9-3-03

ELSEVIER

Marine Geology 138 (1997) 119-126

MARINE GEOLOGY

An abrupt drowning of the Black Sea shelf

William B.F. Ryan [a,*], Walter C. Pitman III [a], Candace O. Major [a], Kazimieras Shimkus [b], Vladamir Moskalenko [b], Glenn A. Jones [c], Petko Dimitrov [d], Naci Gorür [e], Mehmet Sakinç [e], Hüseyin Yüce [f]

[a] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[b] Southern Branch of the P.P. Shirshov Oceanology Institute, Gelendzhik-7, 353470, Russia
[c] Texas A&M University at Galveston, Galveston, TX, USA
[d] Bulgarian Academy of Sciences, Institute of Oceanology, PO Box 152, 9000 Varna, Bulgaria
[e] İ.T.Ü. Maden Fakültesi Jeoloji Bölümü, 80626 Ayazaga, Istanbul, Turkey
[f] Seyir, Hidrografi ve Osinografi Dairesi, 81647 Çubuklu, Istanbul, Turkey

Received 16 December 1996; accepted 17 December 1996

Abstract

During latest Quaternary glaciation, the Black Sea became a giant freshwater lake. The surface of this lake drew down to levels more than 100 m below its outlet. When the Mediterranean rose to the Bosporus sill at 7,150 yr BP[1], saltwater poured through this spillway to refill the lake and submerge, catastrophically, more than 100,000 km^2 of its exposed continental shelf. The permanent drowning of a vast terrestrial landscape may possibly have accelerated the dispersal of early neolithic foragers and farmers into the interior of Europe at that time. © 1997 Elsevier Science B.V.

Keywords: Black Sea; Bosporus; Mediterranean; Sapropel; Transgression

1. Introduction

The most widely-accepted hypothesis, based on data from the deep basin floor sediments (Ross et al., 1970; Degens and Ross, 1972; Deuser, 1972; Ross and Degens, 1974), holds that post-glacial inflow of Mediterranean water into the Black Sea's isolated freshwater lake began as a trickle 9000 yr BP. As saline spills intermittently reached the basin floor, they supplied a thickening puddle of stratified brackish bottom water, which eventually became anoxic two thousand years later (Degens and Ross, 1972; Deuser, 1974). Physical models (Deuser, 1974; Glenn and Arthur, 1985) based on this scenario have predicted a shoaling oxic–anoxic interface leading to sapropel accumulation — first on the basin plain and then later on the margins. However, new data from the shallower continental margin and from the inlet itself offer a contradic-

* Corresponding author (e-mail: billr@ldeo.columbia.edu). Additional supporting materials are available at http://imager.ldeo.columbia.edu/BlackSeaShelf.html

[1] Unless otherwise noted, all dates reported are raw carbon-14 ages before reservoir corrections (460 yr) and thus are compatible with previously published dates.

PII S0025-3227(97)00007-8

tory picture of influx commencing later at 7150 yr BP and initiated by a cascade of saltwater pouring into a partly-emptied Black Sea lake following the breaching of an intervening barrier. Catastrophic flooding produced a simultaneous submergence of broad regions of the continental shelf, an invasion of immigrant marine organisms (Shimkus et al., 1973; Wall and Dale, 1974), a four-fold decrease in sediment accumulation rate (Degens and Ross, 1972; Shimkus et al., 1975), and a simultaneous onset of organic-rich sediments at all depths (Jones and Gagnon, 1994).

2. New data

We report the findings of a joint Russian–U.S. expedition in 1993 which surveyed two regions of the outer continental shelf where, at times of a lowered lake surface, ancient rivers may have once approached the shelf edge (Fig. 1). These surveys revealed a buried erosion surface strewn with shelly gravel extending across the broad continental margin of the northern Black Sea to beyond its shelf break (Major, 1994; Evsylekov and Shimkus, 1995). This unconformity (Fig. 2) truncates strata belonging to a terrestrial flood plain with meandering river beds, coastal deltas and wave-cut beaches developed in the last glacial period when the Black Sea had become a giant freshwater lake (Nevesskaya, 1965; Federov, 1971). The gravel is composed entirely of bleached fragments of the freshwater "Caspian" mollusk (*Dreissena rostriformis*) eroded from underlying dry (water content <20%) coquina-bearing sand and clay layers (Fig. 3) where the intact shells are coated with fossilized algae and have an $^{18}O/^{16}O$ isotopic composition ranging from −7.8 to −3.8‰ (Fig. 3P). The stiff clay contains abundant leafy plant material, fluvial gastropods (*Viviparus viviparus*), desiccation cracks and roots indicative of former alluvial to coastal marsh environments presently submerged in water depths down to −140 m. Our AMS ^{14}C ages on individual intact valves of *D.*

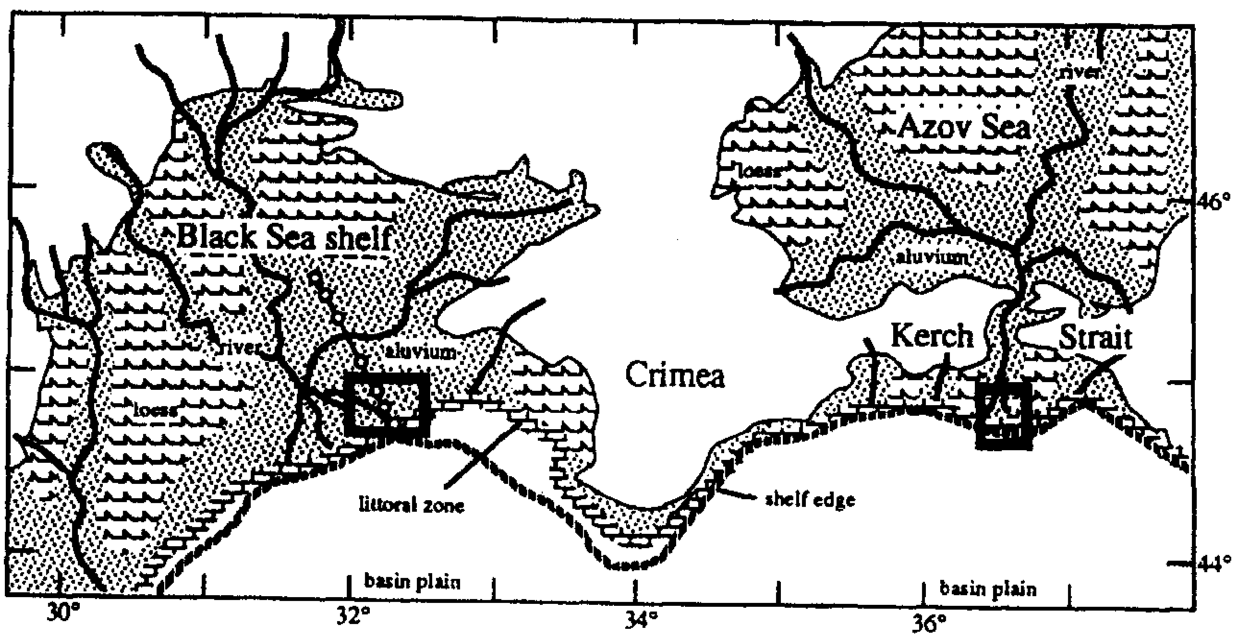

Fig. 1. The arid landscape of the Neoeuxine stage in the Black Sea deduced from the lithologies of more than 250 sediment cores (Kuprin et al., 1974; Scherbakov et al., 1978). The soils of the emerged shelf are dominated by wind-blown loess (*wavy pattern*) and the alluvial deposits (*stippled pattern*) of meandering rivers that flowed hundreds of km beyond their present mouths to shelf-edge deltas. The ancient littoral zone (*brick pattern*) was explored during two surveys of a joint Russia–U.S. expedition in 1993. The *line with small circles* extending northwest from the survey west of the Crimea indicates a transect of new cores.

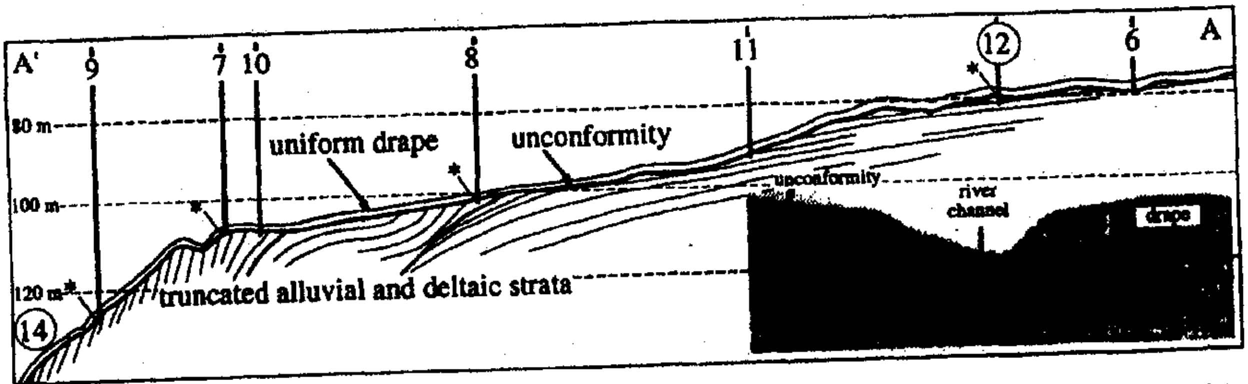

Fig. 2. Interpretation of one of our high-resolution seismic profiles across the outer continental shelf in the Black Sea south of the Ukraine illustrating an erosional unconformity (*bold line*) which has truncated an underlying glacial-age alluvial and delta deposit. This scar is ubiquitous everywhere above the −150-m isobath. Sediment cores obtained in 1993 are indicated by *vertical lines* which mark the extent of sub-bottom penetration into and through the unconformity. *Circled numbers* are for cores which had to be projected onto the profile. The *asterisks* point to locations where mollusks were extracted from the base of the uniform drape resting on the unconformity. The identical radiocarbon ages (7150 ± 100 yr BP) of the shells document a flooding surface which reached inland from the shelf edge to at least the −49-m isobath. The rapid transgression left the erosion surface intact as shown by the uniform burial of a former river channel.

rostriformis in the Neoeuxine coquina below the gravel extend from 14,700 ± 65 to 10,400 ± 55 yr BP. Ages of reworked mollusks in the gravel are as young as 8250 ± 35 yr BP.

These findings of a former emerged land surface complement prior investigations which report loess soils (Kuprin et al., 1974), alluvium (Popov, 1973; Skiba et al., 1975; Scherbakov et al., 1978), littoral deposits (Kuprin et al., 1974; Shimkus et al., 1975; Scherbakov et al., 1978; Dimitrov, 1982; Scherbakov, 1983), and beach terraces (Shimkus et al., 1980) in formations on the continental shelf spanning 17,780 ± 200 to 9,660 ± 70 yrB P at depths between −93 and −122 m, as well as deeply entrenched river valleys (Ostrovskiy et al., 1977; Panin, 1972; Skiba et al., 1975) indicative of a past lake surface in Neoeuxine time at or below −110 m.

The sediment overlying the ubiquitous erosion surface is a wet (water content >60%), dark, jelly-like sapropel with organic carbon contents ranging from 1.5% to 8% (Fig. 3N). Over much of the shelf this deposit comprises a structureless layer of uniform thickness which drapes all of the undulations of the unconformity surface (Fig. 2, insert). The drape shows no evidence of a transgressive systems tract bedding geometry or coastal onlap as is seen on Mediterranean and Atlantic shelves.

3. Discussion

A sapropel has been previously described from the deeper basin where its base records the first post-glacial appearance of euryhaline marine dinoflagellates (Wall and Dale, 1974) (Fig. 3C) and diatoms (Shimkus et al., 1973; Mayard, 1974) (Fig. 3D and E). Cosmopolitan and diverse salinity-tolerant dinoflagellates abruptly replace a novel low-diversity stenohaline flora that lived in an Neoeuxine "lake-sea" of extremely reduced salinities and whose disappearance is indicative that they were unable to survive the influx of saline water which carried in the euryhaline-marine organisms (Wall and Dale, 1974). On the shelf the Neoeuxine mollusk fauna (*Dreissina polymorpha*, *D. rostriformis*, *Monodacna caspia*, *Clathrocaspia gmelini* and *Theodoxus pallas*) have "Caspian" affinities. Several species continue to live today but are confined to river mouths and the fresher parts of the Azov, Caspian and Aral Seas.

The faunal/floral successions on the shelf parallel those from the deep basin cores by also recording at the base of the shelf sapropel the first post-glacial arrival of Mediterranean immigrants — the euryhaline-marine mollusks (*Cardium edule*, *Mytilaster lineatus*, *Mytilus galloprovincialis*, *Hydrobia ventrosa*, and *Abra ovata*) indicative of

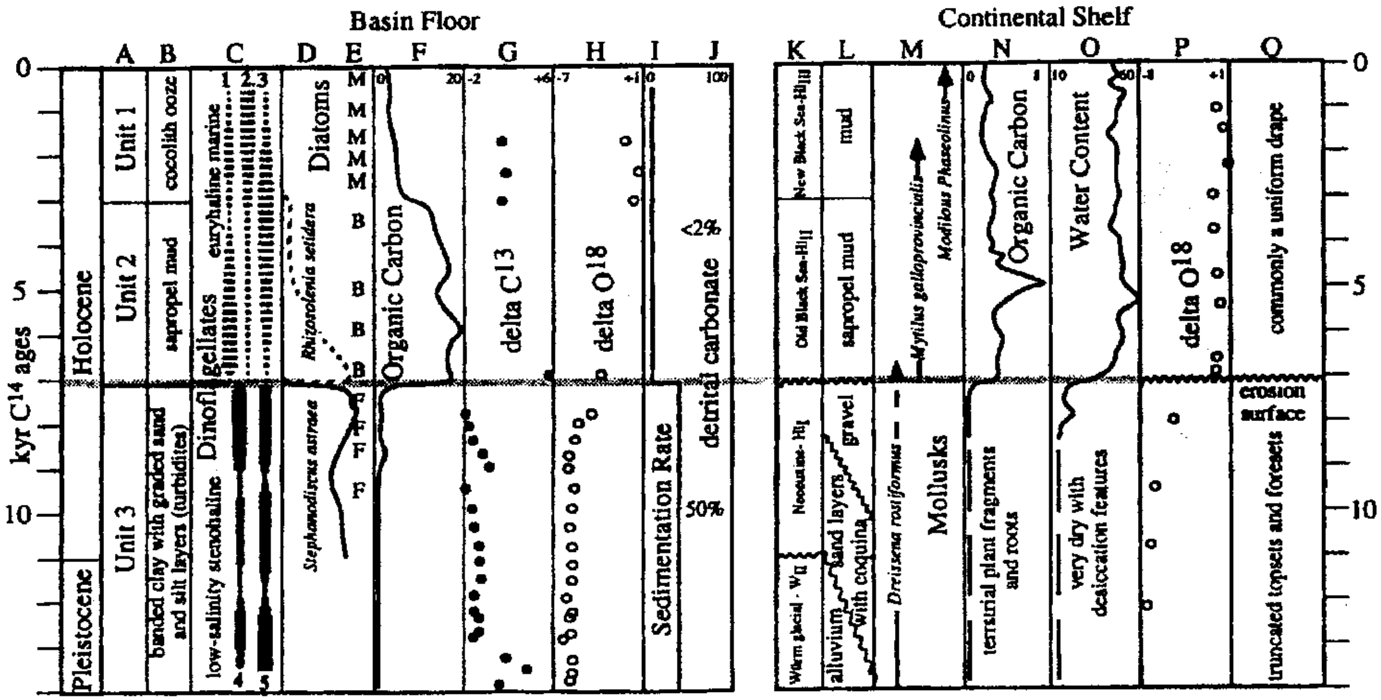

Fig. 3. Indicators of abrupt environmental change in sediment cores from deep basin (*left*) and shallow shelf (*right*) regions of the Black Sea. The ***horizontal bold gray line*** at 7150 yr BP marks a time of simultaneous change in many properties of the sediments. *Columns*:

A. Lithostratigraphic units (Degens and Ross, 1972).

B. Predominant lithology (Ross et al., 1970).

C. Dinoflagellate abundance (Wall and Dale, 1974). *1 = Lingulodinium machaerophorum*; *2 = Peridinium claudicans*; *3 = Spiniferites bulloides*; *4 = Tectatodinium psilatum*; *5 = Spiniferites cruciformis*.

D. Diatom abundance in a core at −920-m depth (Shimkus et al., 1973).

E. Location of fresh (*F*), brackish (*B*) and marine (*M*) diatom specimens in cores below −2000-m depth (Mayard, 1974).

F. Percent organic carbon (Ross et al., 1970).

G. $^{13}C/^{12}C$ ratio (‰ vs. PDB) in the carbonate fraction (Deuser, 1972).

H. $^{18}O/^{16}O$ ratio (‰ vs. SMOW) in the carbonate fraction (Deuser, 1972).

I. Sedimentation rate (cm/kyr) (Degens and Ross, 1972).

J. Calculated percent fraction of reworked detritus (Deuser, 1972).

K. Stratigraphic nomenclature (Shimkus et al., 1975).

L. Predominant lithology (Nevesskaya, 1965; Kuprin et al., 1974; Shimkus et al., 1975; Scherbakov, 1983).

M. Stratigraphic range of selected mollusk species in our core AK93-1 at −68-m depth (Major, 1994).

N. Percent organic carbon in our core AK93-11 at −91-m depth.

O. Percent water content in our core AK93-11.

P. $^{18}O/^{16}O$ ratio (‰ vs. SMOW) measured on *Cardium edule* from core AK93-1 for the Old and New Black Sea sediments and on *Dreissina rostriformis* in core AK93-13 at −165-m depth for the Neoeuxine sediments (Major, 1994).

Q. Synopsis of geometry of clinoforms seen in the high-resolution seismic reflection profiles across the outer shelf.

the Old Black Sea stage of the Holocene (Nevesskaya, 1965; Federov, 1971). This horizon has been dated by the ^{14}C Accelerator Mass Spectrometer (AMS) method using single intact specimens of *C. edule* and *M. Caspia* (bivalves which dwell in the uppermost substrate no deeper than the diameter of their shell) and *M. galloprovincialis* (an epibenthic mussel which dwells on the substrate). In cores from water depths of −49 to −123 m our dates from five cores (Fig. 2) cluster at 7150 ± 100 yr BP and fall within the error limits of ages obtained at the base of the sapropel in another nine cores spanning the depths of −200 to −2200 m (Jones and Gagnon, 1994). Apparently organic carbon-rich sedimentation began synchronously throughout the Black Sea once its barrier to the Mediterranean was breached.

The Neoeuxine sediments on the shelf and basin floor have roughly comparable light $^{18}O/^{16}O$ isotopic compositions (−8.0 to −4.0‰) considered to be typical of freshwater environments (Fig. 3H and P). Though there is insufficient carbonate in the unit-2 sapropel to measure its isotopic variability, the heavier ratios of the mollusks throughout the Old and New Black Sea stages on the shelf (0.0 ± 0.8‰) suggest that the Black Seas water composition may have changed substantially with the invasion of the euryhaline-marine mollusks, for they show little subsequent isotopic variation in the last seven thousand years.

The hypothesis of a Mediterranean inflow beginning at 9000 yr BP was strongly influenced by consideration of global eustatic sea level rise (Milliman and Emery, 1968) to a presumed −50 m sill in inlet at that time (Degens and Ross, 1972). However, reflection profiling in the Strait of Istanbul (SOI-Bosporus) and Strait of Çanakkale (SOÇ-Dardanelles) by the Turkish Navy reveals the straits as exhumed and now partly sediment-filled channels whose bedrock sill depth is no shallower than −85 m (Fig. 4). The sediment body within the SOI-Bosporus has been sampled by drilling (Derman, 1990). The vertical distribution

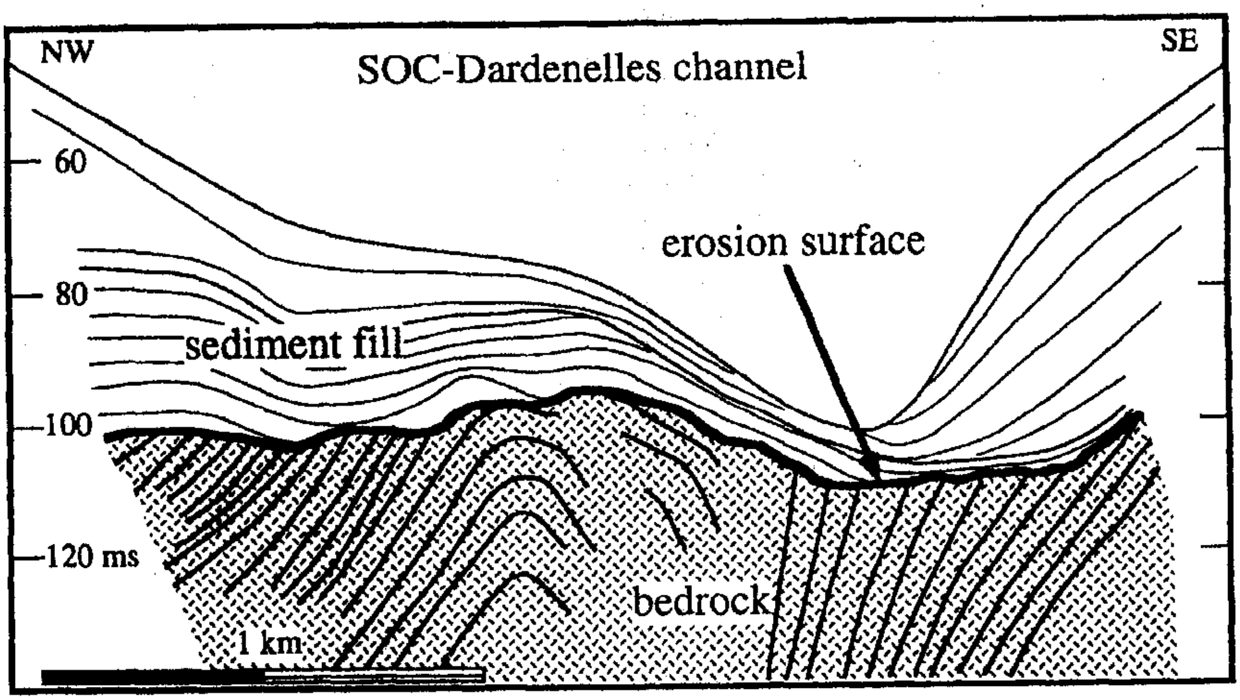

Fig. 4. Interpreted seismic reflection profiles across the SOÇ-Dardanelles showing the channel eroded into the bedrock. The *vertical scale* is in milliseconds, two-way travel time, which places the bedrock sill depth at −85 m. The sediments, which have subsequently buried the erosion surface, accumulated after the establishment of inflow to the Black Sea from the Mediterranean.

of its mollusk (Taner, 1990) (*Corba gibba, Cerithidea insulaemaris*) and benthic foraminiferal (Meriç and Sakinç, 1990) (*Ammonia beccarii, Eliphidium crispum*) assemblages indicate that the first environmental conditions were euryhaline.

Although the indicator used most assertively as a proxy for salinification 9000 yr BP is the $^{18}O/^{16}O$ ratio of the carbonate component of unit-3 sediment, its excursion beyond the typical range of unit-3 variability (−5.5±0.8‰) only occurs in the topmost sample from this unit (−3.9‰) with an interpolated age of 7900 yr BP (Fig. 3H). The tiny grain size of this carbonate material is but a few hundred ångströms. Such grains, no larger than 15 unit cells dimensions in any direction, present the possibility of post-depositional oxygen exchange (Degens and Ross, 1972; Deuser, 1972), caused by dense saline bottom water percolating into the seabed for a few decimeters after inflow had commenced.

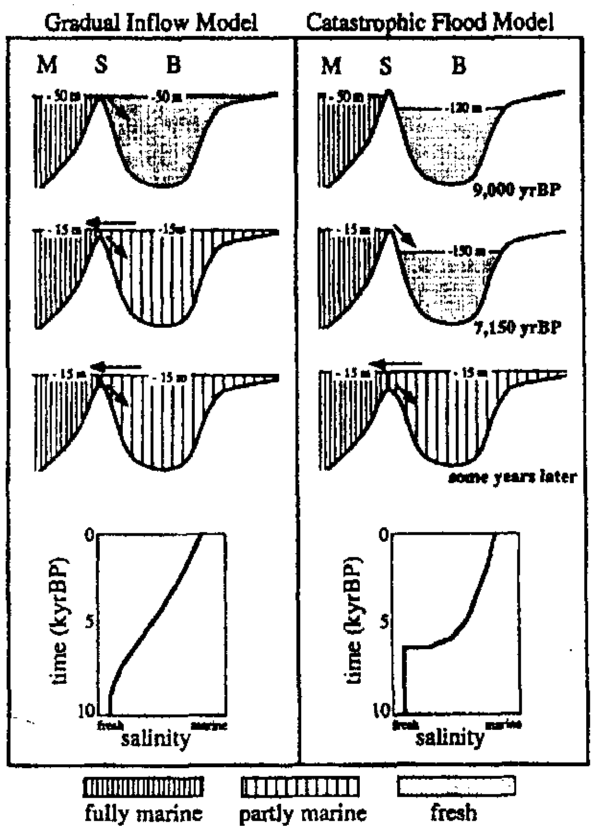

Fig. 5. Reconstructed levels in the Mediterranean (*M*) and Black Seas (*B*), and their connections/isolations via the SOÇ-Dardanelles and SOI-Bosporus sill (*S*). On the left is a portrayal of the gradual inflow model (Degens and Ross, 1972; Deuser, 1972, 1974) in which the first connection was made at 9000 yr BP. The depth of the strait deepened slowly as global eustatic sea level continued to rise, leading to an acceleration in the strengthening of the Black Sea's salinity. On the right is our catastrophic flood model in which the Mediterranean broke through a barrier in the inlet at 7150 yr BP and rapidly flooded a partly evaporated freshwater lake. Here increase in the Black Sea's salinity is shown to have been initially abrupt and then to have later decelerated.

4. Conclusions

Our reluctance to accept an early salinification at 9000 years ago (Fig. 5) is identical to the concerns of Wall and Dale (1974) who have asked

"why was the major reentry of marine organism delayed for nearly 2,000 years" Furthermore, we have looked for and find no evidence for a pre-sapropel lithostratigraphic layer on the outer shelf at a time when it would have been overlain by more than 60 m of water (Fairbanks, 1989) if, indeed, an early connection had been made with the Mediterranean.

We interpret the instantaneous submergence of a broad former land surface of 100,000 km^2 as the consequence of Mediterranean waters invading an isolated inland lake whose surface had been drawn down beyond its shelf break by evaporation and reduced river input (Fig. 5). Such a cascade, once underway, would posses the power to further enlarge its orifice through positive-feedback erosion. The bedrock cross-sections of the SOI-Bosporus and SOÇ-Dardanelles observed at dozens of points along their lengths present a flume capable delivering a flux in excess of 50 km^3 per day, initially filling the lake at a rate approaching 10's of cm/day.

At this time (7550 calendar years BP), farming, which had already been established in Greece, Bulgaria, Romania and along the coast of the Marmara Sea (Özdagan, 1983; van Andel and Runnels, 1995), spread rapidly inland along the major river valleys of southeastern Europe (Greg, 1988; Hodder, 1990). The light plow and simple irrigation appear abruptly in the Transcaucasus

(Glumac and Anthony, 1991). Such "wave-of-advance" population movements (Sokal et al., 1991) could have been induced by the permanent expulsion of inhabitants which had adapted to the natural resources of the formerly-emerged Black Sea periphery — namely, its arable loess, alluvial soil, and the moist loam of the freshly exposed bed of its shrinking shoreline.

Acknowledgements

The 1993 expedition materialized though the generous assistance of the officers and crew of the R/V *Aquanaut*, the Datasonics Corporation (Falmouth, Massachusetts), R. Kosyan and E. Kontar of the P.P. Shirshov Oceanology Institute, and V. Artemenko of Yuzhmorgeologiya Gelendzhik. M. Bruckner, R. Fairbanks, T. Guilderson, B. Hatau, W. Haxby, B. Il'ina, S. Klimley, W. Menke, L. Nevesskaya, S. O'Connell, Ç. Sengor and J. Weissel provided crucial technical and analytical help. Discussions with D. Bailey, D. Harris, I. Hodder, J. Mellaart, A. Moore, J. Oates, C. Renfrew, J. Renfrew and A. Sherratt have substantially contributed to our understanding of possible archeological implications of the Black Sea connections with the Mediterranean. Lamont-Doherty Earth Observatory Contribution No. 5604.

References

Degens, E.T., Ross, D.A., 1972. Chronology of the Black Sea over the last 25,000 years. Chem. Geol. 10, 1–16.

Derman, A.S., 1990. Genç Çökellerin (Holosen) sedimentolojik özellikleri ve ortamsal yorumu. In: Meriç, E. (Ed.), Late Quaternary (Holocene) Bottom Sediments of the Southern Bosphorus and Golden Horn. Matbaa Teknisyenleri Basimevi Divanyolu, Istanbul.

Deuser, W.G., 1972. Late-Pleistocene and Holocene history of the Black Sea as indicated by stable isotope studies. J. Geophys. Res. 77, 1071–1077.

Deuser, W.G., 1974. Evolution of anoxic conditions in the Black Sea during the Holocene. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea — Geology, Chemistry and Biology, Vol. 20. Mem. Am. Assoc. Pet. Geol., pp. 133–136.

Dimitrov, P.S., 1982. Radiocarbon datings of bottom sediments from the Bulgarian Black Sea Shelf. Bulg. Acad. Sci. Oceanol. 9, 45–53.

Evsylekov, Y.D., Shimkus, K.M., 1995. Geomorphological and neotectonic development of outer part of continental margin to the south of Kerch Strait. Oceanology 35, 623–628.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature (London) 342, 637–642.

Federov, P.V., 1971. Postglacial transgression of the Black Sea. Int. Geol. Rev. 14, 160–164.

Glenn, C.R., Arthur, M.A., 1985. Sedimentary and geochemical indicators of productivity and oxygen contents in modern and ancient basins: the Holocene Black Sea as the "type" anoxic basin. Chem. Geol. 48, 325–354.

Glumac, P., Anthony, D., 1991. The Caucasus. In: Ehrich, R. (Ed.), Chronologies in Old World Archaeology, 1. University of Chicago Press, Chicago, IL, pp. 196–207.

Greg, S.A., 1988. Foragers and Farmers — Polulation Interaction and Agricultural Expansion in Prehistoric Europe. University of Chicago Press, Chicago, IL, 275 pp.

Hodder, I., 1990. The Domestication of Europe. Blackwell, Oxford, 331 pp.

Jones, G.A., Gagnon, A.R., 1994. Radiocarbon chronology of Black Sea sediments. Deep-Sea Res. 41, 531–557.

Kuprin, P.N., Scherbakov, F.A., Morgunov, I.I., 1974. Correlation, age, and distribution of the postglacial continental terrace sediments of the Black Sea. Baltica 5, 241–249.

Major, C.O., 1994. Late Quaternary sedimentation in the Kerch area of the Black Sea shelf: response to sea level fluctuation. BA Thesis, Wesleyan University, Middletown, CT, 116 pp.

Mayard, N.G., 1974. Diatoms in Pleistocene deep Black Sea sediments. In: Degens, E.T. Ross, D.A. (Eds.), The Black Sea — Geology, Chemistry and Biology, Vol. 20. Am. Assoc. Petrol. Geol. Mem., pp. 389–395.

Meriç, E., Sakinç, M., 1990. Foraminifera. In: Meriç, E. (Ed.), Late Quaternary (Holocene) Bottom Sediments of the Southern Bosphorus and Golden Horn. Matbaa Teknisyenleri Basimevi Divanyolu, Istanbul, pp. 13–26.

Milliman, J.D., Emery, K.P., 1968. Sea levels during the past 35,000 years. Science 162, 1121–1123.

Nevesskaya, L.A., 1965. Late Quaternary bivalve mollusks of the Black Sea: Their systematics and ecology. Akad. Nauk S.S.S.R. Paleontol. Inst. Tr. 105, 1–390.

Ostrovskiy, A.B., Izmaylov, Y.A., Balabanov, I.P., Skiba, S.I., Skryabina, N.G., Arslanov, S.A., Gey, N.A., Suprunova, N.I., 1977. New data on the paleohydrological regime of the Black Sea in the Upper Pleistocene and Holocene. In: Kaplin, P.A., Shcherbakov F.A. (Eds.), Paleogeography and Deposits of the Pleistocene of the Southern Seas of the USSR. Nauka Press, Moscow, pp. 131–141.

Özdagan, M., 1983. Pendik, a Neolithic site of Fikirtepe culture in the Marmara region. Festschrift für K. Bittel, University of Mainz, Mainz, pp. 401–411.

Panin, N., 1972. Quaternary history of the Danube delta. Cercet. Mar. 4, 5–15.

Popov, G.I., 1973. New data on the stratigraphy of Quaternary marine sediments of the Kerch Strait. Dokl. Akad. Nauk S.S.S.R. 213, 84–86.

Ross, D.A., Degens, E.T., 1974. Recent sediments of the Black Sea. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea — Geology, Chemistry and Biology, Vol. 20. Am. Assoc. Pet. Geol. Mem., pp. 183–199.

Ross, D.A., Degens, E.T., MacIlvaine, J., 1970. Black Sea: recent sedimentary history. Science 170, 163–165.

Scherbakov, F.A., 1983. Continental Margins in the Late Pleistocene and Holocene. Nauka, Moscow, 123 pp.

Scherbakov, F.A., Kuprin, P.N., Potapova, L.I., Polyakov, A.S., Zabelina, E.K., Sorokin, V.M., 1978. Sedimentation on the Continental Shelf of the Black Sera. Nauka Press, Moscow, 211 pp.

Shimkus, K.M., Mukhina, V.V., Trimonis, E.S., 1973. On the role of diatoms in Late Quaternary sedimentation in the Black sea. Oceanologia 13, 1066–1071.

Shimkus, K.M., Emelyanov, E.M., Trimonis, E.S., 1975. Seafloor sediments and the late Quaternary history of the Black Sea. In: The Earth's Crust and the History of Development of the Black Sea Basin. Nauka, Moscow, pp. 138–162.

Shimkus, K.M., Evsyukov, Y.D., Solovjeva, R.N., 1980. Submarine terraces of the lower shelf zone and their nature. In: Malovitsky, Y.P., Shimkus, K.M. (Eds.), Geological and Geophysical Studies of the Pre-Oceanic Zone. P.P. Shirshov Inst. Oceanol., Acad. Sci. U.S.S.R., Moscow, pp. 81–92.

Skiba, S.I., Scherbakov, F.A., Kuprin, P.N., 1975. On paleogeography of the Kerch–Taman region in late Pleistocene and Holocene. Oceanologia 15, 862–867.

Sokal, R.R., Oden, N.L., Wilsin, C., 1991. Genetic evidence for the spread of agriculture in Europe by demic diffusion. Nature (London) 351, 143–145.

Taner, G., 1990. Lamellibranchiata ve gastropoda. In: Meriç, E. (Ed.), Late Quaternary (Holocene) Bottom Sediments of the Southern Bosphorus and Golden Horn. Matbaa Teknisyenleri Basimevi Divanyolu, Istanbul, pp. 81–93.

van Andel, T.H. and Runnels, C.N., 1995. The earliest farmers of Europe. Antiquity 69, 481–500.

Wall, D., Dale, B., 1974. Dinoflagellates in the late Quaternary deep-water sediments of the Black Sea. In: Degens, E.T., Ross, D.A. (Eds.), The Black Sea — Geology, Chemistry and Biology, Vol. 20. Am. Assoc. Pet. Geol. Mem., pp. 364–380.