymmetric ridges at the distal part.

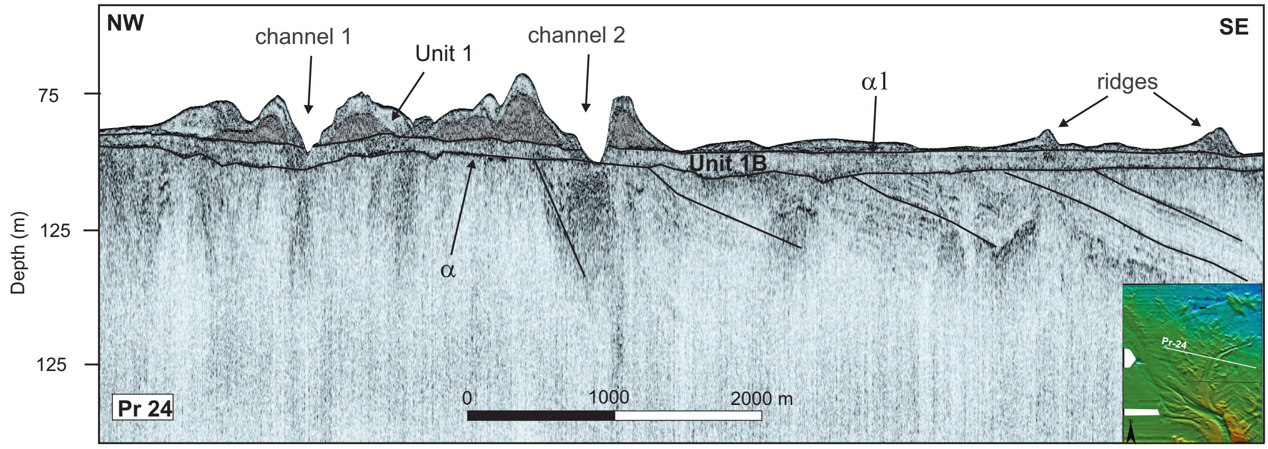

Figure 5. Part of seismic section Pr-24 across the channels 1 and 2 of the fan.

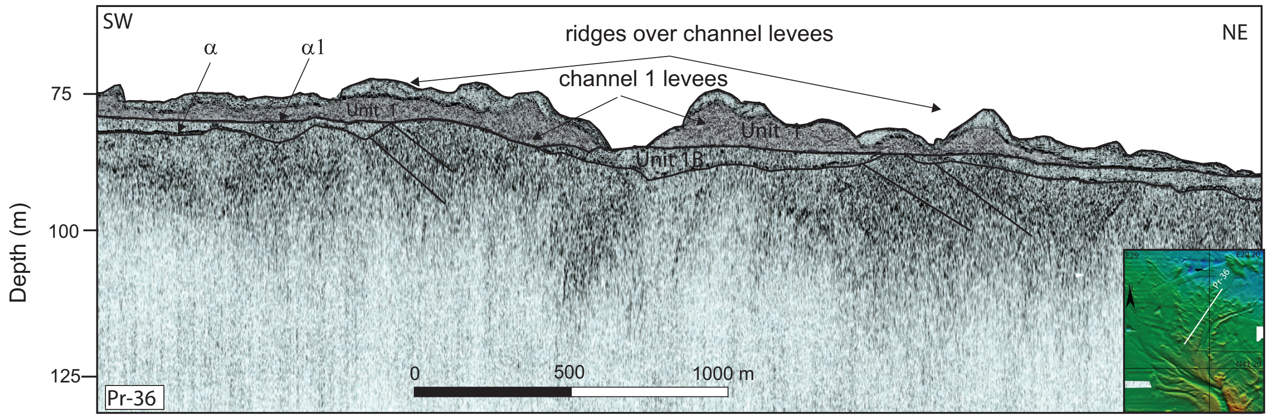

Figure 6. Shelf part of profile Pr-36 which cuts the whole study area in SW–NE direction, crossing channel 1. Ridges are situated on the levees of the channel.

the ridges on shelf part (parallel ridges to the main channel). Profile 36 trends almost parallel to channel 1 with a high angle (~20° to normal), in order to see the levees longitudinally cut. The inner structures of these ridges are chaotic, with high reflectivity causing acoustic masking of the underlying sediments.

Seismic Stratigraphy of the Channel System

The internal structure of the subaqueous fan was 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 7, 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 is 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 a volcano-sedimentary formation (Aksu *et al.* 2002a). This unit is made of seaward-dipping strata truncated at the shelf edge by the

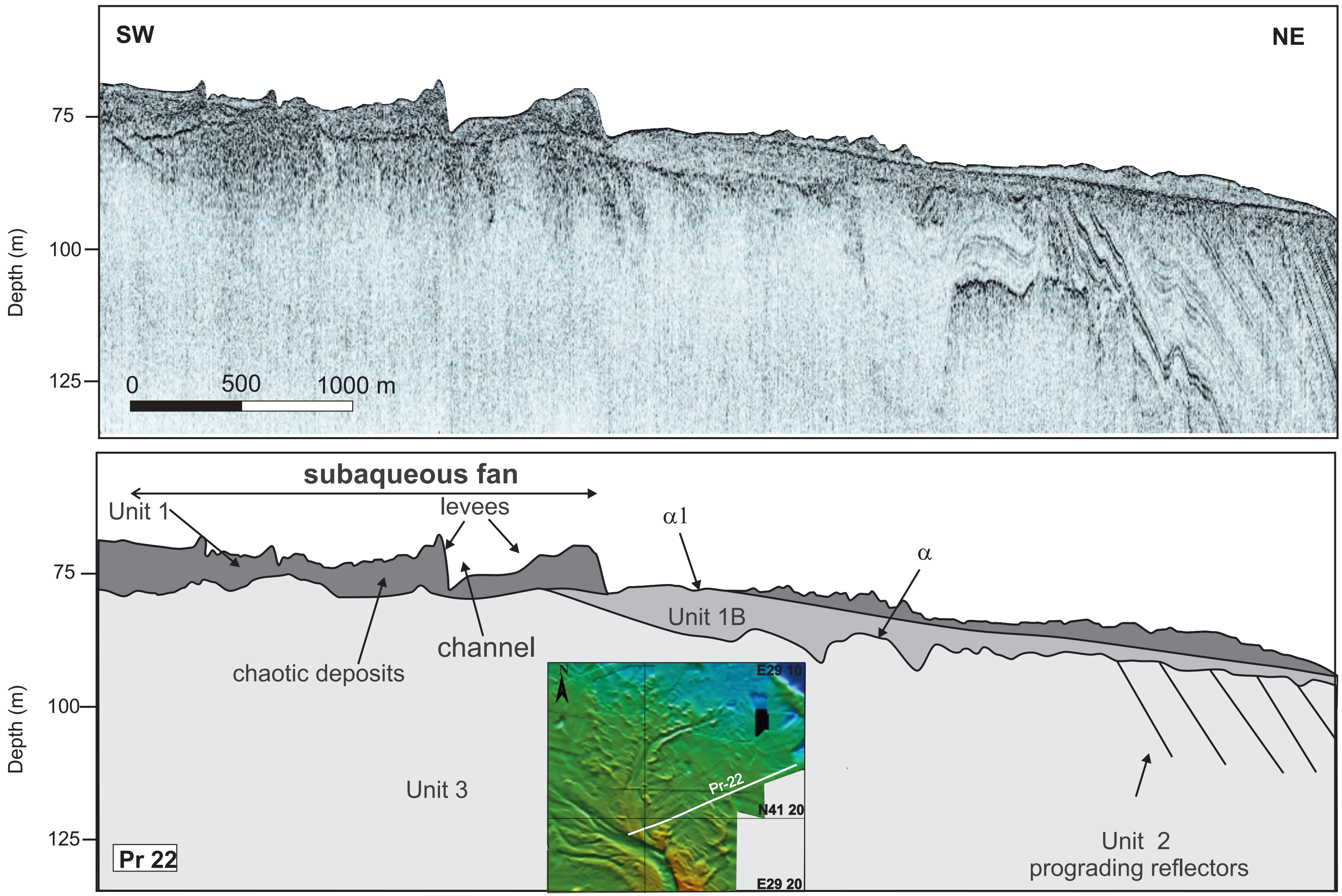

Figure 7. Seismic structure model of the shelf fan, on a SW–NE profile cutting the fan. Four different units are interpreted. Unit 3 is the basement unit, Unit 2 consists of seaward prograding reflectors and it toplaps to the upper unit, Unit 1 B has a chaotic structure and Unit 1 was deposited during the formation of the fan. α and α_1 are different unconformity surfaces.

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 shells of brackish-water molluscs (Figure 8) (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 8). To the north, 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 Figures 9 & 10. 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, so the existence of Unit 1B can be explained by deposition before the fan formed. A second erosional surface $\alpha_{1,}$ which truncates most of Unit 1B, formed due to a sea level fall. ^{14}C age measurements yield an uncorrected age for this erosional surface of ~10750 yr BP (William Bill Ryan, pers. comm. 2008, 2009). In contrast, the sediment thickness map of Unit 1 is compatible with the structure of the channel system (Figure 10), indicating that Unit 1 was deposited during the formation of the channel system.

Lowstand Wedge– A prograding wedge has been recognised at the shelf edge of the studied area. It overlies the α unconformity and gives information about the level of the correlative low sea level (Figure 11). The wedge overlies the underlying clinoforms (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 a ~11800 yr BP ^{14}C uncalibrated age (William Bill Ryan, pers. comm. 2008, 2009) for Unit 1B.

Dating of the Subaqueous Shelf Fan

Foraminiferal assemblage compositions were analysed from core B2KS02 at the Department of Marine Sciences, Università Politecnica delle Marche (Giunta *et al.* 2007). Samples were dried (at 40 °C), weighed, washed with running water, sieved (63 micron), and dried again at the same temperature. The residues (> 63 micron) were split (with a microsplitter) 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 were prepared for isotopic analysis. 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 ^{14}C AMS (accelerator mass spectrometry) dates were obtained from this core (Table 2).

Benthic foraminifera in core B2KS02 are present throughout the core (Figure 12). In Unit I-B and II-B benthic assemblages are characterised by a scarcity and low diversity of specimens. In the transitional phase (upper part of Unit III-B) the benthic assemblage is dominated by *Ammonia genera*, which is very abundant in the bottom part of the core. The presence of benthic foraminifera in the entire core testified that ecological conditions were ideal for the development of benthic microfauna since 6700 yr ^{14}C BP. The site recorded the introduction of salt water (bottom of the core) and a strong increase in the sedimentation rate, ending with the beginning of the normal sedimentation (Unit II-B).

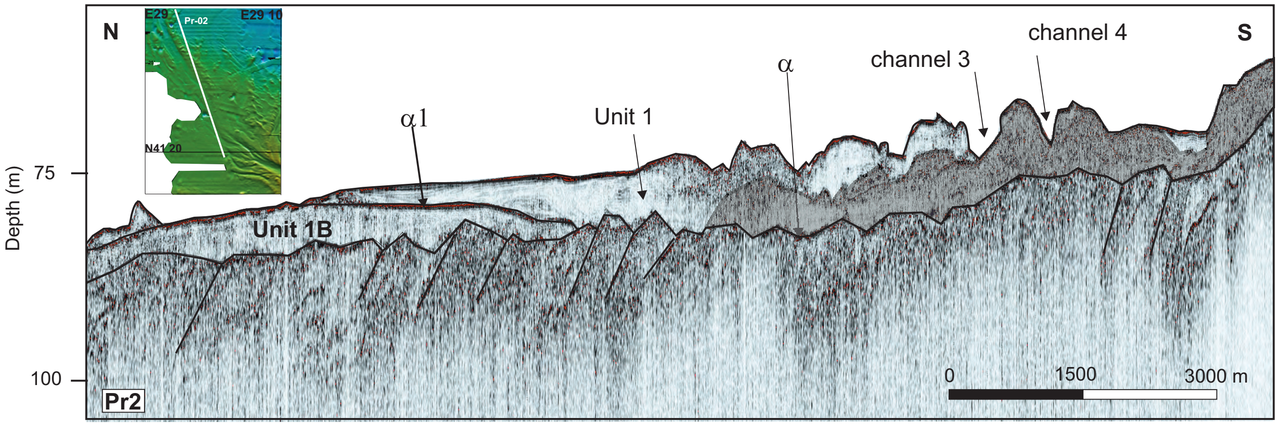

Figure 8. Seismic section Pr-2 across channels 3 and 4 where Unit 1B does not exist.

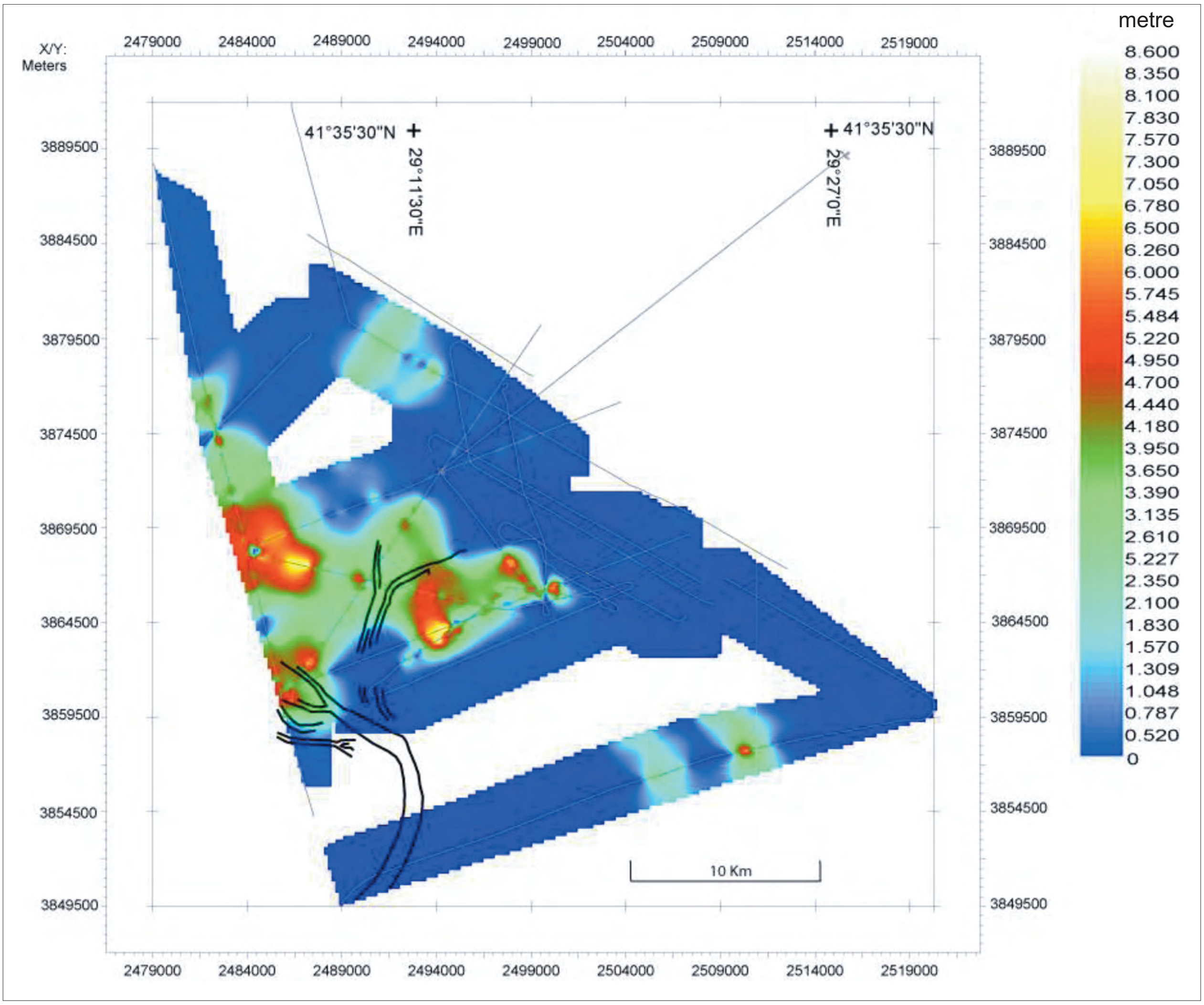

Figure 9. Sediment thickness map of Unit 1B.

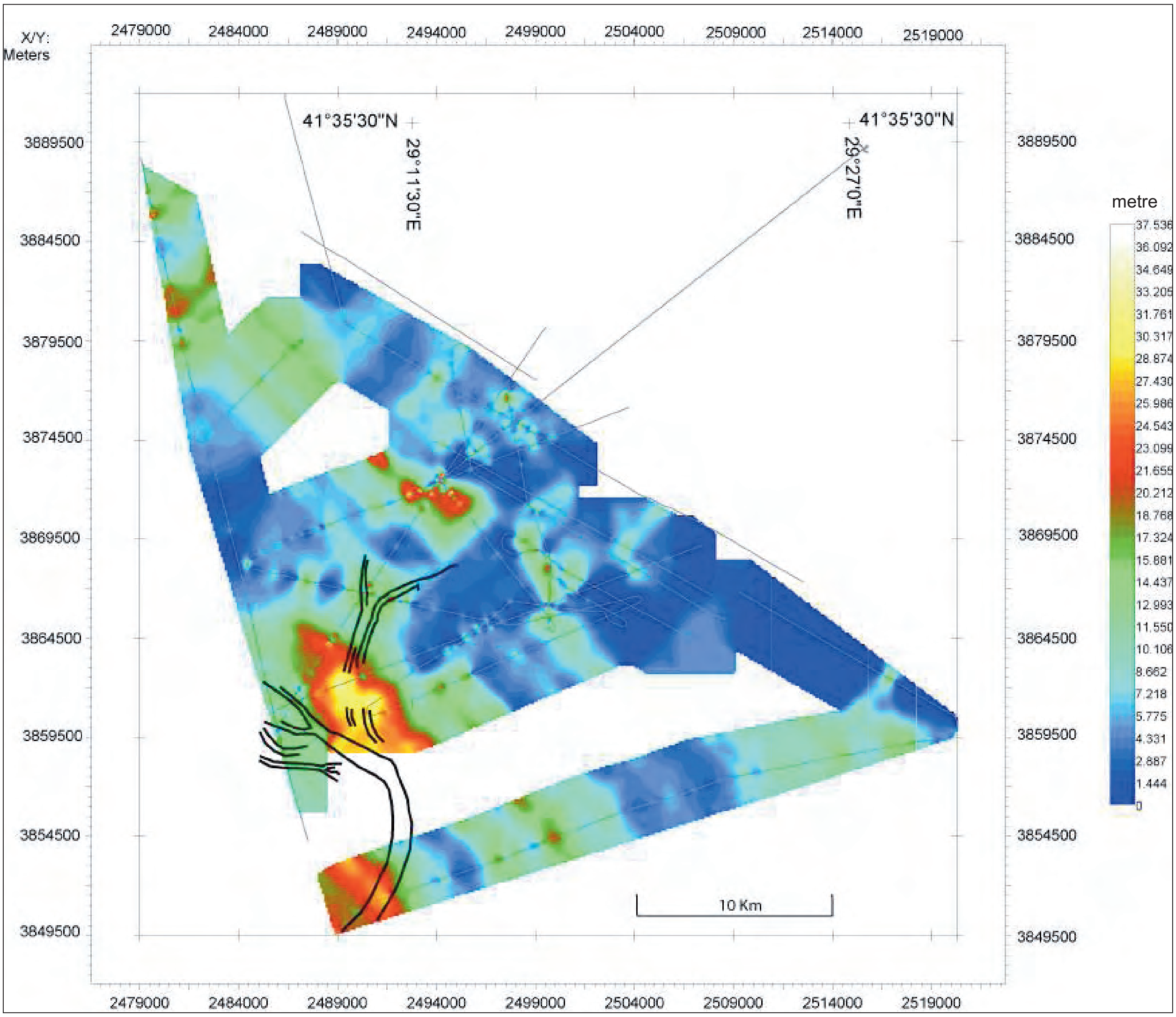

Figure 10. Sediment thickness map of Unit 1.

Shelf cores show the regional response of the platform during the Holocene evolution of the Black Sea. In the northwestern part of the Black Sea, benthic foraminifera colonised the sea bottom after sapropel deposition had 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.

Discussion and Conclusions

This study presents new results obtained from the subaqueous fan located on the shelf at the Black Sea outlet of the Bosphorus (Di Iorio & Yüce 1999; Flood *et al.* 2009). The shelf fan comprises 1 main channel and 6 tributary channels, which occur on the shelf area at the Black Sea exit of the İstanbul Strait (Figure 13). 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. Figure 13 shows the continuation of channel 6 on the 2D multibeam map. The continuations of the channels are in the direction indicated by Flood *et al.* (2009). A modern channel is evident on the chirp profile 53 (Figure 14). Furthermore, there is a wide older channel underlying the modern one.

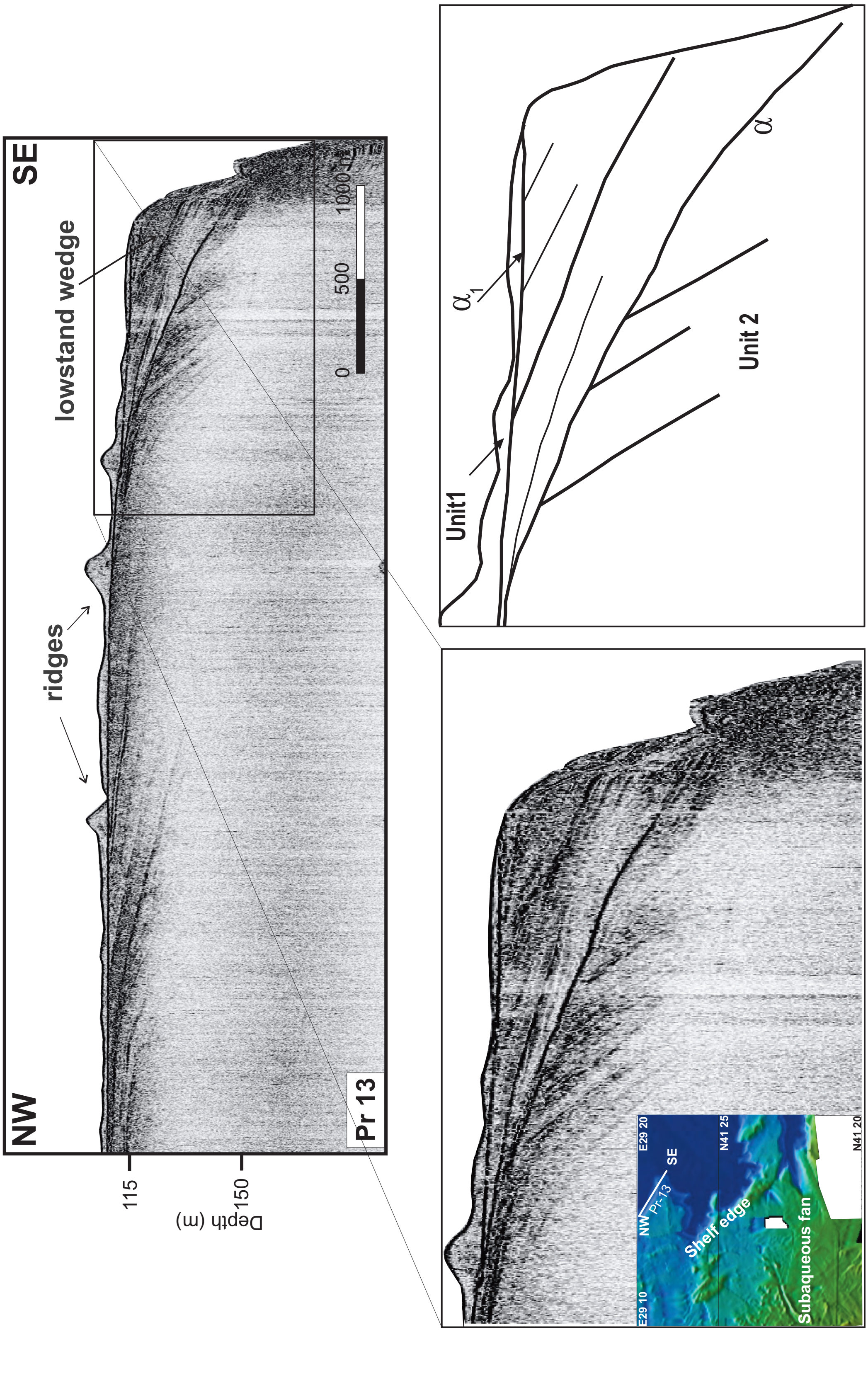

Figure 11. Low stand wedge on the seismic section Pr-13, indicating old shoreline at LGM.

Table 2. Sample type for [14]C 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	Hydrobia	0.16
4	B2KS 02	875–876	*Ammonia beccarii*	0.0
5	B2KS 02	893–894	*Hydrobia*	0.08

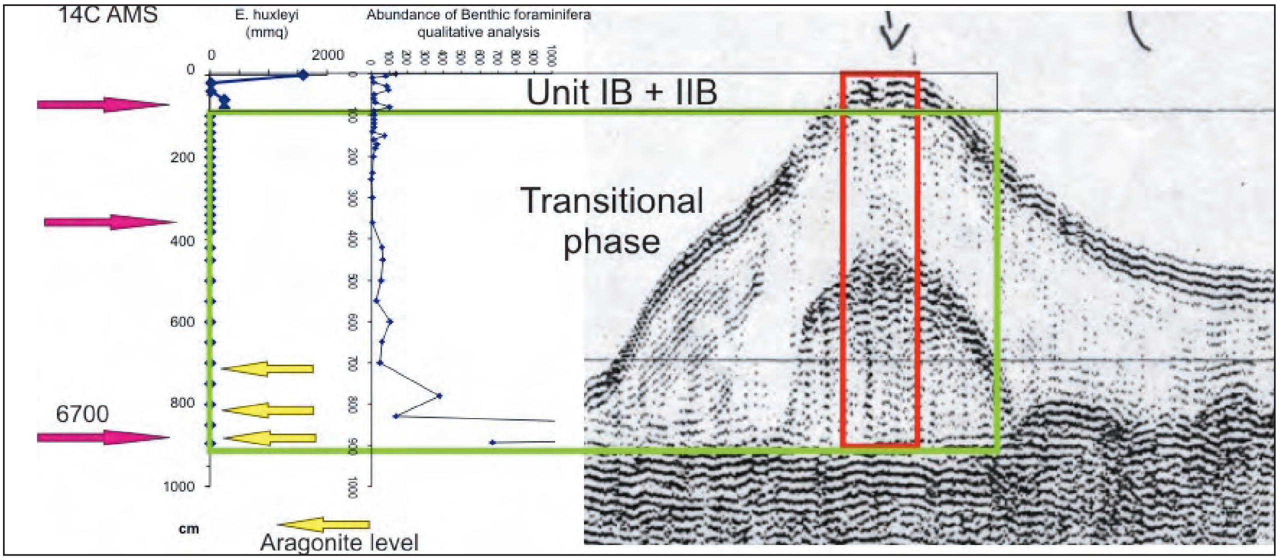

Figure 12. Benthic foraminifera in core B2KS02.

This probably indicates that, before the modern channel there was another similarly oriented channel during the low stand. This may indicate that the system is reworking. However, only one chirp profile is available for this region, and more profiles are required to test this hypothesis.

In this study, 3 different units and 2 erosional surfaces were observed. The main erosional surface, named α (Aksu *et al.* 2002a, b) delineates Unit 1B, which was deposited directly on this erosional surface α, already 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 in the shelf area and has been divided into 4 subunits by Aksu *et al.* (2002a). These 4 subunits were characterised by 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 are transgressive features formed by relatively rapid sea level rise. Similar bodies have been observed on the Ukranian and Romanian shelves, where they were interpreted as beaches, sand dunes and coastal features surrounding the Black Sea shrunken lake before the flood (Lericolais *et al.* 2003; Ryan *et al.* 2003).

Unit 1 is interpreted as the unit that was deposited during the formation of the channel system. Unit 1 is located in the core of the fan, and consists of grey to green mud. It yields an uncorrected [14]C age of 6700 yr BP (Giunta *et al.* 2007). Unit 1B is present from the inner to the outer shelf, while Unit 1 forms the

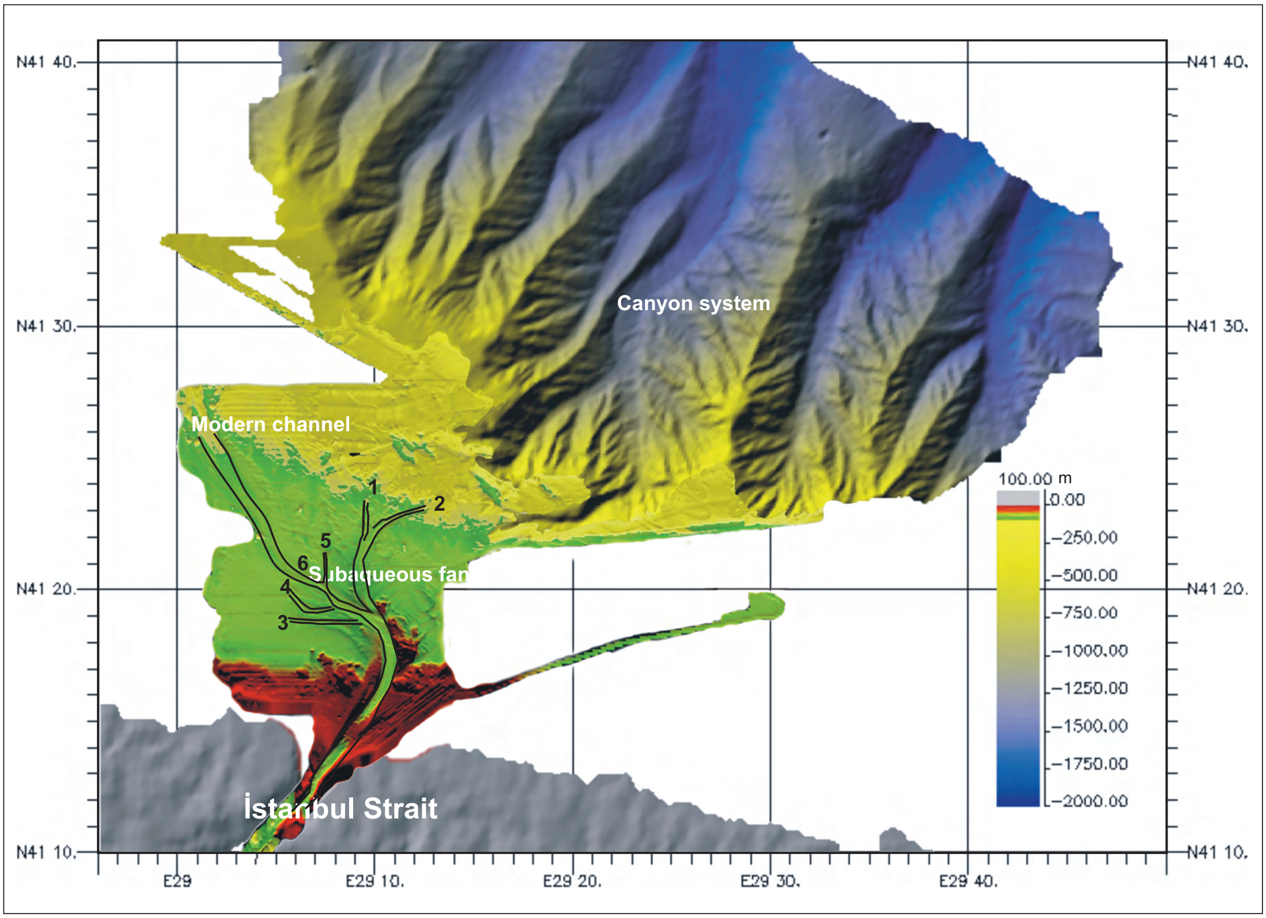

Figure 13. Drawing of the shelf fan channels. Numbers show the channel numbers in the order of activity. Mediterranean flow is currently active in channels 5 and 6.

upper unit of the fan system. Therefore, Unit 1B has different age and formation conditions from Unit 1, and cannot be considered a subunit of it. The craggy surface of α indicates that a huge amount of water carrying grained material entered to the Black Sea.

Features interpreted as ridge-style features, increase in number towards the shelf edge, probably because of 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 1995). The current velocity map published by Özsoy *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 (Flood *et al.* 2009), some of the levees are clearly 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 with a weak acoustic masking. No gas indication was observed in the core sediments. Therefore, our data indicates that these kinds of structures present on the middle shelf area cannot be interpreted as mud volcanoes. However, we observed other structures resembling mud volcanoes on other profiles which

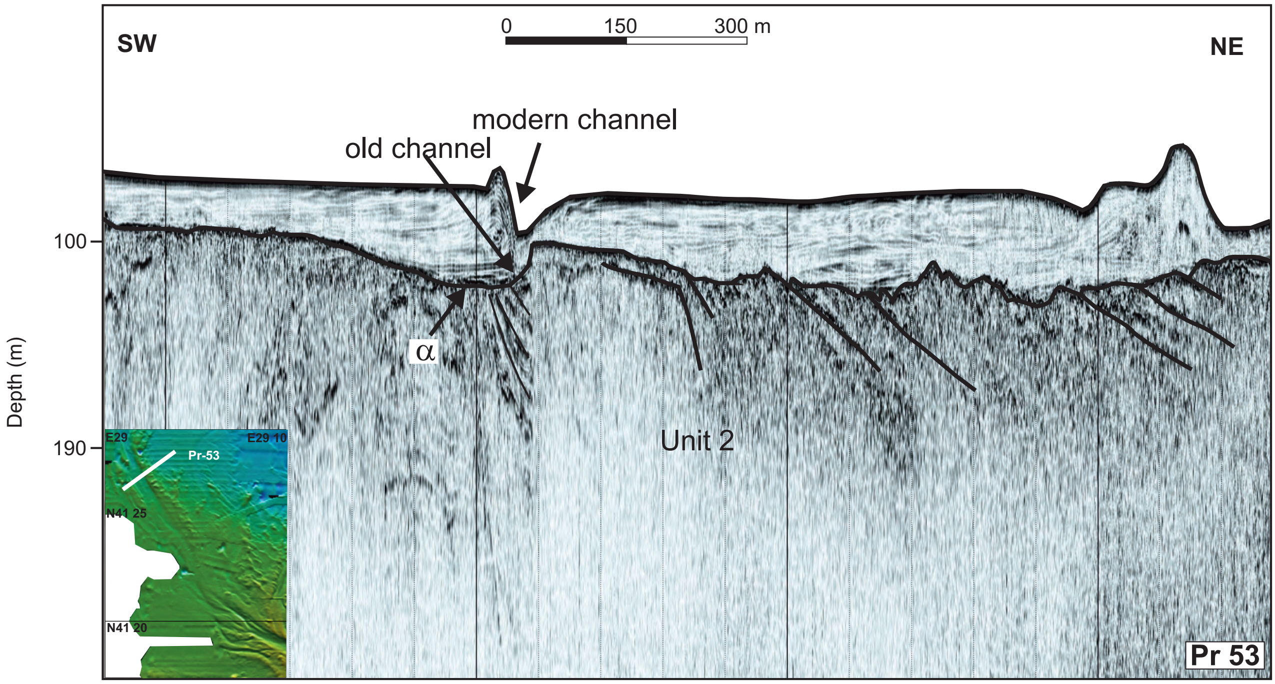

Figure 14. Chirp profile 53, passing through the modern channel.

are not shown in the study area. The box on the bathymetric map in Figure 2, shows the location of structures resembling mud volcanoes.

The core B2KS02 dated the base of Unit 1 at 6700 yr ^{14}C BP, allowing us to estimate that water input was synchronous with the onset of Unit 1. Besides dating the fan, the core supplied major information vital to the understanding of its formation. The strong concentration of benthic foraminifera at the base of this unit indicates that Mediterranean water introduced them while entering 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 metres 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 have formed during the sea level drop when α was formed (Figure 11). The wedge contains downlapping clinoforms and the top of the prograding horizon is truncated by the α_1 surface, indicating that this region was exposed to a sea level drop immediately after a sea level rise.

Besides these structures, some palaeocanyon heads were also observed near the shelf edge. The preservation of these canyon heads also led us to assume a rapid rise in Black Sea level. Had the rise been slow, these structures would have been eroded by the strength of ravine incision.

High resolution chirp data show, with dating, that after the last low stand the southwestern Black Sea shelf was drowned by Mediterranean waters. Figure 15 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 18000 yr BP and the flow of big rivers, the Dniepr, Dniestr, Bug and Volga increased. Also, melted ice from the Alps fed the Danube. Such phenomena were accelerated after the meltwater pulse 1 MWP1 (14500

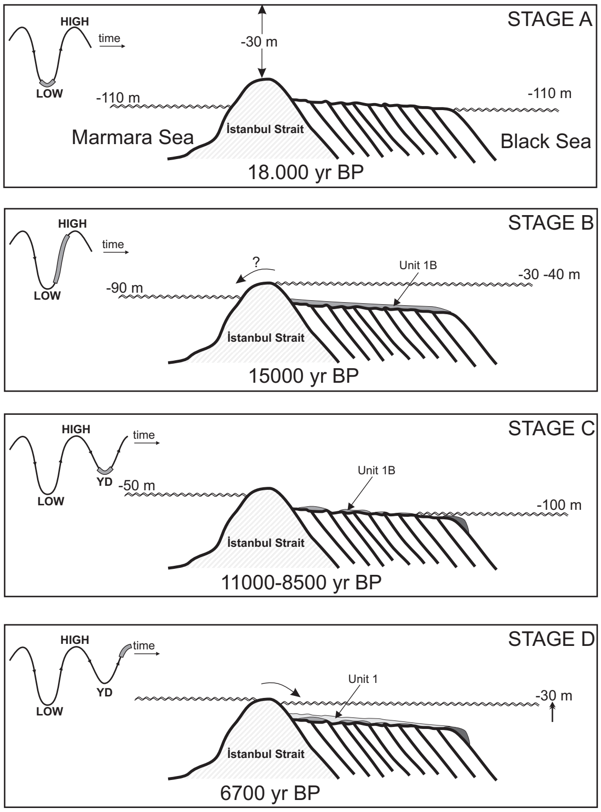

Figure 15. Schematic representation of the stages of the connection between the Black and Marmara Seas since the Last Glacial Maximum.

Cal yrs BP or 12500 yr ^{14}C BP). This transgression raised the level of the Black Sea (Black Sea basin was previously a closed basin) by 80 m until it reached the –30/–40 m isobaths. It is not obvious whether the sea level of Black Sea reached a level higher than the Bosphorus sill and whether fresh water from the Black Sea passed into the Marmara Sea, but some clues such as faunal studies seem to agree with this hypothesis and are coherent with recent publications of Marmara Sea studies (Eris *et al.* 2007). Unit 1B was deposited during a high stand period.

After the melting stage, (Stage C) the Black Sea level began to decrease and a second low-stand systems tract between –80 m and –100 m led to a second erosion surface α_1 on the shelf. Evidence of this decrease includes the dated Unit 1B (William Bill Ryan, pers. comm. 2008, 2009), which does not exist everywhere on the shelf: a big erosive phase probably removed most of it. The age of this low level from this analysis is between 11410 yr ^{14}C BP and 10640 yr ^{14}C BP (uncorrected ages).

Finally, based on the age data from the dating of core B2KS02 we can affirm that the Black Sea received salty water from the global ocean at 6700 yr ^{14}C BP. It is not clear whether this event happened catastrophically, but the two way connection previously proposed by anti-catastrophists cannot explain how such a large amount of material was 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 yr ^{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 to discover how the fan material was supplied to the shelf.

Acknowledgements

The research was supported by the French Ministry of Foreign Affairs within the frame of a bi-lateral collaboration between France and Romania, and prolonged by a European project of the 5th framework program called ASSEMBLAGE (EVK3-CT-2002-00090). This study is part of Okay's PhD Thesis defended at Dokuz Eylül University and supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK) grant (Project Code: 102Y112) and by a Dokuz Eylül University Research Foundation grant (Project Code: 2005.KB.FEN.034). We are grateful to Eliane Le Derezen for Multibeam processing and Tuncay Taymaz for his review. Discussions with Ali E. Aksu and Oya Algan contributed to our understanding. Also we are grateful to William B. Ryan for helpful discussions during Okay's stay in Lamont Doherty Earth Observatory from March to June 2009. Finally, we give special thanks to the crew of the vessels 'Le Suroit' (Ifremer) and 'Marion Dufresne' (IPEV).

References

Aksu, A.E., Hiscott, R.N. & Yaşar, D. 1999. Oscillating Quaternary water levels of the Marmara Sea and vigorous outflow into the Aegean Sea from the Marmara Sea Black Sea drainage corridor. *Marine Geology* **153**, 275–302.

Aksu, A.E., Hiscott, R.N., Mudie, P.J. & Rochon, M.A. 2002a. Persistent Holocene outflow from the Black Sea to the eastern Mediterranean contradicts Noah's Flood hypothesis. *GSA Today* **12**, 4–10.

Aksu, A.E., Hiscott, R.N., Kaminski, M.A., Mudie, P.J., Gillespie, H., Abrajanod, T. & Yaşar, D. 2002c. Last glacial-Holocene paleoceanography of the Black Sea and Marmara Sea: stable isotopic, foraminiferal and coccolith evidence. *Marine Geology* **190**, 119–149.

Aksu, A.E., Hiscott, R.N., Yaşar, D., İşler, F.I. & Marsh, S. 2002b. Seismic stratigraphy of Late Quaternary deposits from the southwestern Black Sea shelf: evidence for non-catastrophic variations in sea-level during the last ~10000 yr. *Marine Geology* **190**, 61–94.

Algan, O., Gökaşan, E., Gazioğlu, C., Yücel, Z., Alpar, B., Güneysu, C., Kirci, E., Demirel, S., Sari, E. & Ongan, D. 2002. A high-resolution seismic study in Sakarya Delta and Submarine Canyon, southern Black Sea shelf. *Continental Shelf Research* **22**, 1511–1527.

Arslanov, K.H.A., Gei, N.A., Izmailov, Y.A.A., Lokshin, N.V., Gerasimova, S.A. & Tertychny, N.I. 1983. O vozraste i klimaticheskikh usloviakh formirovania osadkov ozdnepleisotsenovikh morskikh terras poberez'ia Kercheskogo proliva [On the age and climatic conditions of sediment formation in the Late Pleistocene marine terraces of the Kerch Strait]. *Vestnik Leningradskogo Gosudarstvennogo Universiteta (LGU), seriia geologiia-geografiia* **12**, 69–79.

Bahr, A., Arz, H.W., Lamy, F. & Wefer, G. 2006. Late glacial to Holocene paleoenvironmental evolution of the Black Sea, reconstructed with stable oxygen isotope records obtained on ostracod shells. *Earth and Planetary Science Letters* **241**, 863–875.

Bahr, A., Lamy, F., Arz, H.W., Major, C., Kwiecien, O. & Wefer, G. 2008. Abrupt changes of temperature and water chemistry in the late Pleistocene and early Holocene Black Sea. *Geophysical Journal International* **169**, 29–40.

Balabanov, I.P. 2007. Holocene sea-level changes of the Black Sea. *In*: Yanko-Hombach, V., Gilbert, A.S., Panin, N. & Dolukhanov, P.M. (eds), *The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement*. Springer. New-York (USA), 603–631.

Balandin, Yu.G. & Trashchuk, N.N. 1982. Kolebaniia urovnia moria v golotsene i ikh otrazhenie v stroenii litifitsirovannykh rakushechnykh otlozhenii Arabatskoi kosy Azovskogo moria [Sea-level changes in the Holocene and their reflection in the structure of lithified coquina sediments of the Arabatkaia spit on the Sea of Azov]. *In*: Kaplin, P.A. (ed), *Izmeneniia urovnia moria* [*Sea Level Fluctuations*], 227–237. Izdatel'stvo Moskovskogo Universiteta, Moscow [In Russian].

Demirbağ, E., Gökaşan, E., Oktay, F.Y., Şimşek, M. & Yüce, H. 1999. The last sea level changes in the Black Sea: evidence from the seismic data. *Marine Geology* **157**, 249–265.

Di Iorio, D. & Yüce, H. 1999. Observations of Mediterranean flow into the Black Sea. *Journal of Geophysical Research* **104C**, 3091–3108.

Eriş, K., Ryan, W.B., Çağatay, M.N., Sancar, U.G., Lericolais, G., Ménot G. & Bard, E. 2007. The timing and evolution of the post-glacial transgression across the Sea of Marmara shelf south of İstanbul. *Marine Geology* **243**, 57–76.

Fedorov, P.V. 1988. The problem of changes in the level of the Black Sea during the Pleistocene. *International Geology Review* **30**, 635–641.

Flood, R.D., Hiscott, R.N. & Aksu, A.E. 2009. Morphology and evolution of an anastomosed channel network where saline underflow enters the Black Sea. *Sedimentology* **56**, 807–839.

Fontugne, M., Guichard, F., Strechie, C. & Lericolais, G. 2009. Reservoir age of the Black Sea waters during anoxic periods. *Radiocarbon* **51**, 969–976.

Giosan, L. 2007. Book Review: Changes in Coastline, Climate and Human Settlement, edited by V. Yanko-Hombach, A.S. Gilbert, N. Panin, P.M. Dolukhanov. Springer, Berlin (2007). *Quaternary Science Reviews* **26**, 1897–1900.

Giunta, S., Morigi, C., Negri, A., Guichard, F. & Lericolais, G. 2007. Holocene biostratigraphy and paleoenvironmental changes in the Black Sea based on calcareous nannoplankton. *Marine Micropaleontology* **63**, 91–110.

Guichard, F. & Assemblage Partners. 2006. *Assemblage Deliverable 14: Isotope Curves; Tables of Absolute Ages Obtained from on Dating of Sample*. European Community, Energy, Environment and Sustainable Development, Brest.

Hiscott, R.N. & Aksu, A.E. 2002. Late Quaternary history of the Marmara Sea and Black Sea from high-resolution seismic and gravity-core studies. *Marine Geology* **190**, 261–282.

Hiscott, R.N., Aksu, A.E., Mudie, P.J., Marret, F., Abrajano, T., Kaminski, M.A., Evans, J., Çakiroğlu, A.İ. & Yaşar, D. 2007. A gradual drowning of the southwestern Black Sea shelf: evidence for a progressive rather than abrupt Holocene reconnection with the eastern Mediterranean Sea through the Marmara Sea Gateway. *Quaternary International* **167**–**168**, 19–34.

Hiscott, R.N., Aksu, A.E., Yaşar, D., Kaminski, M.A., Mudied, P.J., Kostylev, V.E., MacDonald, J.C., İşler, F.I. & Lord, A.R. 2002. Deltas south of the Bosphorus Strait record persistent Black Sea outflow to the Marmara Sea since ~10 ka. *Marine Geology* **190**, 95–118.

Kwiecien, O., Arz, H.W., Lamy, F., Bahr, A., Wulf, S. & Haug, G.H. 2006. Preliminary results on core MD04 2760 from the southwestern Black Sea. *European Geosciences Union* 2006. *Geophysical Research Abstracts*, *Wien*, **8**, p. 06947.

Lericolais, G., Le Drezen, E., Nouzé, H., Gillet, H., Ergun, M., Çifçi, G., Avci, M., Dondurur, D. & Okay, S. 2002. Recent canyon heads evidenced at the Bosphorus outlet. American Geophysical Union (AGU Fall Meeting), San Francisco, California, Abstracts, *EOS, Transactions*, p. 83 (47).

Lericolais, G., Popescu, I., Guichard, F. & Popescu, S.M. 2007. A Black Sea lowstand at 8500 yr B.P. indicated by a relict coastal dune system at a depth of 90 m below sea level. *In*: Harff, J., Hay, W.W. & Tetzlaff, D.M. (eds), *Coastline Changes: Interrelation of Climate and Geological Processes*. GSA Books, Allen Press Inc., Special Paper **426**, 171–188.

Lericolais, G., Popescu, I., Panin, N., Ryan, W.B.F. & Guichard, F. 2003. Last rapid flooding in the Black-sea. *In*: Uscinowicz, S. & Zachowicz, J. (eds), *Rapid Transgressions Into Semi-enclosed Basins*. IGCP 464. Polish Geological Institute, Gdansk, p. 39.

Özsoy, E. 1995. Exchanges with the Mediterranean, fluxes and boundary mixing processes in the Black sea. *Bulletin de l'Institut Océanographique Monaco* no spécial **15**, 1–25.

Özsoy, E., Di Iorio, D., Gregg, M. & Backhaus, J. 2001. Mixing in the Bosphorus Strait and the Black Sea continental shelf: observations and a model of the dense water outflow. *Journal of Marine Systems* **31**, 99–135.

Ryan, W.B.F., Pitman, W.C., Major, C.O., Shimkus, K., Moskalenko, V., Jones, G.A., Dimitro, P., Görür, N., Sakinç, M. & Yüce, H. 1997. An abrupt drowning of the Black Sea shelf. *Marine Geology* **138**, 119–126.

Ryan, W.B.F., Major, C.O., Lericolais, G. & Goldstein, S.L. 2003. Catastrophic flooding of the Black Sea. *Annual Review Earth and Planetary Sciences* **31**, 525–554.

Svitoch, A.A., Selivanov, A.O. & Yanina, T.A. 2000. Paleohydrology of the Black Sea Pleistocene Basins [translated from Vodnye Resursy, volume 27, No. 6, 2000, pp. 655–664. Original Russian Text Copyright © 2000 by Svitoch, Selivanov, Yanina]. *Water Resources* **27**, 594–603.

Yanko, V. 1990 Stratigraphy and paleogeography of marine Pleistocene and Holocene deposits of the southern seas of the USSR. *Memorie della Società Geologica Italiana* **44**, 167–187.

Yanko-Hombach, V., Balabanov, I., Mitropolsky, A. & Glebov, A. 2002. Late Pleistocene-Holocene history of the Black Sea: is there any room for the Ryan-Pitman Hypothesis 'Noah's Flood'. *Third International Congress on Environmental Micropaleontology, Microbiology and Meiobenthology (EMMM 2002; 1–6 September 2002, Vienna, Austria), Program and Abstracts*, p. 203–206.

Yanko-Hombach, V., Gilbert, A.S., Panin, N. & Dolukhanov, P.M. 2007. *The Black Sea Flood Question. Changes in Coastline, Climate and Human Settlement*. Springer, New-York (USA) **975**.